# DETERMINING ENVIRONMENTAL SENSITIVITIES AND UNCERTAINTIES OF ALTERNATIVE FUELLED, ADVANCED TECHNOLOGY AND CONVENTIONAL ROAD VEHICLES USING LIFE CYCLE ASSESSMENT

By

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| | |
|---|---|
| **ABS** | Australian Bureau of Statistics |
| **ADAC** | Allgemeiner Deutscher Automobil-Club |
| **ADR** | Australian Design Rules |
| **AusLCI** | Australian Life Cycle Inventory |
| **BD** | Biodiesel |
| **BD5** | Contains 5% biodiesel and 95% diesel |
| **BD20** | Contains 20% biodiesel and 80% diesel |
| **BD100** | Contains 100% biodiesel (pure biodiesel) |
| **BEV** | Battery Electric Vehicle |
| **BITRE** | Bureau of Infrastructure, Transport and Regional Economics |
| **BRTS** | Bus Rapid Transit System |
| **CARB** | California Air Resources Board |
| **CIDI** | Compression-Ignition Direct-Injection |
| **CNG** | Compressed Natural Gas |
| **CO** | Carbon Monoxide |
| **CO2** | Carbon Dioxide |
| **CO2 eq** | Carbon Dioxide Equivalent |
| **C2G** | Cradle to Grave |
| **CUEDC** | Composite Urban Emissions Drive Cycle |
| **DPTI** | Department of Transport, Energy and Infrastructure |
| **E** | Ethanol |

| | |
|---|---|
| **E5** | Contains 5% ethanol and 95% gasoline |
| **E10** | Contains 10% ethanol and 90% gasoline |
| **E25** | Contains 25% ethanol and 75% gasoline |
| **E40** | Contains 40% ethanol and 60% gasoline |
| **E85** | Contains 85% ethanol and 15% gasoline |
| **E100** | Contains 100% ethanol |
| **EIA** | Environmental Impact Assessment |
| **ELV** | End-of-Life Vehicle |
| **ELCD** | European Life Cycle Database |
| **EPA** | Environmental Protection Agency |
| **EU** | European Union |
| **FCV** | Fuel Cell Vehicle |
| **GHG** | Greenhouse Gas |
| **GREET** | Greenhouse Gases, Regulated Emissions and Energy Use in Transportation |
| **GV** | Green Vehicle |
| **GVG** | Green Vehicle Guide |
| **GWP** | Global Warming Potential |
| **g/pkm** | Gram Per Passenger Kilometre |
| **g/tkm** | Gram Per Tonne Kilometre |
| **HC** | Hydrocarbon |
| **HEV** | Hybrid Electric Vehicle |
| **HTc** | Human Toxicity, Cancer |

| | |
|---|---|
| **HTnc** | Human Toxicity, Non-Cancer |
| **ICE** | Internal Combustion Engine |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISO** | International Organisation for Standardisation |
| **Kg** | Kilogram |
| **Km** | Kilometre |
| **kw** | Kilowatt |
| **kwh** | Kilowatt hour |
| **L** | Litter |
| **LSD** | Low Sulphur Diesel |
| **LCA** | Life Cycle Assessment |
| **LCCA** | Life Cycle Cost Assessment |
| **LCIA** | Life Cycle Impact Assessment |
| **LPG** | Liquified Petroleum Gas |
| **MJ** | Megajoule |
| **MPa** | Megapascal |
| **MJ/pkm** | Megajoule Per Passenger Kilometre |
| **NG** | Natural Gas |
| **NGAF** | National Greenhouse Accounts Factors |
| **NPI** | National Pollution Inventory |
| **NOx** | Oxide(s) of Nitrogen |
| **N2O** | Nitrous Oxide |

| | |
|---|---|
| **NEDC** | New European Driving Cycle |
| **NEPM** | National Environment Protection Council |
| **PHEV** | Plug-in Hybrid Electric Vehicle |
| **pkm** | Passenger Kilometre Travelled |
| **PRe** | Professional Organisation that Focuses on Sustainability Metrics |
| **PTW** | Pump to Wheel |
| **PM** | Particulate Matter |
| **PM2.5** | Particulate Matter less than 2.5 micron |
| **PM10** | Particulate Matter less than 10 micron |
| **THC** | Total Hydrocarbon Content |
| **SD** | Standard Deviation |
| **UNEP** | United Nation Environment Programme |
| **USA** | United States of America |
| **US EPA** | United States Environmental Protection Agency |
| **UK** | United Kingdom |
| **VOC** | Volatile Organic Compounds |
| **WTP** | Wheel to Pump |
| **WTW** | Well to Wheels |
| **$** | Australian Dollar |

# ABSTRACT

The Australian road vehicles, including conventional internal combustion engine running on petrol or diesel, is considered one of the main sources of greenhouse gas (GHG) emissions and environmental air pollution globally. Any methods that could be developed to improve environmental performance, thereby reducing GHG emissions, energy demand, particulate matter and human toxicity from vehicle emissions, can greatly benefit society globally. With the advent of alternative fuels and vehicles, new methods to evaluate their environmental benefits need to be developed. Life cycle assessment (LCA) has gone a long way to ensure that environmental evaluations of all types of vehicles and fuels are performed on a consistent, whole-of-life basis. However, a rigorous analysis of the input data for these LCA evaluations, plus their relatability and sensitivity to the results produced, needs to be undertaken to ensure that society, industry and government can make informed decisions based on the analysis of sound and reliable data. This thesis aims to:

1. examine the GHG emissions, particulate matter and human toxicity-cancer and non-cancer of transportation over a vehicle's lifetime using the life cycle assessment (LCA) method
2. examine the uncertainty of the input data for LCA evaluations
3. examine the sensitivity of the input data for LCA evaluations
4. apply the results from 1– 3 to a case study
5. make recommendations regarding how LCA can be used to evaluate conventional and alternative vehicle types to ensure a reduction of GHG and toxic emissions.

Internal combustion engine vehicle exhaust emissions are regulated by governments worldwide, and due to this important point, the environmental impact assessment of transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles is examined over vehicles' lifetimes. Given the recent uptake of alternative vehicles and fuels, there is now a requirement for vehicles' environmental impact to be examined over its lifetime. This thesis examines the environmental impact assessment of the road transport sector in Australia. Decision-makers should heed LCA methods in order to reduce the total effect of vehicle exhaust emissions on the environment and human health.

The LCA SimaPro software by PRé Consultants has been used to estimate the life cycle energy use and emissions of road transportation using the Australian National Life Cycle Inventory Database (AusLCI). Also, where possible, the case studies developed used Australian emissions sources, detailing the fuel pathway, tailpipe emissions, vehicle manufacture, vehicle maintenance and vehicle disposal over a vehicle's lifetime, as input for the LCA.

The thesis results indicate that advanced vehicle technologies and vehicles powered by alternative fuels are reducing energy use and emissions by 80%–90% compared to conventional internal combustion engine vehicles that are running on petrol or low sulphur diesel (LSD). Also, the results show that for most vehicles the major contributor to LCA energy use (ranging from 70%–90% of total LCA emissions) occurs during the vehicle operation phase. However, the contribution of the vehicles' manufacture phase for advanced vehicle technologies is higher (up to 90% of total LCA emissions). Furthermore, although battery electric vehicles have zero tailpipe emissions, the power supply generation creates significant emissions to the environment because electricity is usually generated from non-renewable energy sources (fossil fuels) in Australia.

Additionally, biofuel vehicle LCA results reveal that high biofuel blends, including $E_{85}$ and pure biodiesel, may be worse options due to the need to change the powertrain design.

Consequently, the use of low biofuel blends, including $E_{10}$ and BD5, is recommended to achieve lower vehicle exhaust emissions without changing the engine design.

In the case of vehicles' environmental rating, the results indicate that advanced vehicles or vehicles powered by alternative fuels have higher overall ratings or stars (indicating a high ranking), while conventional vehicles have lower scores (indicating a low ranking).

Furthermore, this thesis uses the environmental impact of public buses (Department of Planning Transport and Infrastructure [DPTI] Trial Buses) in the city of Adelaide, South Australia as a case study. The results indicate that the 1905/micro hybrid bus uses significantly less energy and produces fewer GHG emissions and less air pollution compared to other bus models, including the conventional LSD bus, due to many factors, including low fuel usage, high engine efficiency, the driving cycle and driver skills/behaviour.

In addition, in order to demonstrate the accuracy and reliability of the data and methods used to model LCA, this thesis used sensitivity and uncertainty analysis techniques to ensure that the input data was sound and thus able to produce reliable LCA results. The results show that the data used to build LCA human toxicity-cancer and non-cancer is the most unreliable. Moreover, the study used sensitivity analysis to examine how these parameters impact the outcomes. The analyses also show that many parameters, including vehicle occupancy rate, fuel consumption, distance travelled, vehicle manufacture, average load and electricity consumption, significantly impact all LCA results.

Finally, regarding direction for future research, the life cycle of automotive technology should include fuel production, vehicle manufacture, operations and maintenance of the vehicle throughout its lifetime, in addition to scrappage and recycling. The case of an automobile using a new fuel, such as electricity, resulting in little to no air pollution per kilometre travelled but that has much higher environmental impacts when the vehicle is scrapped or recycled, demonstrates why LCA is essential.

Hence, an important objective of this thesis is to make the LCA process transparent and usable for policy analysts. This is important thanks to the advent of new information, and as future technologies develop, LCA needs to be robust and trusted to provide reliable results.

# DECLARATION

I declare that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university and that, to the best of my knowledge, it does not contain any materials previously published or written by another person, except where due reference is made in the text.

**Ali Majeed Murshed**

**October 20, 2021**

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# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

Environmental Impact Assessment (EIA) is a process of evaluating the likely environmental impacts of a proposed project or development, considering interrelated socioeconomic, cultural and human-health impacts, both beneficial and adverse. The purpose of the assessment is to ensure that decision makers consider the environmental impacts when deciding whether to proceed with a project. Australian governments were amongst the first in the world to introduce EIA in the 1970s (Macintosh, 2010). The intention is to inform the policy development processes at the federal, state and local levels.

Transportation, mobility and accessibility are essential requirements for people and societies worldwide. The ability to move people and goods provides access to employment, delivery of goods, provision of services and societal interaction. Moreover, the transport sector is one of the essential facilitators of economic development in both developed and developing countries. Added to that, the number of vehicles has grown continuously worldwide, with most of these vehicles using fossil fuel, which contributes large amounts of emissions to the environment in Australia and around the world (BITRE, 2009). One of the aims of this thesis is to develop an evaluation framework that can contribute to reducing transportation's effect on the environment and human health.

In Australia, transportation is the third highest producer of greenhouse gas (GHG) emissions and air pollutants to the environment (Australian Government, 2008); however, it also brings a lot of economic benefits and social inclusion. Although railway and water transport have many economic benefits, their environmental impacts within the transport sector are small. Hence, in the context of this thesis, the transport sector includes passenger vehicles, public transport buses and heavy-duty truck vehicles, as commonly used in the Australian road transport sector (Van Fan et al., 2018). Most types of transportation are fuelled by non-renewable fuels (fossil fuels), causing a major challenge for the world's future because they release large amounts of GHG emissions and air pollutants into the environment. For every litre of fuel that is combusted, approximately 2.3 kg of GHG emissions and numerous toxic emissions are produced (Australian Government, 2019). Hence the transport sector affects both human health and the environment worldwide and is responsible for a lot of human disease, including human toxicity-cancer and non-cancer (Australian Government, 2008).

The transport sector, which includes passenger vehicles, public transport buses, heavy-duty truck vehicles and airplanes, has become one of the main sources of GHG emissions. It accounts for 17% of the Australian national GHG emissions inventory, and it is growing faster than any other sector due to powering by non-renewable energy (fossil fuels) (Barrett and Stanley, 2008).

Many studies and research projects have been undertaken in order to assess and reduce the effect of vehicle emissions on the environment. Unfortunately, the demand for private vehicles has increased and has contributed to exceeding the supply of transport infrastructure in both developing and developed countries: consequently, congestion, exhaust emissions and traffic accidents are increasing. Therefore, in order to decrease the effects of climate change and provide a pollution-free environment, it is necessary to address the problem of GHG emissions and air pollutants, and this is the goal of sustainable development (Intergovernmental Panel On Climate (IPOC), 2007).

Unlike many types of transportation, public transport buses have lower GHG emissions and air pollutants per passenger kilometre when compared to other types of transportation, including passenger vehicles, airplanes and heavy-duty truck vehicles. Transport vehicles account for 2% of total GHG emissions to the environment (King and Hensher, 1999). Therefore, advanced vehicle technology and/or alternative fuels can be considered a significant sustainable transportation option.

Most freight transport relies on fossil fuels, which release high amounts of emissions into the environment. In order to mitigate heavy-duty truck vehicle exhaust emissions, both advanced vehicle technologies and alternative fuels can be used to make the transport sector sustainable. The Australian government encourages and supports efforts to decrease the impact of freight transport on the environment because the transport sector has become a significant source of air pollutants and GHG emissions in Australia, especially in urban areas. Two methods for reducing vehicle exhaust emissions are detailed below:

1. Increase the use of alternative fuels, including compressed natural gas (CNG), liquified petroleum gas (LPG) and biofuel.
2. Increase the use of electric vehicles, including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs).

These two options (alternative-fuelled and advanced vehicles) have the potential to reduce both fuel consumption and emissions, thus helping mollify the concerns about climate change and human health. These types of heavy vehicles could be the best solution to lessen the impact of GHG emissions and air pollutants; however, they have many problems, including charging time, travel distance and electricity grid mix production that limit public acceptance.

Another option that produces zero tailpipe emissions is the FCV. This can use whether hydrogen instead of petrol or diesel in an internal combustion engine vehicle, so the vehicle exhaust emissions contain more oxides of nitrogen (NOX) and air pollutants or fuel cell vehicle uses hydrogen to power a fuel cell that increases car efficiency by more than 45% compared to conventional internal combustion engine vehicles (James, 2009).

To make the transportation system more sustainable and to reduce the effect of transportation on the environment and human health, there are many factors to consider. After a review of the literature (An Australian Government Initiative, 2020), the most common factors are listed below:

1. the role of public and private transportation
2. types of fuels
3. driving conditions, including speed limits
4. the price of $CO_2$ and other gas emissions
5. electricity generation (whether it is from renewable or non-renewable sources, such as fossil fuels)
6. battery manufacturers.

## 1.2 Climate Change and Transportation

There are many definitions of climate change. The Intergovernmental Panel on Climate Change (IPCC) defines it as a significant variation in the composition of the atmosphere due to many factors, such as natural processes, including volcanos, or due to external processes, including industry operations(Intergovernmental Panel On Climate (IPOC), 2007). Climate change is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as a change of climate, which is attributed directly or indirectly to human activity, which alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods(Yevdokimov, 2010). Therefore, generally, climate change can be defined as a significant change in temperature, rainfall, moisture and wind velocity, or a change that occurs over time due to human activities or natural variability. Climate change is caused by many factors as listed below (Yevdokimov, 2010):

1. the variation of global atmosphere composition that has an effect on the planet's balance
2. the absorption of gases in the atmosphere
3. the GHG emissions that derive from human activities, such as industry, oil companies and transportation. Carbon dioxide is considered the main GHG emitted by the transport sector globally, accounting for around 21% of total gas emissions, and it is expected to reach about 23% in the future. It is not the only gas that is classified within GHG emissions: two more gases, methane and nitrous oxide, are also classified as GHG emissions.

Climate change affects many sectors and has become a global problem. The affected sectors include agriculture, human health, ecosystems, water resources and tourism. By changing the transport sector's design, such as vehicle powertrain, vehicle operation phase, vehicle service and maintenance, vehicle emissions will be reduced. Figures 1.1, 1.2 and 1.3 represent the total GHG emissions released globally by human activities, and Figure 1.4 illustrates the trend in GHG emissions worldwide (BITRE, 2009).

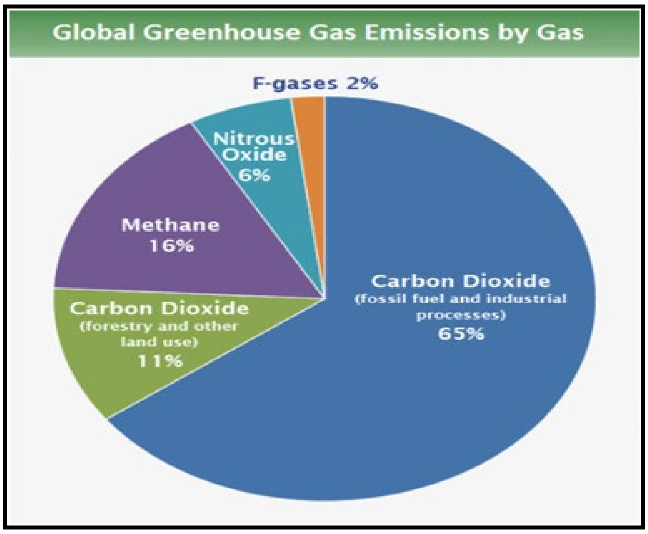


**Figure 1.1: GHG emissions worldwide (BITRE, 2009)**

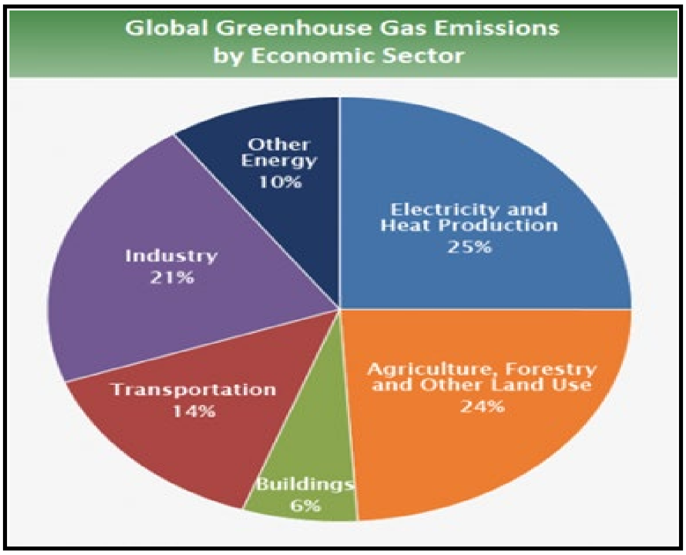


Figure 1.2: The contribution of GHG emissions by sector (BITRE, 2009)

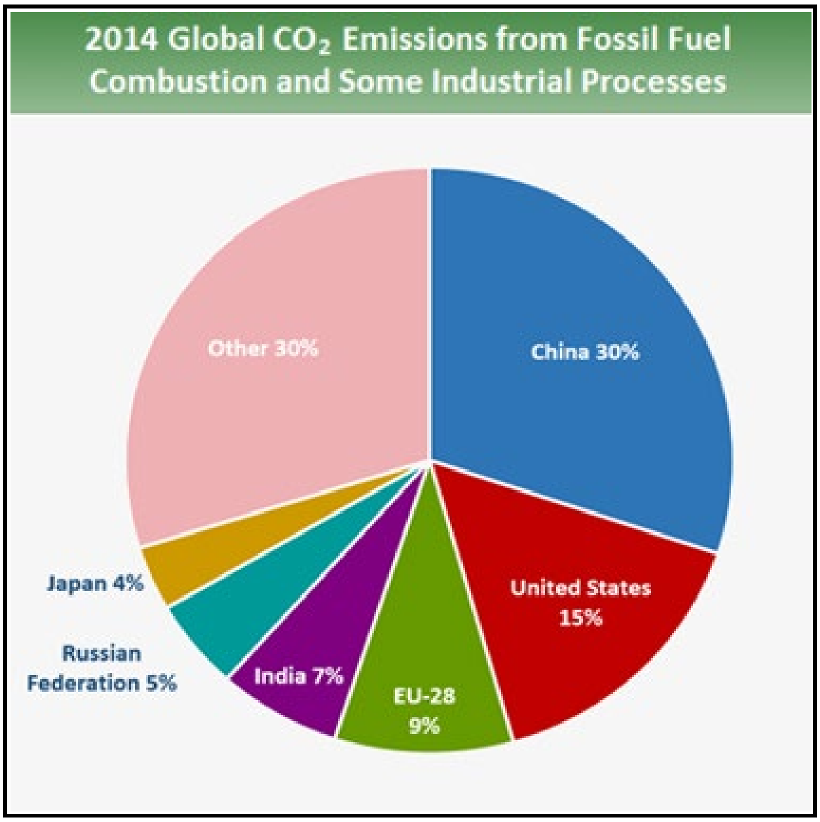


Figure 1.3: Worldwide GHG emissions by region (BITRE, 2009)

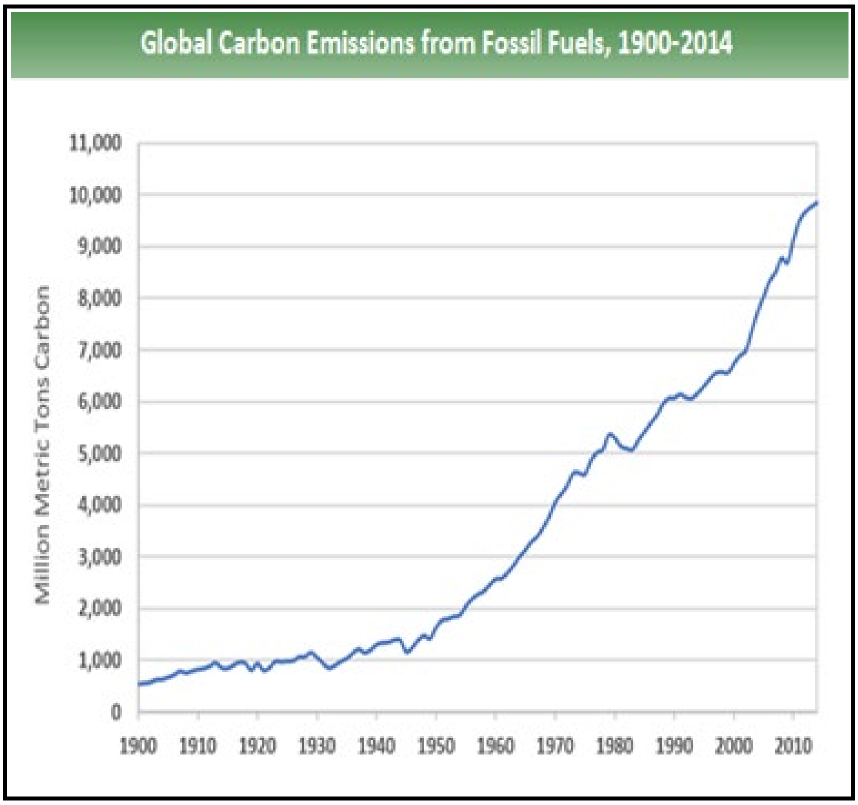


**Figure 1.4: The trend of GHG emissions globally (BITRE, 2009)**

## 1.3 The Environmental Impact Assessment of Vehicles

Globally, energy production is dominated by fossil energy sources, and if this consumption continues, the amount of emissions released into the atmosphere will continue to increase dramatically. This is because fossil fuels, derived from non-renewable sources, create challenges for the future due to high emissions that are released into the environment.

Road transportation is considered the second largest source of GHG emissions in the United States of America (USA), and their contribution to GHG emissions is huge compared to both developed and developing countries worldwide (Nigro and Jiang, 2013). In order to mitigate the effect of vehicle exhaust emissions on the environment and human health, vehicles powered by alternative fuel are an option because alternative fuels are usually derived from renewable energy sources (low carbon feedstock). Alternative fuels, including biofuel and biomass, can replace conventional gasoline or diesel (Puppan, 2002).

The Australian government is considered the first in the world to introduce the environmental impact assessment (EIA) in the 1970s. Since then, the government has encouraged reducing the effects of the transport sector on both the environment and human health by improving fuel production, resources and vehicle powertrains, introducing vehicle design rules that limit vehicle exhaust emissions and, lastly, encouraging better driving behaviour to lower vehicle exhaust emissions to the level of typical driving cycle emission production (Macintosh, 2010).

Historically, light vehicle emissions have been assessed by using a chassis dynamometer for regulatory and testing purposes. This can simulate typical regional driving conditions using the Australian driving cycle, the European driving cycle (NEDC) and the American driving cycle in a laboratory for different types of transportation, including both conventional vehicles and advanced vehicle technologies. Then, fuel consumption, GHG emissions, air pollutants and energy demand can be determined. Also, the vehicular on-board emissions database can be assessed and analysed. These results can be used to estimate the impact of vehicle emissions on human health in Australia, especially in urban areas (Bluett et al., 2008).

## 1.4 The Environmental rating of Vehicles

An environmental rating score for vehicles offers consumers information on fuel consumption and emissions performance when selecting a vehicle. It provides the following information:

1. the impact of vehicle/fuel combined use on the environment
2. the type of fuel
3. the fuel consumption
4. the kilometres travelled by the vehicle.

A vehicle's environmental rating score is found by estimating the vehicle's GHG emissions, air pollutants and fuel consumption during its lifetime. Then, a vehicle rating score is determined, as developed by the Australian Green Vehicle Guide (GVG), the European ADAC (Allgemeiner Deutscher Automobil-Club) EcoTest and the United States' Environmental Protection Agency (US EPA) (An Australian Government Initiative, 2020).

### 1.4.1 Green Vehicles

A green vehicle (GV) is defined as a vehicle that has a less harmful impact on both the environment and human health than conventional petrol or diesel vehicles because it produces less or even no GHG emissions and air pollutants. A GV might use renewable rather than conventional fuel or could be powered by liquid or gaseous hydrogen. A GV might use advanced vehicle technologies, which include HEVs, plug-in HEVs, BEVs and FCVs. GVs contribute to the sustainable transport sector by reducing the amount of emissions produced and energy used when they use biofuel or their blends at various proportions and can achieve a lower amount of energy consumption during the operation phase (tailpipe emissions) of the vehicle (An Australian Government Initiative, 2020). Three methods, as listed below, are used to determine the vehicle rating score for GVs.

#### *1.4.1.1 The Australian Green Vehicle Guide*

The Australian GVG is an important source of information about vehicle fuel consumption and emissions performance for Australian consumers. It is based on many factors, including kilometres travelled, annual fuel cost, fuel economy, fuel type, fuel emission regulations and annual fuel cost. It can provide customers with a great deal of information, such as $CO_2$ emissions, energy consumption, air pollution standards, fuel and electricity consumption, noise, vehicle manufacturer, vehicle tailpipe emissions (in the operation phase) in both urban and rural areas, fuel cost, electric range and fuel pathway (fuel cycle). In addition, it has the potential to evaluate the vehicle environmental assessment during the cradle-to-grave ($C_2G$) phase (vehicle manufacture, assembly and disassembly, vehicle service and maintenance, vehicle disposal and vehicle recycling) (An Australian Government Initiative, 2020).

#### *1.4.1.2 The European ADAC Eco Test*

The Eco Test is defined as a test that gives consumers more information on the vehicle rating score, vehicle manufacturer, fuel type, emission standards, fuel consumption, engine power, air pollutants and GHG emissions. It is evaluated and based on both GHG emissions, including CO2, CH4 and N2O, and air pollutants, such as CO, HC, $NO_x$, VOC, and particle matter (PM). The Eco Test can give information about different types of vehicles, including conventional and alternative, and it considers the EIA of the vehicle associated with fuel (oil extraction, oil transportation, oil refining), fuel distribution, vehicle operation, vehicle manufacture, vehicle service and maintenance, vehicle disposal and vehicle recycling. In addition, it covers various driving cycle conditions, such as Europe's, the USA's, Australia's and Japan's. Therefore, the Eco Test assesses vehicles using both the NEDC and ADAC cycle. Finally, it provides a rating for vehicles in different sizes and classes, such as family cars, passenger cars, supercars and luxury cars (ADAC, 2020).

#### *1.4.1.3 The United Stated Environmental Protection Agency*

The GVG, developed by the US EPA, offers consumers a database and information on conventional vehicles and advanced vehicle technologies. This information and the database pertain to exhaust emissions and fuel economy so that the environment will be safe and clean, and transportation will be sustainable (EPA, 2020).

## 1.5 Australian Design Rules

Transportation is the main source of air pollution and GHG emissions. It affects both the environment and human health, and it will affect the quality of life in our cities. Australian design rules (ADRs) are the standard used to regulate the amount of vehicle exhaust emissions produced from a vehicle, all Australian vehicles need to comply with these. It is important to define ADRs in order to reduce the harmful effects of the transport sector on the environment. ADRs address vehicle emissions, and noise and fuel consumption labelling. They are divided into seven headings as listed below (An Australian Government Initiative, 2020):

1. Smoke Emission Control for Diesel Vehicles (ADR30/01)
2. Emission Control for Light Vehicles (Euro 4) (ADR79/02)
3. Emission Control for Light Vehicles (Euro 5) (ADR79/03)
4. Emission Control for Light Vehicles (Euro 5) (ADR79/04)
5. Emission Control for Heavy Vehicles (Euro V with equivalent US and Japanese alternatives) (ADR80/03)
6. Fuel Consumption Labelling for Light Vehicles (ADR81/02)
7. External Noise (ADR83/00).

## 1.6 Types of Transportation and Exhaust Emissions

The transport sector, including passenger vehicles, public transport buses and heavy-duty truck vehicles, is responsible for emitting different kinds of gases. They are divided into two main types, which are outlined below:

### 1.6.1 GHG Emissions

GHG emissions are considered the main emissions released from human activity, such as industry, oil drilling and refining, manufacturing and transportation. They cause many natural phenomena, including global warming, hurricanes and extreme weather. GHG emissions are the combination of the following gases:

1. carbon dioxide ($CO_2$) that is generated from the combustion of coal, natural gas, oil, wood and waste
2. methane ($CH_4$), which is produced during the production of natural gas, coal, oil and organic waste
3. nitrous oxide ($N_2O$), produced via agricultural activities and industry.

All GHG emissions have a relationship with fuel sources and fuel economy. The exhaust emissions are used as a reference to provide information on vehicle use (tailpipe emissions). This is available on the GVG website. Furthermore, if the fuel is produced from renewable energy sources (low carbon feedstock), there will be fewer emissions; however, the emissions will increase if the fuel feedstock is from non-renewable energy (fossil fuels) (An Australian Government Initiative, 2020).

### 1.6.2 Air Pollutants

Toxic emissions can cause human toxicity-cancer and non-cancer, and it can directly impact human life. The main source of air pollution is from both the transport sector and industry, but the majority are generated from transportation. Typically, the focus is on three kinds of air pollutants from vehicles as listed below:

1. PM, produced when many gases react in the atmosphere
2. human toxicity, cancer (HTc), referring to any substance, radionuclide or type of radiation that causes cancer in humans, including some bacteria
3. human toxicity, non-cancer (HTnc), referring to a substance that can damage human health.

The amount of air pollutants can be limited based on the production of fuel or fuel sources. Furthermore, the amount of air pollutants can be changed by using different types of vehicles, including conventional or advanced technologies (Australian Government, 2008).

There are many ways in which the effects of vehicles on humans and the environment can be evaluated. The following sections introduce some of the more common approaches.

## 1.7 Life Cycle Assessment

Life cycle assessment (LCA) is an environmental management tool that generates information on the environmental impact of the production or service of a vehicle over the course of its lifetime. Also, it is defined as a technique to systematically evaluate the environmental impact associated with a product during its lifetime. Moreover, it is known as a cradle-to-grave ($C_2G$) assessment of a product, from material extraction, use, recycling and disposal. LCA is designed to help identify the manufacturing processes that can be improved for sustainability. It is considered an integral part of the evaluation of the vehicle/fuel system. It is often used to determine the energy inputs and emissions from various fuel and vehicle options (UNEP, 2013). Emissions related to vehicle manufacture, maintenance and disposal, and road building are relevant to total transport emissions, but they are not likely to vary significantly according to the fuel used. The infrastructure associated with refuelling various alternative fuels is difficult to assess and is therefore ignored in many studies.

LCA measures the impact of each component of the production – from fuel production (oil extraction, oil transportation, oil refining and fuel distribution), to vehicle production (raw material extraction, material transportation, material production, vehicle manufacture, assembly and disassembly, service and maintenance, recycling, and end of life) and to the vehicle operation phase (tailpipe emissions). Moreover, LCA calculates the total energy use, GHG emissions and air pollutants for transportation, including passenger vehicles, public transport buses and heavy-duty trucks, associated with different fuel resources during vehicle lifetime (Unnasch and Chan, 2007). The whole life cycle, as shown in Figure 1.5, is divided into three independent stages as listed below:

1. the fuel cycle (fuel pathway) stage, which includes the recovery or production of the feedstock for the fuel, transportation and storage of the energy source, and distribution of the fuel to the vehicle tank
2. the vehicle operation phase stage, which refers to the vehicle operation activities throughout its lifetime, including vehicle servicing and maintenance
3. the vehicle's manufacture, including material extraction and production, vehicle assembly and disassembly, recycling and the vehicle's end of life.

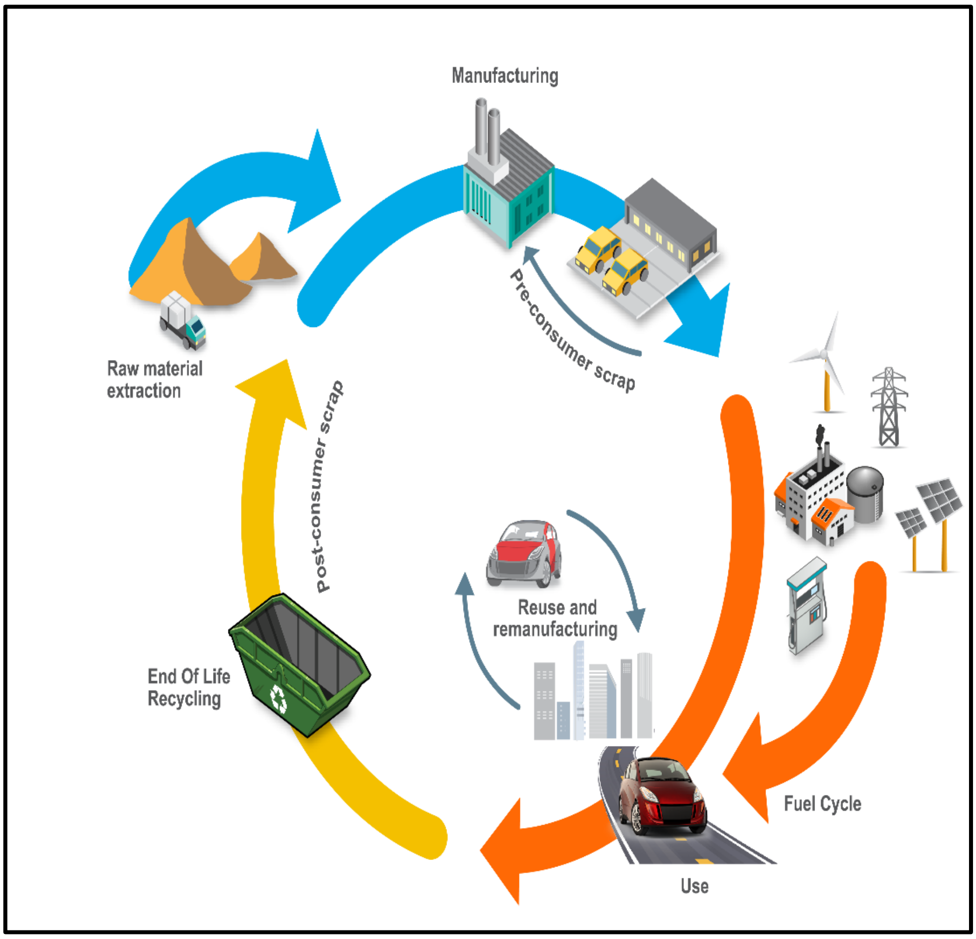


Figure 1.5: LCA phases (Unnasch and Chan, 2007)

Basically, life cycle assessment has three phases with a general interpretation step for each phase (Williams, 2009). Figure 1.6 shows the life cycle assessment steps as listed below:

1. the goal and scope of the project, including the boundaries, assumptions, allocations and procedures
2. the life cycle inventory analysis where the data is collected and analysed, and the calculations of the energy and material flows occur
3. life cycle impact assessment, which depends on the results to evaluate and estimate the effects of emission factors on the environment.

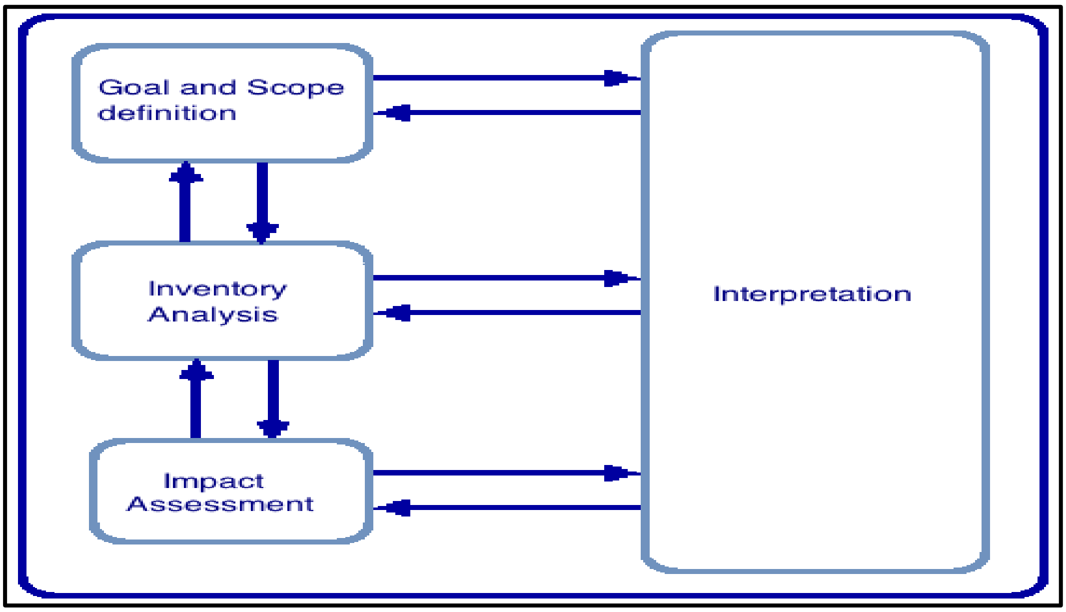


**Figure 1.6: LCA steps (Williams, 2009)**

Both the fuel cycle (fuel pathway) and vehicle operation phase (tailpipe emissions) are considered parts of the life cycle emissions, as defined in many studies; however, the emissions during the vehicle operation phase (service and maintenance) and the vehicle non-operational phase (manufacture, disposal and recycling) are also an important part of the life cycle emissions that are impossible to ignore because the level of emissions sometimes exceeds the emissions released during fuel cycle (fuel pathway). The full life cycle emissions comprise emissions from the fuel cycle and from both the vehicle operational and non-operational phases.

### 1.7.1 The Fuel Cycle (Fuel Pathway)

The processes of fuel production, from oil extraction to transportation and distribution to refuelling, require energy use. Furthermore, these processes produce significant GHG emissions and air pollutants. The level of emissions during the fuel cycle depends on the specific fuel resources used, such as crude oil, canola, tallow, oil sands or biomass. If the fuel is produced from renewable sources, the emissions will be lower; however, the emissions will increase if the fuel feedstock is from non-renewable energy. This is followed by electricity generation – whether the electricity is produced from fossil fuels or renewable energy sources. Fuel life cycle emissions can be calculated and estimated, according to the GVG website, by defining the direct, indirect and various emissions factors from the Australian National Greenhouse Accounts Factors (NGAF) so that the final GHG emissions and air pollutants can be determined (Australian Government, 2019).

### 1.7.2 The Vehicle Operation Phase (Tailpipe Emissions)

The transport sector is a major source of both GHG emissions and air pollutants relative to other sectors, such as factories, power plants and heavy industry. Yet, it is possible to reduce or minimise emissions during the vehicle operation phase because most forms of transportation are currently powered by fossil fuels. Transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles, contributes more than 10% of the total global $CO_2$ emissions (WorldAutoSteel, 2020). Added to that, during the vehicle operation phase, the vehicle requires servicing and maintenance. This process involves large energy consumption over the vehicle’s lifetime, so their impact on the environment and human health cannot be ignored.

### 1.7.3 The Vehicle Non-Operational Phase (Vehicle Manufacture)

Vehicle manufacture involves multiple processes, including manufacturing the vehicle components, vehicle assembly and disassembly, vehicle end of life and recycling. Each process can generate a lot of GHG emissions and air pollutants. The LCA of the vehicle non-operational phase includes the energy consumption and emissions released during the manufacture of the vehicle body, powertrain, transmission (manual or automatic), chassis, generator, controller and other auxiliary parts, and the replacement of vehicle components, including the powertrain, battery and tyres. The environmental impact of vehicle manufacture is lower than that of the vehicle operation phase and fuel cycle; nonetheless, the vehicle manufacture processes are not factored into the GVG, ADAC and US EPA rating scores due to uncertainty of the values and the high costs involved to determine them. In general, though energy consumption and the volume of emissions released tend to be higher during the vehicle operation phase (tailpipe emissions) than during vehicle manufacture and the fuel cycle, these phases cannot be ignored (Cooperation, 2004).

### 1.7.4 Vehicle End of Life

End-of-life vehicles (ELV) refer to vehicles that are removed from use for a range of reasons, including damage, age or at the owners’ request. This definition is based on the Australian context (Victoria, 2007). It is worth noting that some vehicle parts, including steel and aluminium components and batteries, can be recycled. Furthermore, it is possible to estimate or calculate the energy used and GHG emissions and air pollutants released during the recycling process. However, due to the difficulty of obtaining these values and their unreliability, the environmental impact of vehicle component recycling is usually ignored. Yet, ELV disposal is a significant contributor to Australia's annual waste and is increasing because more vehicles are discarded each year as the average lifetime (age) of vehicles decreases.

## 1.8 Life Cycle Cost Assessment

Life cycle cost assessment (LCCA) is a method used to estimate the cost associated with fuel use over a vehicle's lifetime. Vehicle life cycle cost can be divided into two categories:

1. fixed vehicle costs, including insurance, fees and interest costs
2. variable vehicle costs, including fuel, maintenance, tyres, oil and battery costs.

The evaluating vehicle costs is very important because it provides consumers with information about external (exhaust emissions) costs, servicing and maintenance costs, and operation costs, plus a vehicle's economic worth over the course of its lifetime.

The life cycle cost of a vehicle is divided into five phases, as listed below:

1. capital cost, including purchase, insurance and infrastructure
2. operation cost, including servicing and maintenance, spares and insurance
3. fuel cost, based on the vehicle model
4. manufacture cost, including assembly, and disassembly
5. disposal cost.

Furthermore, the vehicle life cycle cost can help purchasers make decisions about whether keeping a vehicle remains economically viable based on a large amount of data, including vehicle efficiency, fuel economy, emissions, insurance and servicing and maintenance.

The cost of vehicle maintenance depends on many factors, such as vehicle age, driving cycle, vehicle payload and kilometres travelled. Most vehicles have predictable mid-life costs for the replacement of components, such as the battery, tyres, oil and powertrain, and repair of exhaust, cooling system, fuel system, brake pads and transmission (Guo, 2016).

## 1.9 Well-to-Wheels Analysis

Well-to-wheels (WTW) analysis refers to a specific LCA that is used to estimate the energy consumption, GHG emissions and air pollutants for fuel/vehicle combined use during a vehicle's lifetime. It is used to calculate LCA for the fuel cycle from raw material acquisition (the eponymous 'well') to the energy consumption used to move the vehicle. The difference between life cycle assessment and WTW analysis is that the latter does not consider energy consumption, GHG emissions and air pollutants associated with vehicle manufacture, recycling and disposal. Moreover, WTW analysis focuses on tank-to-wheel (the operation phase) because it primarily considers the contributions of energy use and emissions. WTW is divided into two stages:

1. well-to-tank analysis (WTT), which includes resource extraction, oil production, oil transportation, oil refining, fuel production, fuel distribution and refuelling
2. tank-to-wheel analysis (TTW), which includes the energy used, plus the GHG emissions and air pollutants released during vehicular activities.

In short, the total WTW energy use, GHG emissions and air pollutants is a combination of both the fuel cycle (WTT) and vehicle operation phase (TTW) (Rousseau and Sharer, 2004).

## 1.10 Thesis Aims

This thesis aims to holistically determine the environmental impact of the transport sector in Australia. The total life cycle assessment of vehicles needs to include an assessment over the entire vehicles' lifetime. This includes life cycle assessment of passenger vehicles, public transport buses, heavy-duty truck vehicles fuelled by renewable energy. This thesis aims to determine the environmental rating of vehicles to help consumers obtain more information about exhaust emissions, fuel economy and a vehicle's impact on the environment based on a holistic life cycle approach. The thesis will use uncertainty analysis to examine the data used to build life cycle modelling in the transport sector. Sensitivity analysis of LCA results will be conducted and analysed to check the effect of selecting different assumptions, factors and parameters on output results. The thesis will examine different types of transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles, and ask whether each mode of transportation uses conventional or advanced technologies. The thesis will examine the South Australian Department of Planning Transport and Infrastructure's (DPTI) public transport buses as a case study. The thesis's specific objectives are outlined below:

1. Perform life cycle assessment:

   In this section, LCA energy demand; GHG emissions; air pollutants, such as particulate matter; and human health, cancer and non-cancer toxicity originating in the transport sector, including passenger vehicles, public transport buses and heavy-duty truck vehicles, are estimated for vehicles' lifetimes. This includes the fuel pathway (all types of fuels and electricity generation) and vehicle operation (tailpipe emissions and vehicle maintenance) manufacture and disposal phases.
2. Develop an approach to estimate vehicles' environmental rating scores.
3. Perform life cycle assessment of biofuel vehicles:

   This section includes the energy demand and emissions of biofuel vehicles, including bioethanol passenger vehicles and biodiesel public transport buses, during the vehicle's lifetime. Also, renewable fuels and fossil fuels will be compared and assessed.
4. Use LCA to quantify GHG emissions, energy consumption and human health affect.

5. Undertake a check using uncertainty analysis to investigate all data and parameters used to build the final LCA results.
6. Check LCA results using sensitivity analysis.

## 1.11 Thesis Structure

The thesis structure consists of eleven chapters, described below:

1. **Chapter 1** introduces the EIA of vehicles over their lifetime and discusses how transportation impacts climate change and human health. It then defines the life cycle assessment approach to estimating total energy use and emissions over a vehicle's lifetime.
2. **Chapter 2** offers a literature review of life cycle emissions of vehicles using different fuels over the vehicles' lifetimes. Also, it provides the thesis's research background.
3. **Chapter 3** provides the formulation for an approach that simulates and estimates the whole life cycle GHG emissions, energy consumption and air pollutants of both conventional and advanced vehicle technologies associated with different types of fuels. In addition, it presents the thesis's conceptual model.
4. **Chapter 4** reports the results of the LCA for transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles, using different fuels.
5. **Chapter 5** examines the uncertainty analysis of the LCA.
6. **Chapter 6** presents a sensitivity analysis of the LCA's input parameters.
7. **Chapter 7** assesses the LCA results for biofuel vehicles.
8. **Chapter 8** presents the LCA case study, looking at South Australia's public transport buses.
9. **Chapter 9** estimates vehicles' environmental rating scores.

10. **Chapter 10** discusses the study’s conclusions and makes recommendations for future work relating to the EIA of the transport sector in Australia to improve life cycle assessment theory.
11. **Chapter 11** contains the bibliography.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Literature Review

This section includes a summary of the literature reviewed for this study. The literature review focuses on the following six main areas:

1. The environmental evaluation of fuel: This section will focus on studies that examined different types of fuel, including conventional and alternative fuels.
2. Life cycle assessment (LCA) of vehicles: All types of transportation, including passenger vehicles, public transport buses, heavy-duty truck vehicles and biofuel vehicles, will be considered in this section, and it will include conventional and advanced vehicle technologies. It will focus on the environmental impact assessment during the fuel cycle (fuel pathway), vehicle operation phase (tailpipe emissions and maintenance) and vehicle non-operational phase (vehicle manufacture and disposal). Furthermore, studies that look at the life cycle costs of vehicles will be reviewed.
3. Well-to-wheel analysis studies of fuel/vehicle combined use.
4. The environmental rating scores of vehicles: This section will focus on vehicle rating scores that give consumers more information on the impact of vehicles on both the environment and human health.
5. Software used to estimate the whole life cycle assessment, including the LCA SimaPro software and gases, regulated emission and energy use in transportation (GREET) model.
6. Uncertainty and sensitivity analysis studies: This section will focus on the studies that examined uncertainty in and sensitivity of data used to build LCA modelling and the impact of key parameters, assumptions and factors on outcomes.

## 2.2 Environmental Evaluation of Sustainable Fuel

Sustainable fuel, or fuel derived from renewable energy, such as biofuel, is considered an environmentally friendly fuel due to its lower impact on the environment. In this area, there are many authors who have conducted studies (Sato et al., 2012, Unnasch et al., 2011, Pleanjai et al., 2007, Feehan and Petersen, 2004, Puppan, 2002). They assessed the impact of biofuel on both the environment and human health. They chose different types of biofuel production (different fuel resources) and assessed each type, seeking results that could benefit the transport sector in the future. Additionally, authors considered whether the use of biofuel instead of conventional fuel is the best option to reduce GHG emissions and air pollutants and hence be environmentally friendly. Also, the authors used various driving behaviours, such as Australian driving conditions, on-road Japanese driving tests, vehicle chassis dynamometer test and engine tests. The results indicated that biomass is the best option compared to other types of biofuel due to its low price and low impact on the environment. Moreover, the results showed that biofuel plays a major role in making the environment safer due to their lower GHG emissions (Sato et al., 2012). Furthermore, authors found that palm oil is the highest producer of $N_2O$, $NO_2$, CO and PM, which impact ozone formation (Unnasch et al., 2011). Lastly, the authors concluded that $NO_x$ increases when biodiesel fuel is used while $NO_x$ emissions do not change much when the vehicle switches to diesel fuel during both chassis' dynamometer and on-road driving cycle tests.

Nevertheless, due to the lower emissions to the environment, the use of biofuel-powered vehicles is increasing in Australia. A number of researchers (Özçelik et al., 2015, Ashnani et al., 2015, Nair et al., 2013, Anderson, 2011, Xue et al., 2011, Tessum et al., 2010, Beer and Grant, 2007, Wu et al., 2006a, Beer et al., 2004, Durbin and Norbeck, 2002, Wang et al., 1999) have studied the environmental impact assessments of biofuel-powered vehicles. They examined various types of transportation, including passenger vehicles and public transport buses, and used both conventional and advanced vehicle technologies to measure vehicle exhaust emissions. In addition, the authors used on-road and dynamometer tests to estimate the GHG emissions and air pollutants of vehicles over their lifetimes. They indicated the advantages of both bioethanol and biodiesel and their impact on the environment. Results showed that the use of biodiesel can significantly reduce both GHG emissions and air pollutants (PM, CO and HC); however, there were significant increases in both NOx and fuel consumption when compared to conventional vehicles (vehicles powered by either petrol or diesel). The authors were concerned about two issues. First, when pure biofuel is used, it requires modification of the powertrain system, and loss of engine power will occur due to a lower heating value of the fuel, even though it has a lower energy content and produces fewer emissions compared to both conventional fuels and biofuel blends. The second concern is that vehicles can emit toxic gases, including PM10 and PM2.5, which can impact human health (and therefore human life) directly. The authors concluded the following points:

1. In order to control the vehicle exhaust emissions and engine power, it is important to use a low level of biodiesel blends with diesel (Xue et al., 2011).
2. $E_{10}$ is the best option to power vehicles compared to conventional petrol vehicles. Although its use results in a decrease in vehicle power and emissions, it does not require powertrain modification(Tessum et al., 2010).
3. Public and private consumers' acceptance of fuel/vehicle are factors to be considered when developing sustainable transportation (Özçelik et al., 2015).

## 2.3 Life Cycle Assessment

### 2.3.1 LCA Explanation

Life cycle assessment (LCA) is an important approach to estimate the energy use, GHG emissions and air pollutants of fuel/vehicle over a vehicle's lifetime. (Williams, 2009) presented a report on life cycle assessment (a step-by-step approach). He indicated that in order to complete a successful LCA, information and details to complete a full life cycle assessment are needed. He defined the four steps to evaluate the impact on both human health and the environment. These steps include (1) scope and definition development, (2) life cycle inventory, (3) life cycle impact assessment and (4) a discussion of the results and recommendations (Williams, 2009). Also, (Van Mierlo et al., 2009) published a report on life cycle assessment and policy measures. They submitted a number of suggestions, such as how to develop LCA and how to estimate the whole life cycle assessment, including fuel cycle, the vehicle operation phase and vehicle manufacture phase ($C_2G$). The authors concluded that LCA can be classified into three phases: goal and scope, inventory analysis and impact assessment. Finally, (Rahman et al., 2013) presented a study on an integrated life cycle assessment of vehicles by focusing on both the vehicle operation and non-operational phases. They formulated a driving cycle in Singapore to estimate GHG and air pollution emissions. The authors showed that the operation and non-operational phases contribute 55% and 45% of total life cycle GHG emissions, respectively.

### 2.3.2 Life Cycle Assessment of Passenger Vehicles

Globally, passenger vehicles (especially private cars) play a very large role in emissions production. There are many references describing how GHG emissions and air pollutants from passenger cars over their lifetimes can be reduced (Wolfram and Wiedmann, 2017, Jochem et al., 2015, Nealer and Hendrickson, 2015, Messagie et al., 2014, Joseck and Ward, 2014, Nigro and Jiang, 2013, Agarski et al., 2012, Baptista et al., 2011, Taylor et al., 2010, Lane and Consultancy, 2006, MacLean and Lave, 2003, Castro et al., 2003, Davis et al., 2003, MacLean et al., 2000).The authors used various types of passenger vehicles, including conventional internal combustion engines, hybrid, plug-in, fuel cell and battery electric, associated with different types of fuels, including conventional and alternative fuels. They indicated that there are two options to make vehicles sustainable: the first option is to reduce the use of fossil fuels by using renewable fuel (low carbon intensity), and the other option is to use advanced vehicle technologies, including battery electric, hybrid and plug-in vehicles. In addition, they identified many factors, including electricity production, vehicle weight, vehicle age and vehicle driving cycle, all of which affect the overall LCA results. Results showed that fuel feedstock is an important factor in reducing GHG emissions, namely, if the feedstock has low carbon intensity, there will be fewer emissions; however, the emissions increase when fuel the feedstock has high carbon intensity. The results also showed that advanced vehicle technologies, such as electric vehicles, save a lot of emissions if the electricity is generated from renewable sources. Furthermore, the results indicated that the vehicle operation phase (tailpipe emissions) is still the main contributor of GHG emissions for conventional vehicles. The authors concluded by outlining the following points:

1. The fuel pathway (fuel feedstock) is very important to analyse, compare and select the best way to achieve low carbon intensity and reduce GHG emissions (Jochem et al., 2015).
2. The vehicle manufacture phase (vehicle cycle) contributes 10%–22% of total life cycle GHG emissions, but in battery/plug-in electric vehicles, the manufacturing phases only accounted for 1%–8% of total life cycle GHG emissions (Nealer and Hendrickson, 2015).

3. Improving the driving cycle and recharging time and using electricity generated from renewable energy are good options for making a vehicle ‘green’ (Nigro and Jiang, 2013).
4. Vehicle size plays an important role in increasing or decreasing vehicle exhaust emissions due to its effect on fuel economy (Castro et al., 2003).
5. Alternative fuel-powered vehicles produce 18%–24% fewer emissions in their total LCA compared to baseline petrol vehicles (Messagie et al., 2014).
6. The use of fuel cell vehicles can significantly reduce GHG and air pollution emissions (CO and NOx) and can be a sustainable means of transportation when the hydrogen is produced from renewable energy sources (Joseck and Ward, 2014).
7. The challenge facing hydrogen FCVs is how to store enough high-pressure hydrogen for/in on-board vehicle systems (Taylor et al., 2010).

### 2.3.3 Life Cycle Assessment of Public Transport Buses

Due to their low price, the use of public transport buses by passengers is increasing worldwide. Unsurprisingly then, many studies focused on life cycle assessment for buses associated with different types of fuel, (Cuéllar et al., 2016, Cooney et al., 2013, Ally and Pryor, 2007, King and Hensher, 1999). Authors used different techniques, such as bus rapid transit systems (BRT), to compare other types of passenger transportation, and they also used both automatic and manual buses. This system will improve public transport by giving buses priority by either providing separate transit lanes or dedicated bus-only roads. The future for BRT is bright. Rapid motorization and ever worsening traffic conditions in many rapidly emerging economies and fast-growing cities make investments in high capacity, high performance transit systems more imperative than ever (Cervero, 2013).

In addition, the authors examined various types of buses, such as conventional, hybrid, plug-in, fuel cell and battery electric. Furthermore, they considered both conventional and alternative fuels. The authors identified many factors that significantly influence vehicle exhaust emissions, including fuel cell stack manufacturing, recycling and hydrogen infrastructures.

Results showed that hydrogen-powered buses produce more than 50% fewer GHG emissions compared to conventional and advanced buses, and electric buses also display a significant reduction in emissions compared to the BRT system (buses powered by diesel fuel )(Ally and Pryor, 2007). In addition, the results highlighted that the BRT system is growing and has become a sustainable transportation mode in many cities worldwide. Moreover, the results revealed that the tailpipe emissions phase of conventional buses contributes significant emissions to the environment, while the battery manufacture phase for electric buses also contributes a lot of GHG emissions (Cuéllar et al., 2016). Lastly, (Cooney et al., 2013) that battery electric buses can achieve a significant reduction in GHG emissions if the electricity is generated from low carbon resources and improving the battery electric bus can save emissions relative to other types of transportation. Furthermore, as the bus industry replaces manual vehicles with automatic vehicles, it can see a noticeable overall increase in CO2 emissions. This is even though automatic vehicles over time are becoming more emission friendly. The challenge remains to find ways of reducing CO2 emissions of automatic buses as they replace manual buses in similar operational contexts without increasing the amount of emissions. This will be quite a challenge given that manual transmissions produce emissions that are typically 60-70% lower than those produced by automatic transmissions (King and Hensher, 1999).

Many authors focused on the advantages of advanced bus technologies (Ercan and Tatari, 2015, Kytö et al., 2012, Cooper et al., 2012, Williamson, 2012, Victorian department of transport, 2010). These authors examined various types of alternative buses and used different programmes, including sustainable urban transportation fuel/vehicle (SUTFV). Also, to measure bus GHG emissions and air pollutants, they examined buses in different cities around the world (namely, India, Brazil and Mexico). The results indicated that the battery electric bus has a significant reduction in $CO_2$ emissions relative to conventional and alternative fuel-powered buses, and that driving behaviour and average driving cycle speed also affect bus exhaust emissions and fuel consumption. Moreover, the results revealed that due to lower GHG emissions and air pollutants, the use of compressed natural gas (CNG) buses has increased in Australia. Additionally, the authors assessed the effect of buses on human health. They found that hybrid buses produce more HC and NOx emissions than conventional low sulphur diesel (LSD) buses. Furthermore, the results demonstrated that public transport buses powered by natural gas produce fewer PM and NOx emissions than diesel buses because the former use spark ignition from gas engines (Cooper et al., 2012). Finally, (Williamson, 2012) highlighted the importance of modifying the spark ignition engine by using dual cycle heat to increase engine efficiency in order to reduce air pollution and GHG emissions.

### 2.3.4 Life Cycle Assessment of Heavy-Duty Truck Vehicles

Freight transport accounts for about 27% of global transport energy use, and up to 90% of that is used by heavy-duty truck vehicles. Moreover, heavy-duty truck vehicles' energy consumption is predicted to increase by 50% by 2050 (Fulton et al., 2009).

Unfortunately, few studies have been done on the environmental impact assessment of heavy-duty truck vehicles., (Hao et al., 2012, Nwanze et al., 2010, Kamakate and Schipper, 2009), (Mötzl, 2009, Facanha and Horvath, 2007, Spielmann and Scholz, 2005, Beer et al., 2002, Gaines, 1998), all submitted papers, journals and reports on the life cycle GHG emissions of heavy-duty truck vehicles associated with conventional and alternative fuels. The authors questioned whether there is potential to reduce the fuel consumption and emissions of heavy-duty truck vehicles in the future, and they demonstrated that alternative fuel is the best option to power heavy-duty truck vehicles due to its low effect on human health and the environment. In addition, they indicated that improving the vehicle powertrain system and driving behaviour and reducing truck load and weight can significantly reduce GHG emissions and fuel consumption. The results revealed that when heavy-duty truck vehicles are powered by alternative fuels, the GHG and air pollution emissions are lower than when powered by fossil fuels. Finally, the authors concluded with the following points:

1. There are many types of alternative fuel, but supplies are limited or are expensive in Australia, and they require modification in vehicle powertrain (change of design) (Beer et al., 2002).
2. During the operation phase, heavy-duty truck vehicles have lower NOx emissions than water transportation (Gaines, 1998).
3. If the fuel consumption rate, mileage utilisation rate and use of liquefied natural gas are improved, fuel consumption and GHG emissions will be significantly reduced (Hao et al., 2012).
4. NOx emissions are relevant to fuel consumption, while PM10 emissions are affected by both the fuel cycle and vehicle manufacture phase (Facanha and Horvath, 2007).
5. Heavy-duty truck vehicles will be a sustainable means of transportation if driving cycle, load factor and truck capacity are improved (Kamakate and Schipper, 2009).

The literature reviewed did not consider travel demand options to reduce emissions from travel. The focus was on the emissions produced from the vehicles themselves in their various configurations. While travel demand reduction is important in the overall context of reducing the impact of transportation, its significance in life cycle assessment is limited.

### 2.3.5 Life Cycle Assessment of Biofuel Vehicles

A biofuel vehicle is considered a sustainable vehicle that releases fewer GHG emissions and air pollutants into the environment. There have been many studies into the life cycle assessment of biofuel vehicles. (Xue et al., 2011) presented a study on the effect of biodiesel fuel on engine performance and emissions. They stated that biodiesel buses produce significantly less $CO_2$, PM, CO and HC but significantly more $NO_x$ than conventional LSD buses. They suggested that it is important to use a low level of biodiesel in order to control air pollution.

(Tessum et al., 2010) presented a study of the LCA of biofuel vehicles compared to petrol vehicles. They showed that $E_{85}$ has the lowest impact on the environment, followed by BD20, then E10. (Wang et al., 1999) studied the effect of using ethanol fuel on the fuel cycle. They indicated that compared to vehicles fuelled by petrol, E10 vehicles have 6% lower fuel consumption, 1% lower GHG emissions and 3% less energy consumption. Additionally, they showed that E85 vehicles enjoy a 75% reduction in fuel consumption, a 19% reduction in GHG emissions and a 35% reduction in energy consumption compared to petrol vehicles. (Wu et al., 2006a) examined the LCA of biofuel vehicles. They showed that there is a significant reduction in energy consumption and GHG emissions when biofuels are used instead of petrol. Also, they indicated that when biofuel vehicles are driven in urban areas, there is a huge reduction in PM, $SO_x$ and $NO_x$ compared to conventional vehicles. (Ashnani et al., 2015) evaluated the environmental impact assessment of vehicles associated with different fuels, such as petrol, diesel and CNG. They proved that biofuel vehicles are better for climate change and human health than conventional vehicles. (Nair et al., 2013) presented a study on the life cycle assessment of biodiesel buses. They indicated that biodiesel buses release fewer GHG emissions, particulate matter and air pollutants relative to conventional vehicles; however, biodiesel buses release more $NO_{x\ in}$to the environment (Nair et al., 2013). (Özçelik et al., 2015) revealed that the use of 2%–5% ethanol blended with 95% petrol can significantly reduce a vehicle's exhaust emissions, including $CO_2$, CO, HC and $NO_x$. Similarly, (Anderson, 2011) examined the effect of biodiesel fuel on vehicle exhaust emissions and found no significant difference for light and heavy-duty vehicles, except when BD20 was used. (Durbin and Norbeck, 2002) showed that when vehicles switched to BD20, there was a significant reduction in HC, CO and PM, but $NO_x$ emissions increased.

In summary, scholars concluded that it is important to use a low level of biofuel so that vehicle exhaust emissions can be reduced without changing the design of a vehicle's engine or reducing engine power. Using a high level of biofuel necessitates changing the engine design and increases toxic gas emissions.

### 2.3.6 Comparative Life Cycle Assessment of Vehicles

It is necessary to compare different types of transportation in order to offer users information about various vehicles' environmental impact. Multiple studies have been conducted comparing the LCA of conventional and advanced vehicle technologies associated with conventional and alternative fuels. (Huo et al., 2015, Hawkins et al., 2013, Aguirre et al., 2012, Gao and Winfield, 2012, Lucas et al., 2012, Baptista et al., 2009, Granovskii et al., 2006), have all presented papers, journal articles and reports on the comparative environmental life cycle assessments of conventional and advanced passenger vehicles. They focused not only on the vehicle operation phase (tailpipe emissions) but also on the vehicle manufacture phase, which is a substantial contributor of emissions to the environment. Regarding BEVs, results indicated that battery electric vehicles using European electricity grid mix produce far fewer GHG emissions than conventional vehicles when the electricity mix is from renewable sources. However, the emissions are higher when electricity is generated from fossil fuels (Hawkins et al., 2013). It is anticipated that battery electric vehicles will be a key future component of Europe's mobility system, helping reduce impacts on climate change and air quality. There is, therefore, an increasing requirement to view these vehicles from a systems perspective (Hampshire et al., 2018). Also, the manufacture, maintenance and disposal phases of BEVs involve higher energy consumption and emissions relative to conventional vehicles (Granovskii et al., 2006). Lastly, the authors stated that energy supply facilities contribute considerable emissions, and the energy demands of BEVs are high, but if the manufacturing process for BEVs improves, and if the electricity is generated from renewable sources, BEVs will be considered a sustainable form of transportation (Lucas et al., 2012).

Regarding the comparative life cycle assessment of heavy-duty truck vehicles, (McKenzie and Durango-Cohen, 2012, Karman, 2006) found through life cycle assessment that CNG-fuelled and hybrid buses have lower GHG emissions than LSD-fuelled buses and that fuel cell buses produce significantly fewer GHG emissions compared to other types of bus. However, this last point depends on how the hydrogen is produced: if it is produced from renewable energy sources, the emissions will be lower; if not, the emissions will be high. The studies concluded firstly that in order to reduce emissions, battery manufacturing and recycling must be improved, and secondly, vehicle size, loading, electricity production and driving behaviour are all factors that significantly influence vehicle exhaust emissions (McKenzie and Durango-Cohen, 2012).

### 2.3.7 Sensitivity and Uncertainty Analyses of LCA Results

The possible variations in the results' collected data should be assessed to check the data used in LCA assumptions. A sensitivity analysis technique is used to quantify uncertainty in life cycle assessments. There are many studies and pieces of research in this field. (Matheys et al., 2006) presented a study about the LCA of the environmental impact of BEVs. They performed a sensitivity analysis of the LCA results and used sensitivity analysis on the parameters, such as energy consumption, vehicle manufacture and vehicle recycling. The results showed that the parameters had no significant impact on the overall LCA results (Matheys et al., 2006). (Groen et al., 2014) study performed a sensitivity analysis on the effect of electricity production parameters on the total LCA results, and they concluded that it is important to use the sensitivity analysis in life cycle assessment in order to identify parameters that can considerably change the results. (Boureima et al., 2009) published a comparative study of the LCA of battery electric, hybrid, liquefied petroleum gas (LPG) and gasoline vehicles. They performed a sensitivity analysis for each model and concluded that the sensitivity analyses allowed the correlation of the results to be assessed (Boureima et al., 2009). (Huang et al., 2013) presented a study on the sensitivity analysis of methodological choices in road pavement LCA. They showed that sensitivity analysis helped establish the influence of method and boundary selection on the LCA results, and they recommended undertaking sensitivity analyses to check the effect of maintenance parameters on LCA results.(Noshadravan et al., 2015) used the uncertainty database to check LCA results. They focused on the uncertainty analysis of the data used to build the LCA model during the use phase, and they argued that the parameters can affect the overall LCA results (Noshadravan et al., 2015). Moreover, they revealed that the data used in the use phase can be improved, while it is hard to analyse data from other phases, such as the fuel pathway and vehicle manufacture, due its scant nature (Noshadravan et al., 2015). Lastly, (Seager et al., 2008) study examined the uncertainty data in LCA for Li-ion batteries used in BEVs. The authors discussed the sources and the reliability of battery production, and the results of the study showed that in order to reduce the uncertainty in the LCA results, it is important to assess the types and properties of materials.

Similarly, life cycle assessment requires many input parameters, many of which are uncertain. (Groen et al., 2014) considered sensitivity analysis to be an important part of the final interpretation. Their study used seven parameters in three case studies, and the results showed that sensitivity analysis is a useful tool in the case of nonlinear life cycle assessment models. (Cellura et al., 2011) studied the effect of life cycle assessment on uncertainty sources. They concluded that significant differences in the energy and environment indices can be obtained, and uncertainty analysis method needs to develop a sensitivity analysis to strengthen the reliability of the results. Uncertainty and sensitivity analysis techniques were also used by (Wei et al., 2015) to produce more accurate life cycle assessment results and to investigate the data used in the life cycle assessment model. The results clearly showed that the sensitivity method should be chosen according to the magnitude of uncertainty and the degree of correlation (Wei et al., 2015). Lastly, (Groen et al., 2017) aimed to compare methods for global sensitivity analysis in life cycle assessment. They confirmed that environmental impact can be analysed by means of a global sensitivity analysis to gain more insight into output variance.

In summary, the literature concludes that both uncertainty and sensitivity analyses are valuable tools for ensuring robust results of life cycle assessments and determining their sensitivity to uncertainty factors. Uncertainty and sensitivity analyses are considered the most important set of model parameters to determine whether the data quality needs to be improved and to enhance interpretation of results. Finally, the authors of the aforementioned studies relayed that independent global sensitivity analysis aims to analyse the variability of results because of the variation of input parameters.

Overall, the final report on comparison of transport fuels to the Australian Greenhouse Officer (AGO) by (Beer et al., 2001b), is the latest and most comprehensive report that Australia has on life cycle assessment for light and heavy vehicles. This report responded to a brief from the Australian Greenhouse Office to undertake a comparison of road transport fuel emissions through a full fuel cycle assessment of greenhouse gas emissions and emissions affecting air quality, for conventional and alternative fuel types. However, the input data used, for example global database, is quite broad with some international used where no local Australian data was available. Currently there are better data sets available (Australian Government, 2019, Sustainability, 2018, Australian Bureau of Statistics (ABS), 2017, Australian Government, 2008), which has allowed to use a more rigorous approach.

### 2.3.8 Life Cycle Assessment Using the GREET Model

The greenhouse gases, regulated emission and energy use in transportation (GREET) model has been developed by the United States' Environmental Protection Agency (US EPA) Argonne National Laboratory. It covers the life cycle assessment of the fuel cycle/fuel pathway, vehicle operation phase (tailpipe emissions and maintenance) and the vehicle non-operational phase (vehicle manufacture and disposal) as shown in Figure 2.1. It deals with light vehicles, but the current plan is that it will evaluate the energy use and emissions of heavy-duty vehicles over the course of their lifetimes (Burnham et al., 2006). Argonne has updated the new methods, techniques and technologies to produce renewable fuels that have less of an impact on human health and the environment. It examines the energy consumption and emissions of vehicles powered by hydrogen, LPG, CNG and biofuel in order to make a quality change in their design strategy to reduce vehicle exhaust emissions (Wang et al., 2018). The lowest total LCA energy use, GHG emissions and air pollutions for biofuel vehicle showed a 6–25% reduction in total LCA energy use, GHG emissions and air pollutions compared with conventional internal combustion engine vehicles that running on petrol fuel (Baliga and Powers, 2010).

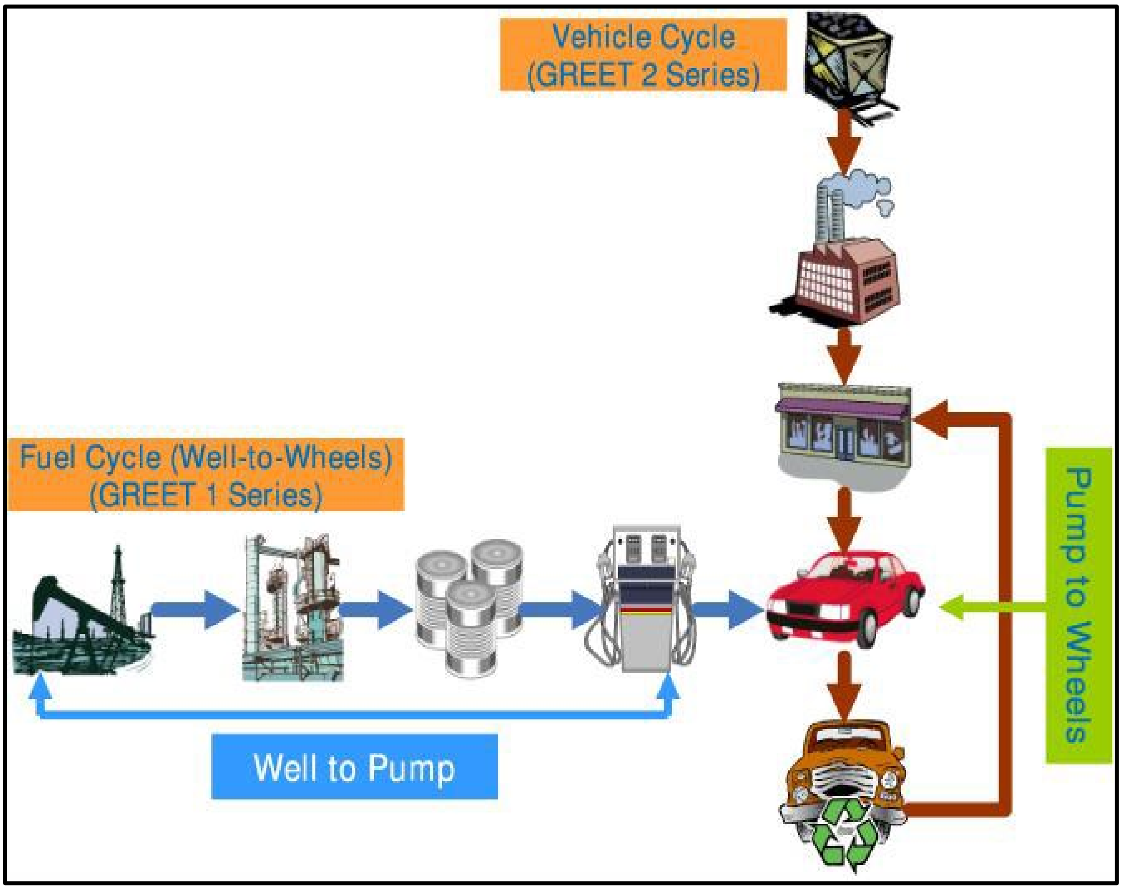


**Figure 2.1: Life cycle assessment of vehicle/fuel systems (Wang et al., 2007)**

### 2.3.9 Life Cycle Assessment Using the LCA SimaPro Software

Based on ISO 14040, life cycle assessment is divided into three stages (Hauschild and Huijbregts, 2015) as shown in Figure 2.2:

1. the goal and scope definition
2. life cycle inventory analysis
3. life cycle impact assessment.

LCA by SimaPro software has the potential to evaluate the environmental impact and energy demand of vehicles during their lifetimes because it covers all stages from the fuel pathway to vehicle operation phase via vehicle manufacture so that the energy resource depletion and environmental impact associated with different types of fuel can be assessed. Furthermore, it can assess conventional, alternative and advanced-technology vehicles. Finally, the LCA SimaPro software contains valuable data from around the world, including the USA, Europe, Japan and Australia.

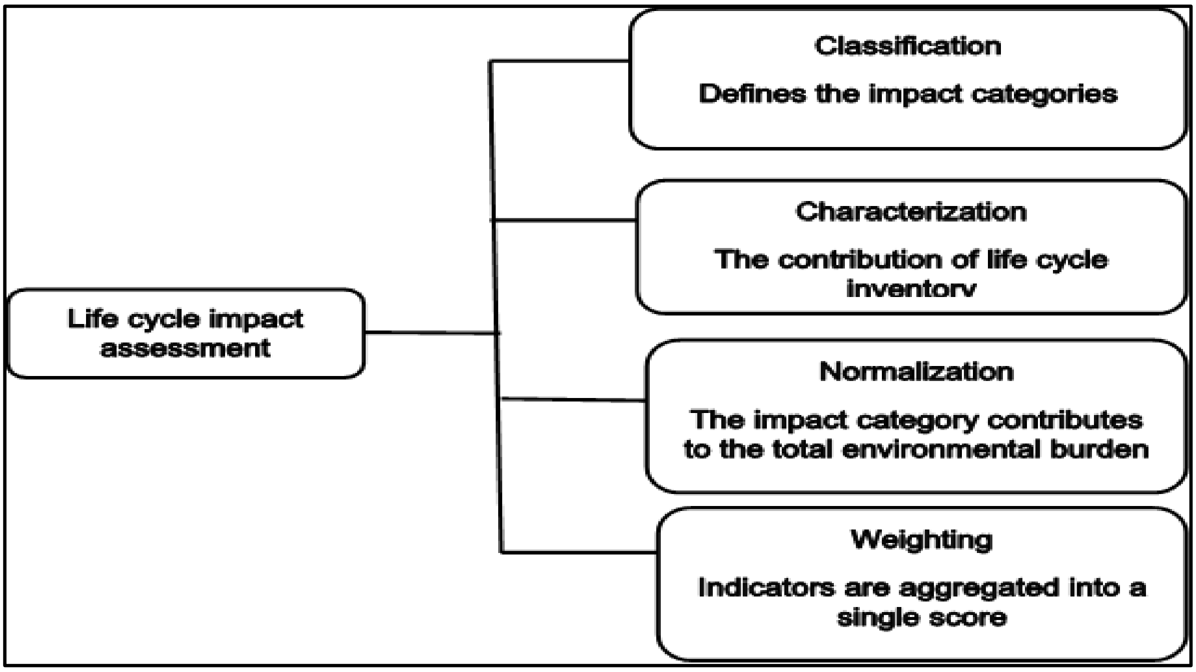


**Figure 2.2: Modelling Life Cycle Impact Assessment using SimaPro software (Hauschild and Huijbregts, 2015)**

### 2.3.10 Life Cycle Cost Assessment of Vehicles

It is important for customers to know the cost of their car. Many resources provide information about the life cycle cost assessment of vehicles over their lifetime, including (Wong et al., 2010), (Zhou et al., 2017, Kara et al., 2017, Sengupta and Cohan, 2017, Prevedouros and Mitropoulos, 2016, Dr Robbie Napper and Dr Paul Thambar, 2016, Lajunen and Lipman, 2016, Kampf et al., 2016, Shahraeeni et al., 2015, Ribau et al., 2014, Lajunen, 2014, Rose et al., 2013, Sharma et al., 2012, Feng and Figliozzi, 2012, Golub et al., 2011, Victorian department of transport, 2010, Silva et al., 2009, Hellgren, 2007, Jeong and Oh, 2002, DeLuchi et al., 1989). The literature shows that BEVs are more expensive than other types of vehicles due to the costly manufacture of the battery; however, researchers have suggested that governments can reduce the life cycle cost of BEVs by reducing the tax on such vehicles, making them more affordable so people are encouraged to use them(Wong et al., 2010). In addition, the authors indicated that vehicle costs can change depending on vehicle taxation, fuel price, electricity price and exhaust emissions(Kara et al., 2017). Moreover, the literature shows that battery performance for BEVs is likely to improve in the future. Furthermore, the authors indicated that the parallel hybrid vehicle is low cost and more suitable than other types of vehicles, and that fuel, electricity and battery prices are important factors when deciding what types of vehicles are low cost(Sengupta and Cohan, 2017). Additionally, the authors revealed that the fuel cell hybrid bus can reduce life cycle costs by 0.620 $/km relative to conventional diesel buses depending on the price of hydrogen. Finally, the authors made the following points:

1. The cost of fuel cell buses can be lower than that of conventional buses if the hydrogen is produced from renewable energy sources, meaning that the cost of the fuel cell is lower, as is the price of the hydrogen (Wong et al., 2010).
2. The hybrid electric bus has a lower life cycle cost relative to diesel and fuel cell buses (Kara et al., 2017).
3. Life cycle cost information allows consumers to make better financial choices regarding a vehicle, including accounting for interest and discounts (Hellgren, 2007).

4. A vehicle energy and emissions database can be used in the future to formulate an approach that estimates the total life cycle cost of buses, including capital, operation, external, maintenance and disposal (Sharma et al., 2012).

## 2.4 Well-to-wheels Analysis of the Vehicle/Fuel System

Well-to-wheels analysis (WTW) of the vehicle/fuel combined use system is a theory that assesses the environmental impact of vehicles over their lifetimes. Many authors have published research in this field, including (He et al., 2018, Jang and Song, 2015, Cai et al., 2015, Curran et al., 2014, Yazdanie et al., 2014, Shen et al., 2012, Hoffrichter et al., 2012, Nylund and Koponen, 2012, Foley, 2012, Gao, 2011, Baptista et al., 2011, Rousseau and Sharer, 2004, Wu et al., 2006b, Cooperation, 2004, Rousseau et al., 2003). Their studies indicate that the use of alternative fuels and advanced vehicle technologies can significantly reduce GHG emissions. The authors showed that BEVs have the potential to reduce GHG emissions by 30% if the electricity is produced from renewable energy sources, though emissions increase when the electricity is derived from fossil fuels(Shen et al., 2012). In addition, the authors revealed that although FCVs consume less energy and release fewer emissions than other types of vehicles, the cost of hydrogen is still the main issue. Similar to FCVs, the charging time of BEVs is still one of the main obstacles to developing this mode of transportation(Jang and Song, 2015). Finally, the authors concluded by indicating the following points:

1. Both alternative fuel and advanced vehicle technologies can be used more in the future and have less of an impact on the environment than conventional vehicles (Shen et al., 2012).
2. A hybrid gasoline vehicle is more efficient than a hybrid diesel vehicle (Jang and Song, 2015).

3. High WTW efficiency reduces a vehicle's total energy consumption and emissions (Curran et al., 2014).
4. A bus powered by biofuel releases fewer WTW emissions than a bus powered by fossil fuels (Foley, 2012).

## 2.5 The Environmental Rating of Vehicles

The scores of vehicles are very important because they give consumers more information on the vehicle/fuel system used and its environmental impact. There are only a few studies in this area. (Timmermans et al., 2006) examined the environmental rating scores of vehicles with different drive trains, powered by different fuels. They used the Ecotest method to determine the rating scores of different types of vehicles, including passenger vehicles and buses. The results revealed that battery electric and CNG vehicles have lower environmental impacts (and therefore high rating scores), and LPG vehicles have the best environmental score of all conventional vehicles (Timmermans et al., 2006). The authors also indicated that electric transport buses have great potential to reduce emissions to the environment, so they are considered high-rating vehicles relative to other types of heavy-duty vehicles (Timmermans et al., 2006). (Van Mierlo et al., 2003) presented a study comparing the environmental damage caused by vehicles in Brussels, Belgium. They used the Ecotest theory to evaluate the environmental impact of vehicles associated with different fuels over the vehicles' lifetimes by using all LCA stages, including the fuel pathway, vehicle operation uses and vehicle manufacture. The authors argued that in order to determine a vehicle's rating score it is necessary to define and include all the relevant parameters, such as different types of pollution (including air pollution) and noise concerning vehicle emissions. Again, the results indicated that CNG and LPG vehicles release fewer emissions to the environment, so they have a high vehicle rating score (Van Mierlo et al., 2003). Furthermore, the authors showed that alternative vehicles, including electric and hybrid vehicles, are sustainable because they cause the least environmental damage (Van Mierlo et al., 2003).

## 2.6 Previous Life Cycle Assessment Studies

In summary, the literature review covered the following topics:

- the environmental impact assessment of vehicles
- fuel types
- vehicles' life cycle emissions
- the environmental rating scores of vehicles
- uncertainty and sensitivity analyses of LCA databases and results
- the LCA software used to model life cycle assessments.

The literature reviewed included research by (Noshadravan et al., 2015, Shen et al., 2012, Aguirre et al., 2012, Baptista et al., 2011) (Tessum et al., 2010, Wong et al., 2010, Matheys et al., 2006, Davis et al., 2003). The following conclusions were drawn:

1. Biofuels pose less of a threat to climate change and human health than conventional fuels. Low concentrations of biofuel are preferable to high concentrations because there is no need to modify engine design, the engine need not reach such a high temperature and fewer toxic emissions are produced (Tessum et al., 2010).
2. BEVs could be most sustainable type of vehicle option because they produce fewer GHG emissions and less air pollution, but this depends on recharging time, battery manufacture, electricity generation feedstock and driving cycle (Aguirre et al., 2012).
3. FCVs have lower emissions than other types of transportation, depending whether the hydrogen production used renewable energy sources or fossil fuels (Baptista et al., 2011).

4. Alternative fuel-powered vehicles have the lowest emissions, but this depends on the fuel feedstock (Davis et al., 2003).
5. The concept of the life cycle cost of a vehicle's emissions is important for consumers so that they may be informed about vehicle economics over the vehicle's lifetime (Wong et al., 2010).
6. WTW analysis of fuel/vehicle combined use can be a useful technique to determine the impact of vehicle tailpipe emissions on the environment (Shen et al., 2012).
7. Studies relating to the environmental rating score of vehicles used different types of transportation, including advanced technologies associated with alternative and conventional fuels, and they did not use the whole life cycle assessment of vehicles to develop the rating score. Furthermore, researchers focused on the operation phase (tailpipe emissions) and sometimes on fuel economy to rank vehicles (Matheys et al., 2006).
8. Regarding the studies relating to the uncertainty database of vehicles and sensitivity analysis of LCA results, the sensitivity analyses performed only focused on one or two parameters that impact life cycle modelling (Noshadravan et al., 2015).

## 2.7 Objectives

Importantly, the literature review revealed a gap in the research since there were no studies found focusing in depth on the uncertainties in the emission factor database, and sensitivity analyses were not conducted with any sort of precision. Additionally, the accuracy of the fuel cycle (fuel pathway), vehicle manufacture, maintenance and disposal phases were not rigorous enough to offer insights into the life cycle assessment over vehicles' lifetimes. Previous studies have focused only on the life cycle assessment of vehicles, including the fuel cycle and vehicle tailpipe emissions, ignoring the non-operational phases, such as vehicle manufacture, maintenance and disposal. In addition, almost all the studies reviewed focused on just two or three types of vehicles, and all the previous studies used merely one or two parameters that impact the overall life cycle modelling. The main objectives of this thesis are to fill the gaps in knowledge described above using the research methodology described below, derived from the reviewed literature:

1. Calculate and quantify the whole life cycle assessment of types of transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles. The environmental impact of and energy demand during the fuel cycle (fuel pathway), vehicle operation phase (tailpipe emissions and maintenance) and the vehicle non-operational phase (vehicle manufacture and disposal) over a vehicle's lifetime will be determined. Also, the life cycle assessment of conventional vehicles and advanced-technology vehicles will be included in the analysis. Additionally, the environmental impact of sustainable fuels, including conventional and alternative fuels, will be assessed. Estimate the environmental impact and depletion in energy resources of biofuel vehicles, including bioethanol passenger vehicles and biodiesel buses.
2. Evaluate the environmental rating scores of vehicles over their entire lifetimes. This includes different types of vehicles associated with different fuels.
3. Assess the environmental impact of public transport buses (DPTI trial buses).
4. Undertake an uncertainty analysis of the data used to build a life cycle model. This section will check the distance of the data from mean values, as well as the standard deviation range of the data, so that the uncertainty analysis covers life cycle modelling, life cycle databases and life cycle results.
5. Undertake a highly accurate sensitivity analysis of the LCA results. This section will focus on the impacts of key parameters, factors and assumptions of the LCA results and evaluate their influence on the LCA results.

# CHAPTER 3: METHOD AND DATABASE

## 3.1 System Boundary Selection

The system boundary selection determines which processes are included in the LCA study. It is partly a subjective choice made during the scope phase when the boundary is initially set.

The system boundary of the whole life cycle assessment of transportation, including passenger vehicles, public transport buses, heavy-duty truck vehicles and biofuel vehicles, is illustrated in Figure 3.1. It takes into account the fuel pathways (oil extraction and production, oil refining or transesterification and fuel distribution) or electricity generation pathway, vehicle operation phase (tailpipe emissions and vehicle maintenance) and the vehicle non-operational phase (material extraction and production, vehicle manufacture, vehicle assembly and disassembly and vehicle disposal). In addition, it considers the driving cycle used to evaluate vehicle exhaust emissions, such as the new European driving cycle (NEDC), smart way driving cycle (US EPA) and Australian driving cycle. The latter cycle is used in this study.

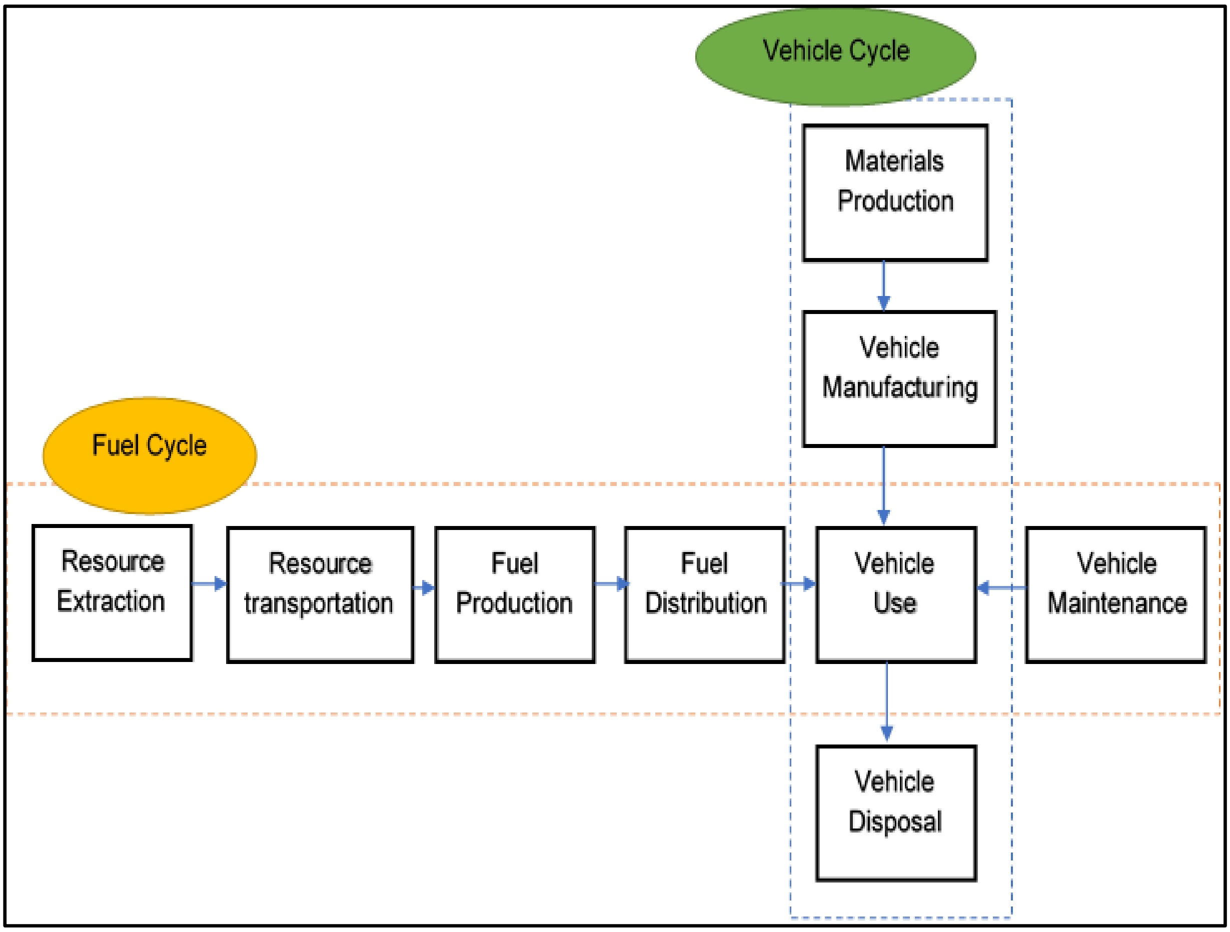


**Figure 3.1: Boundary System of a Vehicle Associated with Fuel**

## 3.2 Database Sources

In this thesis, the LCA results were completed using many different data sources, including the USLCI database, the ecoinvent database, ELCD, EU, UK database, industry database, Swiss input and output database, and the Australian National Life Cycle Inventory Database (AusLCI). All the data mentioned above are in the LCA SimaPro software (Sustainability, 2018).

## 3.3 Life Cycle Assessment Software

In this study, the literature review found that many LCA studies used either the LCA SimaPro software designed by PRé Consultants or the US EPA's GREET (greenhouse gas, regulated emissions and energy use in transportation) model to calculate the full life cycle assessment of transportation over a lifetime (see Chapter 2, Sections 2.3.7 and 2.3.8). An evaluation of both software packages was undertaken and is described below.

### 3.3.1 The Life Cycle Assessment: SimaPro Software

The LCA SimaPro software is a tool used to analyse the environmental impact of products or services, including the transport sector, and it is widely used around the world. In addition, there are many different language options available in the SimaPro software. It allows the user to separate contributions of energy, transport, waste or other parts of the product system (Sustainability, 2018). For additional information regarding the SimaPro software, see Appendix A.

### 3.3.2 GREET Model: Life Cycle Assessment

The Argonne National Laboratory has developed a full life cycle model called GREET. This helps to estimate the environmental impact of the vehicle/fuel system over the vehicle's working lifetime, and it has the potential to analyse vehicle/fuel life cycle emissions over the vehicle's entire lifetime, too. Additionally, the fuel cycle (fuel pathway), vehicle operation phase (tailpipe emissions and maintenance) and the vehicle non-operational phase (vehicle manufacture and disposal) are considered in the GREET model. Moreover, this model includes most types of transportation, including light and heavy-duty vehicles. Finally, it includes conventional and advanced vehicle technologies associated with conventional and alternative fuels (Argonne National Laboratory, 2019). For additional information regarding the GREET model, see Appendix B.

### 3.3.3 The Difference Between the GREET Model and the LCA SimaPro Software

The GREET model, developed by Michael Wang at Argonne National Laboratories, is available at http://www.transportation.anl.gov/ttrdc/greet/ or at http://greet.anl.gov (Wang et al., 2007). The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. For vehicle/fuel combined systems, GREET has can calculate the following:

1. the total energy consumption during the fuel pathway, vehicle operation phase (tailpipe emissions and maintenance) and the vehicle non-operational phase (vehicle manufacture and disposal) over a vehicle's lifetime
2. the GHG emissions ($CO_2$, $CH_4$ and $N_2O$) during the whole life cycle assessment
3. the air pollutants (CO and $NO_x$) and particulate matter ($PM_{10}$ and $PM_{2.5}$) for the operation and non-operational phases.

Furthermore, GREET can evaluate the environmental impact of both conventional and advanced vehicle technologies as listed below:

1. conventional spark-ignition engines
2. direct-injection spark-ignition engines
3. direct-injection compression-ignition engines
4. grid-connected hybrid electric vehicles (HEVs)
5. grid independent HEVs
6. battery electric vehicles (BEVs)
7. fuel cell vehicles (FCVs).

In addition, a new version has been released, known as the GREET 3 series, which is designed to estimate the energy use and emissions of heavy-duty vehicles. This series was modified to assess the energy and emissions of low sulphur diesel (LSD)/compressed natural gas (CNG)-powered heavy-duty truck vehicles.

One of the important advantages of the GREET model is estimating and calculating the details of both the fuel pathway and the vehicle manufacture phase. For instance, it can calculate the energy demand, GHG emissions and air pollutants during vehicle manufacture, including the body, chassis, transmission system, powertrain system, fluid and battery. This advantage is lacking from the SimaPro software. However, the GREET model specifically concentrates on American energy and emission databases, much more than other countries' databases (Argonne National Laboratory, 2019).

The SimaPro software is more suitable for use in the Australian context for the following reasons (Sustainability, 2018):

1. SimaPro can provide embodied energies and emissions.
2. SimaPro has been linked and adapted to the Australian database of energy and emission factors. The LCA SimaPro software has global data including the AusLCI, which covers all sectors in Australia, including transportation.
3. SimaPro can produce process trees that have the potential to evaluate each component of the life cycle.
4. SimaPro is an open structure program that can be used for different types of life cycle assessments, including the fuel pathway stage, manufacture stage, use stage and end-of-life stage.
5. SimaPro can estimate the energy use, GHG emissions and air pollutants of both light and heavy-duty vehicles over vehicle age.

6. SimaPro has the advantage that it can measure the emissions that cause human cancer or non-cancerous disease.
7. SimaPro does not solely focus on transportation but also on other areas, such as food, agriculture, energy and building.

The comparison between the GREET model and the LCA SimaPro software is summarised in Table 3.1.

| **GREET Model** | **The LCA SimaPro Software** |
|---|---|
| It is based on the USA's database with few databases from different countries. | It is based on global databases (such as from the USA, Europe, the Middle East and Australia). |
| It is designed to estimate energy use and emissions for light vehicles only. | It is designed to estimate energy consumption and emissions for light and heavy-duty vehicles. |
| It can estimate more details of products during vehicle manufacture and the fuel cycle. | It has limited information on the fuel pathway and vehicle manufacture cycle. |
| It does not have multiple options with which to analyse the results, such as tree processes. | It has tree processes and other analytical tools, such as network, uncertainty and sensitivity analyses. |
| It includes more fuel cycles, notably the CNG cycle and hydrogen fuel pathways. | It does not have the CNG fuel cycle, so it considers fuel pathways. |
| It does not include an uncertainty database and sensitivity analysis of results. | It deals with uncertainty databases and sensitivity analyses of the software's outcomes, plus it uses tree (network) outcome results. |

**Table 3.1: Comparison Between the GREET Model and the LCA SimaPro Software**

After this comparison, it was determined that SimaPro was the most suitable software to use for the analyses required for this thesis. From this point on, all the LCA analyses in this thesis were performed using SimaPro and its associated databases, complemented with Australian or relevant international data where appropriate.

## 3.4 Life Cycle Assessment Modelling Using SimaPro Software

SimaPro is a software program that helps to quantify the environmental impact of a product's life cycle. It can model all the phases in life cycle assessment (LCA) – from the extraction of raw materials, the production of materials, parts and the product itself and the use of the product right through to its management after it is disposed of. The data that is collected in the factory and from the suppliers can be incorporated into the model. Additionally, the program can use information from the ecoinvent database, which is provided by the LCA SimaPro software. Indeed, SimaPro is equipped with several up-to-date databases containing information on inputs and outputs relating to the environment for most commonly used materials and processes.

When the LCA model runs, it will obtain results on the quantified inputs from nature; this could relate to raw materials and their quantified outputs to the natural environment such as GHG emissions throughout a product's life cycle. These findings can then be converted into impact category indicators. For example, GHG emissions, such as CO2, CH4 and N2O, can be converted into CO2 equivalents according to the Intergovernmental Panel on Climate Changes' (IPCC's) equivalent factors in order to reflect the contribution of these substances to climatic change. Furthermore, SimaPro contains several impact assessment methods that have been developed by different institutes and universities. The IPCC's equivalent factors are one example of a single-issue impact assessment method in the aforementioned software (Intergovernmental Panel On Climate (IPOC), 2007). SimaPro also provides impact assessment methods that take multiple impact categories into account, such as resource depletion, land use, climate change and ecotoxicity (Sustainability, 2018).

In this thesis, the LCA SimaPro software was used to model an LCA for vehicles, including related assumptions. According to ISO 14040, at the life-cycle inventory-assessment stage, the primary flows from the life-cycle inventory are translated into their contribution to the environmental impacts of vehicles. Subsequently, the characterisation factors are used to compare categories, such as GHG emissions, energy use and air pollutants; therefore, the different impact assessments make it possible to compare the impact category indicators with the reference values (Sustainability, 2018). This study has drawn on information from The Australian National Life Cycle Inventory Database (AusLCI) and has made use of other Australian vehicle emission data that is in-built into the LCA program where appropriate. The model is divided into three stages, as shown in Figure 3.2:

1. The fuel pathway or fuel cycle (the well-to-tank or well-to-pump stage), which includes the recovery or production of the feedstock for the fuel, transportation and storage of the energy source through conversion of the feedstock to the fuel and the subsequent transportation, storage and distribution of the fuel to the vehicle tank. It also encompasses the production of electricity from various sources.
2. The vehicle operation phase or vehicle tailpipe emissions (the tank-to-wheel or pump-to-wheel stage) refers to the vehicle’s operational activities (tailpipe emissions and vehicle maintenance) throughout its lifetime.
3. The vehicle (cradle to grave) stage, which includes its manufacture and disposal.

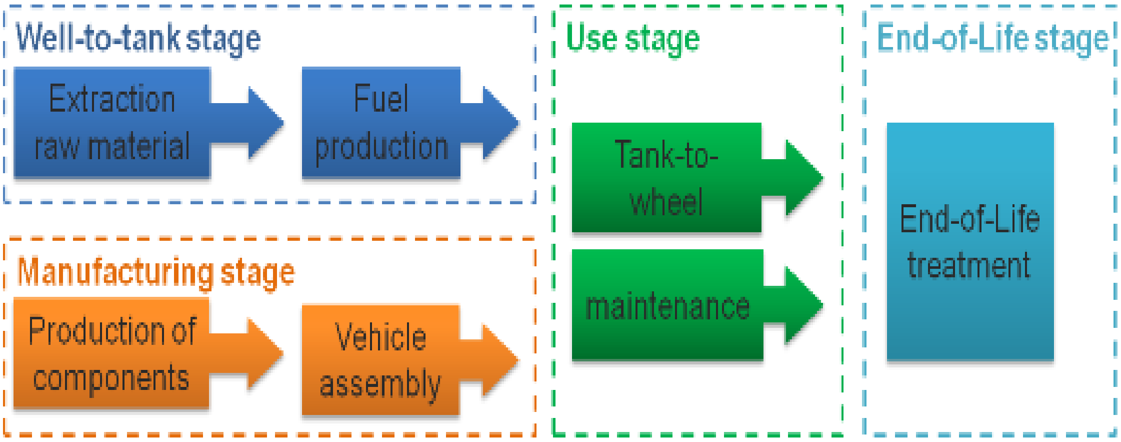


**Figure 3.2: All the LCA Stages of Vehicles in the Thesis Study (Messagie et al., 2014)**

All the databases used for LCA modelling are entered into the LCA boundary system. It includes the data related to fuel pathways, including both the fuel production from different resources (such as crude oil or biomass) and the electricity generated from Australian non-renewable energy sources (fossil fuels) using the AusLCI database (Spielmann et al., 2007). In addition, all the data related to the vehicle operation phase (tailpipe emissions) can be entered using the best available data. This includes fuel consumption, national greenhouse factors, the national pollutions inventory and vehicle kilometres travelled databases regarding vehicle tailpipe emissions (Australian Government, 2019). On the other hand, and in regard to vehicle servicing and maintenance, all the data related to the vehicle operation phase (vehicle maintenance) over a vehicle's lifetime is input using Australian data and the AusLCI database (Spielmann et al., 2007). Furthermore, all the data related to vehicle manufacture, assembly, disassembly and disposal (end of life) is input using Golf A4, Man and Volvo automobile manufacturers' information released from the ecoinvent database (Spielmann et al., 2007). Lastly, although the majority of the data is based on The Australian National Life Cycle Inventory Database (AusLCI) that is in the LCA SimaPro software, data for some vehicles remains unavailable, including for advanced vehicle technologies, battery electric buses and battery-fuelled heavy-duty truck vehicles, so that data is garnered from the sources listed below:

1. vehicle automobile manufacturers, including Toyota Prius, Nissan Leaf, Miev and Mirai (Toyota Motor Corporation, 2020)
2. the average on-board electricity consumption of Bustech/1999-DPTI Bus Trial for battery electric buses (South Australian Government, 2019)
3. EMOSS automobile manufacturers electricity consumption for battery heavy-duty truck vehicles (EMOSS Automobile Vehicles, 2020).

## 3.5 Including Environmental Effects

Life cycle assessment of vehicles refers to the total primary energy use, GHG emissions and air pollutants during the fuel cycle (crude oil extraction, crude oil transportation, crude oil refining and fuel distribution or electricity generation), the vehicle operation phase (tailpipe emissions and maintenance) and the vehicle non-operational phase (vehicle manufacture and disposal) (Wang et al., 2007). In this study, the following kinds of vehicle exhaust emissions are estimated:

1. GHG emissions, including $CO_2$, $CH_4$ and $N_2O$
2. air pollutants, including PM, human toxicity, cancer (HTc) and human toxicity, non-cancer (HTnc).

## 3.6 Fuel Life Cycle Assessment Modelling

Because of the different types of transport fuel used, the life cycle assessment of fuel will detail different amounts of emissions released to the environment. The LCA estimates these amounts of emissions by including both combustion and evaporative emissions. A full life cycle emission assessment considers not only the direct emissions from vehicles (downstream emissions) but also those associated with fuel (upstream emissions or pre-combustion emissions) from extraction, production, transport, processing, refining, conversion and distribution.

### 3.6.1 System Boundary of the Fuel Life Cycle Assessment

The boundary system of the fuel life cycle assessment is shown in Figure 3.3. It contains different sources of fuel, including renewable (vegetable) and non-renewable (fossil fuel) resources.

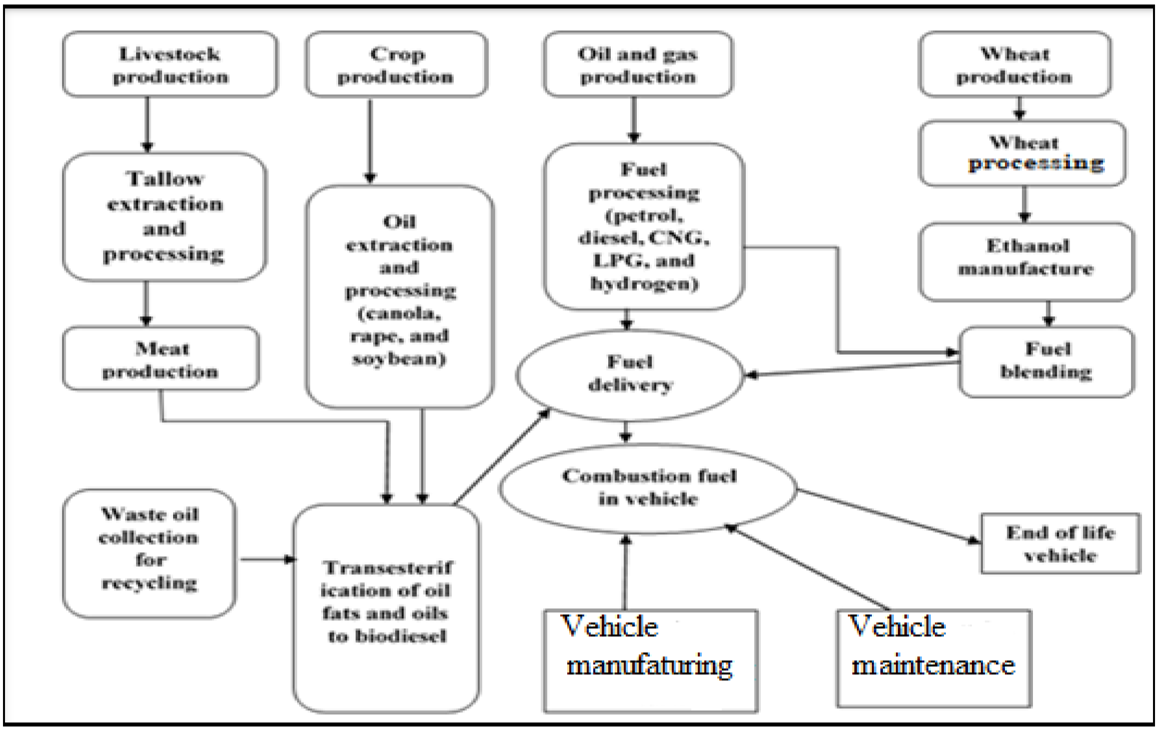


**Figure 3.3: The Boundary System of This Study's Fuel Life Cycle Assessment (adapted from (Beer et al., 2001a)**

### 3.6.2 Convectional Fuel LCA

Conventional fuel, including petrol and diesel, is produced from non-renewable energy sources (fossil fuels). It releases a large amount of GHG emissions and air pollutants into the environment relative to alternative fuels, which produce fewer emissions. The three types of conventional fuel are detailed below.

#### *3.6.2.1 Petrol LCA*

Petrol or gasoline is a fuel that is used to power spark-ignition internal combustion engine vehicles. It is produced from crude oil via petroleum refining processes, such as crude oil distillation, vacuum distillation, naphtha hydrotreating and hydrocracking. Petrol vehicles contribute significant emissions to the environment because petrol fuel is derived from fossil energy (Beer et al., 2001a).

#### *3.6.2.2 Low Sulphur Diesel LCA*

Low sulphur diesel is used in internal combustion engine vehicles that operate by using compression ignition. It is produced from crude oil (fossil fuel) via fractional distillation. Consequently, it emits a lot of emissions into the environment, and its production consumes a lot of energy (Beer et al., 2001a).

#### 3.6.2.3 CNG Fuel

Natural gas (NG) is a mixture of hydrocarbons and mainly methane ($CH4$) and is produced either from gas wells or in conjunction with crude oil production. In Australia, CNG is domestically produced and is compressed to 25 MPa for on-board storage vehicle (Beer et al., 2001). Natural gas is not renewable, but its level of sustainability is dependent on where it comes from (Inspire, 2020).

### 3.6.3 Alternative Fuel LCA

Advanced or alternative fuels are considered types of modified fuel. They are derived from renewable energy sources therefore they produce fewer emissions than conventional fuels. There are many types of alternative fuels, as detailed below:

#### *3.6.3.1 Liquefied Petroleum Gas Fuel*

Liquified petroleum gas (LPG) is produced domestically in Australia. It consists mainly of propane, propylene, butane and butylene in various proportions according to its state or origin. The components of LPG are gases at normal temperatures and pressures that can easily be liquefied for storage by increasing the pressure to eight atmospheres or by reducing the temperature. LPG is used in motor cars by storing it on-board the vehicle. It is produced from two sources: natural gas processing and crude oil refining (Beer et al., 2001a).

#### *3.6.3.2 Hydrogen Fuel*

Transportation can burn pure hydrogen in an internal combustion engine or use it in a fuel cell to drive vehicles. Although it requires more changes to the vehicle design, it is more efficient than other types of transportation. It can be produced through steam reforming natural gas, cleaning up industrial by-product gases or by water electrolysis (Beer et al., 2001a).

#### *3.6.3.3 The Biofuels Pathway*

Biofuel is produced from organic material, including plant and animal waste. There are many processes that can be used to generate biofuel: the fermentation of corn sugars, transesterification processes, the gasification of cellulose to syngas and the hydrogenation of vegetable oil to produce petrol and diesel. Biofuel is classified into two categories, which are outlined below:

#### 3.6.3.3.1 The Bioethanol Pathway

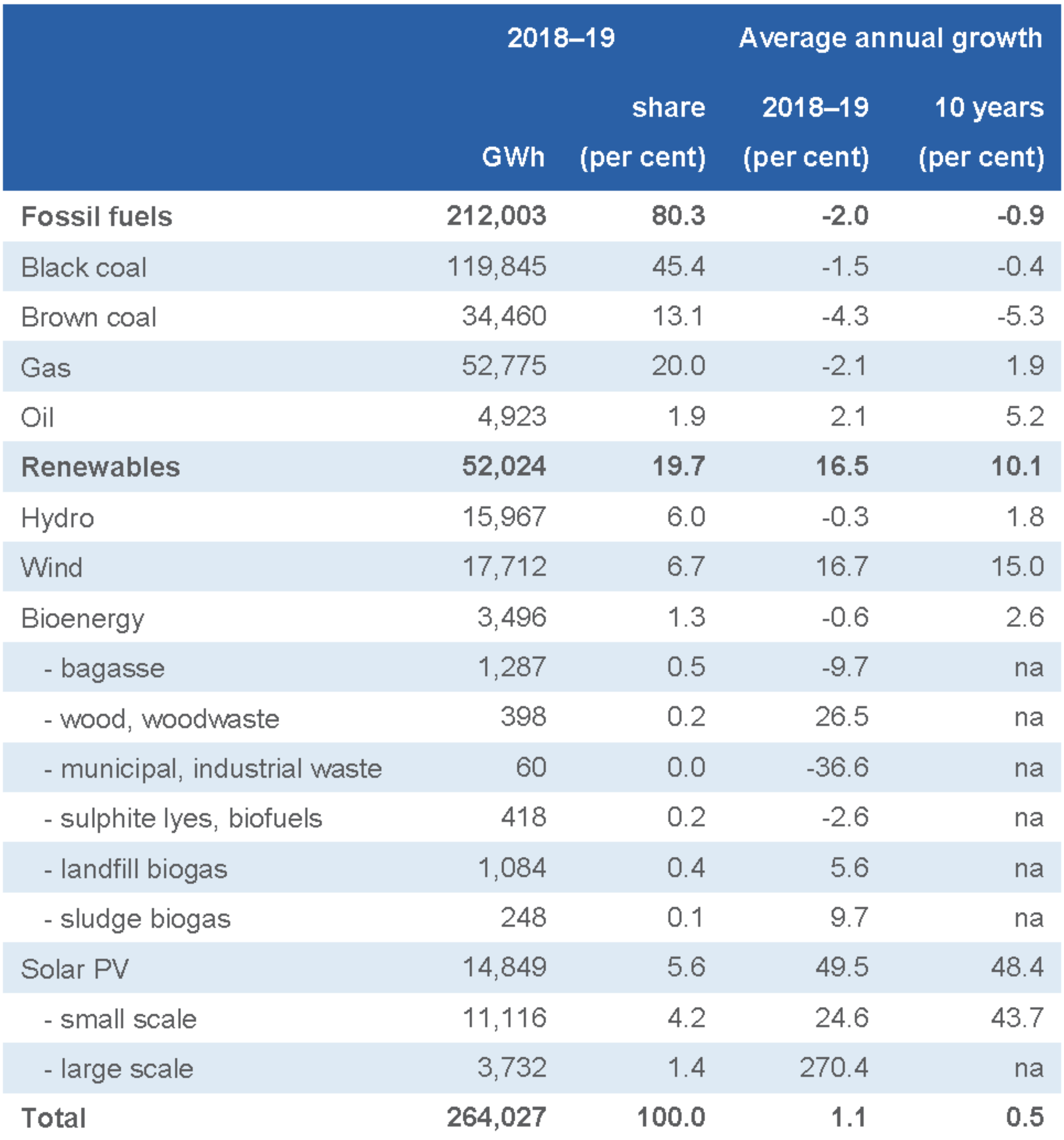
Bioethanol is defined as an alternative fuel, and it is considered one of the most common fuels worldwide. It can be used as an additive to conventional petrol. It is produced from different biomass resources, such as the sugar in corn, sugarcane, cassava, wheat, sugar beets, potato, wood and other cellulosic plants. Ethanol is used in spark-ignition engine vehicles. If 100% ethanol or an ethanol blend with a high proportion of ethanol (such as $E_{85}$) is used, the petrol engine requires modification. Conversely, no engine modification is required to use low-ethanol blends, such as $E_5$, $E_{10}$, $E_{25}$ and $E_{40}$ (Stucley et al., 2012).

#### 3.6.3.3.2 The Biodiesel Pathway

Biodiesel is like diesel fuel and is derived from organic oils, such as vegetable oil, animal fats, soybeans, rapeseeds and palm oil. Transport fuelled by biodiesel is more sustainable because it produces fewer emissions and so has a lower impact on human health and the environment. Biodiesel blended with over 20% diesel can be used directly in compression-ignition engine vehicles; however, the vehicle powertrain must be modified when pure biodiesel or biodiesel blended with less than 20% diesel is used (Biofuels Association, 2020).

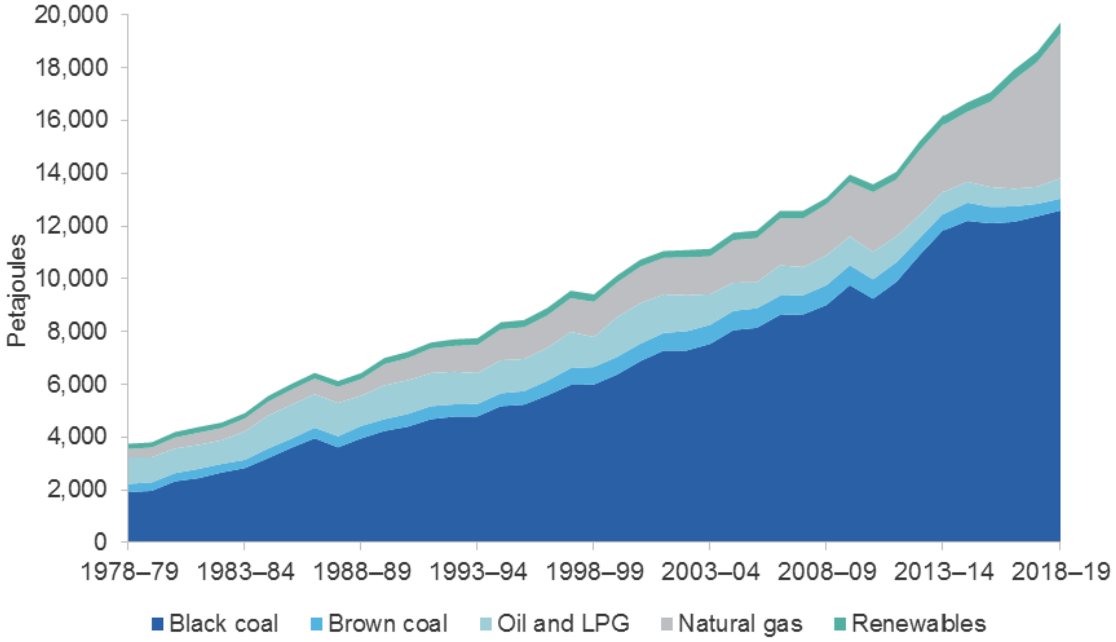
### *3.6.3.4 Electricity (Low Voltage, Australia)*

Electricity is generated from various resources, such as coal, natural gas, oil, wind and solar energy, in Australia. Table 3.2 and Figure 3.4 show electricity generation around Australian and the different types of fuels used. They show that the majority of electricity is generated from coal (68.2%), followed by natural gas (19.4%). Only approximately 10% of electricity is derived from renewable sources (low carbon feedstock) (Department of Industry Science Energy and Resources, 2020).



| | 2018–19 | | Average annual growth | |
|---|---|---|---|---|
| | GWh | share (per cent) | 2018–19 (per cent) | 10 years (per cent) |
| **Fossil fuels** | **212,003** | **80.3** | **-2.0** | **-0.9** |
| Black coal | 119,845 | 45.4 | -1.5 | -0.4 |
| Brown coal | 34,460 | 13.1 | -4.3 | -5.3 |
| Gas | 52,775 | 20.0 | -2.1 | 1.9 |
| Oil | 4,923 | 1.9 | 2.1 | 5.2 |
| **Renewables** | **52,024** | **19.7** | **16.5** | **10.1** |
| Hydro | 15,967 | 6.0 | -0.3 | 1.8 |
| Wind | 17,712 | 6.7 | 16.7 | 15.0 |
| Bioenergy | 3,496 | 1.3 | -0.6 | 2.6 |
| - bagasse | 1,287 | 0.5 | -9.7 | na |
| - wood, woodwaste | 398 | 0.2 | 26.5 | na |
| - municipal, industrial waste | 60 | 0.0 | -36.6 | na |
| - sulphite lyes, biofuels | 418 | 0.2 | -2.6 | na |
| - landfill biogas | 1,084 | 0.4 | 5.6 | na |
| - sludge biogas | 248 | 0.1 | 9.7 | na |
| Solar PV | 14,849 | 5.6 | 49.5 | 48.4 |
| - small scale | 11,116 | 4.2 | 24.6 | 43.7 |
| - large scale | 3,732 | 1.4 | 270.4 | na |
| **Total** | **264,027** | **100.0** | **1.1** | **0.5** |

**Table 3.2: Australian Electricity Generation by Different Fuel Types (Department of Industry Science  Energy and Resources, 2020)**



## 3.7 Life Cycle Method and Database for Transportation

### 3.7.1 Conditions of Transportation

#### *3.7.1.1 Reference (Base) Vehicles*

The conventional petrol internal combustion engine vehicle has been selected as the baseline passenger vehicle for this study, and the LSD bus is the baseline for public transport buses. Furthermore, LSD rigid and articulated heavy-duty truck vehicles are used as the baseline vehicle for the heavy-duty truck vehicles studies.

#### *3.7.1.2 Vehicle Weight and Load Factors*

The payload capacity varies depending on the number of passengers and vehicle kilometres travelled. The numbers of passengers for both passenger vehicles and public transport buses differ from country to country. It varies according to the size of the city: in high population cities, the number of passengers will be high, while the number of passengers in low-population cities will be lower. In addition, passenger vehicle weight is affected by the types of fuel used, while the weight of heavy-duty truck vehicles depends on the loads carried. The most important vehicle data is shown in Table 3.3.

| **Parameters** | **Net Weight (kg)**[1] | **Average Gross Weight (kg)**[1] | **Average Load (kg)**[2] | **Fraction Load Factor**[3] | **Passenger Occupancy Rate**[4] |
|---|---|---|---|---|---|
| **Passenger Vehicle** | 1240 | 1300 | 500 | - | 1.6 |
| **Public Transport Bus** | 11000 | 12000 | 16320 | - | 20 |
| **Rigid Truck** | 10000 | 15800 | 5465 | 0.6 | 1 |
| **Articulated Truck** | 18000 | 29700 | 25753 | 0.6 | 1 |

**Table 3.3: Vehicle Database Conditions**

The above Table is based on the following sources:

1. eco invent report no. 14 (Spielmann et al., 2007)
2. Australian Bureau of Statistics (Australian Bureau of Statistics, 2017)
3. fraction load factor, meaning that truck assumes 40% empty (Spielmann et al., 2007)
4. Australian transport assessment and planning (Australian Transport, 2020).

#### *3.7.1.3 Vehicle Fuel Economy (Fuel Consumption)*

Vehicle fuel consumption is considered an important factor that directly affects vehicle exhaust emissions. Most fuel economy data are based on the Australian database; however, due to the unavailability of data for some types of vehicles, vehicle fuel consumption is based on vehicle automobile manufacturers' databases. Tables 3.4, 3.5 and 3.6 show the fuel consumption of passenger vehicles, public transport buses and heavy-duty truck vehicles been used in this analysis.

| **Passenger Vehicle Model** | **Fuel Consumption** | **Equivalent Fuel Consumption (in kg/km), (in kwh/km)** | **Density (kg/l)[4]** |
|---|---|---|---|
| **Petrol (L/100km)[1]** | 10.6 | 0.079 | 0.75 |
| **LSDV (L/100km)[1]** | 10 | 0.084 | 0.84 |
| **LPGV (L/100km)[1]** | 11.1 | 0.0566 | 0.51 |
| **CNGV (L/100km)[1]** | 11.1 | 8.66E-05 | 0.00078 |
| **FCV (L/100km)[1]** | 11.1 | 0.00786 | 0.0708 |
| **HEV (L/100km)[2]** | 4.4 | 0.033 | 0.75 |
| **PHEV (L/100km)[2], (kwh/km)[2]** | 2.10, 0.1144 | 0.0158, 0.114 | 0.75 |
| **BEV (kwh/km)[3]** | 0.154 | 0.154 | - |

**Table 3.4: Fuel Economy of Passenger Vehicles**

The above Table is based on the following sources:

1. Australian Bureau of Statistics (Australian Bureau of Statistics (ABS), 2017)
2. Toyota Prius manufacturer (Toyota Motor Corporation, 2020)

3. the average electricity consumption (in kwh/km) for Nissan Leaf and Miev (Nissan Motor Corporation, 2020)
4. the GREET model (Burnham, 2012).

| **Bus Model** | **Fuel Consumption** | **Equivalent Fuel Economy (in kg/km)** | **Density (kg/l)[3]** |
|---|---|---|---|
| **Hybrid (L/100km)[1]** | 35 | 0.294 | 0.84 |
| **LSD (L/100km)[1]** | 28 | 0.235 | 0.84 |
| **LPG (L/100km)[1]** | 35 | 0.178 | 0.51 |
| **Fuel cell (L/100km)[1]** | 35 | 0.0248 | 0.0708 |
| **CNG (L/100km)[1]** | 35 | 0.000273 | 0.00078 |
| **Battery electric (kwh/km)[2]** | 1.41 | 1.41 | - |

**Table 3.5: Fuel Economy of Public Transport Buses**

The above Table is based on the following sources:

1. Australian Bureau of Statistics (Australian Bureau of Statistics (ABS), 2017)
2. the average on-board electricity consumption from the DPTI bus trial (South Australian Government, 2019)
3. the GREET model (Burnham, 2012).

| **Heavy-duty Truck Vehicle Model** | **Fuel Consumption** | **Equivalent Fuel Economy (in kg/km) and (in kwh/km)** | **Density (kg/l)[3]** |
|---|---|---|---|
| **Rigid Hybrid (L/100km)[1]** | 44.7 | 0.375 | 0.84 |
| **Rigid LSD (L/100km)[1]** | 28 | 0.2352 | 0.84 |
| **Rigid Battery Electric (kwh/km)[2]** | 0.75 | 0.75 | - |
| **Articulated Hybrid (L/100km)[1]** | 64 | 0.538 | 0.84 |
| **Articulated LSD (L/100km)[1]** | 56.3 | 0.473 | 0.84 |
| **Articulated Battery Electric (kwh/km)[2]** | 1.05 | 1.05 | - |

**Table 3.6: Fuel Economy of Heavy-Duty Truck Vehicles**

The above figures are based on the following sources:

1. Australian Bureau of Statistics (Australian Bureau of Statistics (ABS), 2017)
2. EMOSS automobile manufacturer (EMOSS Automobile Vehicles, 2020)
3. the GREET model (Burnham, 2012).

### 3.7.2 Vehicle Life Cycle Assessment Modelling

The fuel consumption, energy use and emissions over vehicle lifetime were estimated using the Australian driving cycle. The LCA energy consumption and environmental impact of transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles, were formulated as described in the following sections.

#### *3.7.2.1 The Fuel Pathway (Fuel Cycle)*

The LCA GHG emissions, energy use, PM, HTc and HTnc of fuel were estimated. The fuel pathway involves many processes from oil extraction to oil refining or transesterification to fuel distribution. Fuel is produced from various resources, including crude oil, biomass, vegetable and natural gas. Added to that, the fuel pathway includes electricity generation, whether it is from renewable or non-renewable energy sources (it is produced from the fossil fuel coal in Australia) (Spielmann et al., 2007).

#### *3.7.2.2 Vehicle Operation Phase*

The energy consumption, GHG emissions and air pollution of vehicles during the operation phase (tailpipe emissions) were evaluated. Fuel consumption is considered an important factor because it has a direct impact on vehicle exhaust emissions. Added to that, fuel consumption is affected by the performance of the vehicle's powertrain and vehicle's lifetime (vehicle kilometres travelled). Therefore, in the operation phase, the evaluation was based on the following references:

1. the vehicle kilometres travelled in Table C.1, the average fuel consumption in Table D.1 and the fuel combustion emission factors in Table E.1 (see Appendices C, D, and E ) (Australian Government, 2019, Australian Bureau of Statistics (ABS), 2017)
2. fuel consumption from Tables 3.4, 3.5 and 3.6, respectively (see Appendix D)
3. the average electricity consumption of DPTI bus trial (South Australian Government, 2019)
4. vehicle automobile manufacturers, including Toyota Prius, Nissan Leaf and Mirai for advanced passenger vehicles (Toyota Motor Corporation, 2020)

5. EMOSS automobile manufacturers for electricity consumption for battery electric heavy-duty truck vehicles (EMOSS Automobile Vehicles, 2020).

Since the vehicle needs servicing and maintenance during the vehicle operation phase, which create emissions over its entire lifetime, the environmental impact and energy demand during vehicle maintenance are estimated in the Australian context and using the AusLCI database (Spielmann et al., 2007).

### *3.7.2.3 Vehicle Non-Operational Phase*

The energy demands and GHG emissions and air pollutants produced throughout the process of material extraction and production, component manufacture and vehicle assembly were evaluated. For most vehicles, this was based on the life cycle inventories from Golf A4, Man and Volvo automobile manufacturers that are included in the ecoinvent database. To evaluate the manufacture phase of advanced-technology vehicles, the ecoinvent database and automobile manufacturers' databases. Regarding environmental impact and energy consumption of vehicle end of life, including vehicle dismantling, shredding and disposal, the AusLCI database was used. The process of vehicle end of life emits a significant amount of emissions and consumes a lot of energy (Spielmann et al., 2007).

## 3.8 Uncertainty Analysis Modelling Using the Monte Carlo Simulation in SimaPro Software

Due to the nature of vehicle exhaust emissions, the emissions associated with the production of materials and components can have uncertainty ranges. To deal with these unknowns that are associated with assumptions about input values, a Monte Carlo simulation with 100 random samplings is applied to each of the uncertainty analyses in relation to the data used to build the life-cycle assessment model. By using Monte Carlo analysis, the LCA SimaPro software determines the uncertainty of the LCA's results. The same calculation is repeated while taking different values within the uncertainty range, and the overall LCA results are stored after each calculation. This procedure is repeated 1,000 times and will produce 1,000 results that form an uncertainty distribution in themselves, providing information about the reliability of the LCA. Moreover, Monte Carlo analysis can be performed on the inventory of the LCA's findings (Sustainability, 2018).

In this study, the uncertainty analysis examines the uncertain data (variables), which can be used to pick out the certain results and decide whether they are correct or incorrect. It is also employed to check the data that is used to build the LCA model. According to (Huijbregts, 1998), the uncertainty analysis is divided into three components:

1. The uncertainty within the model.
2. The uncertainty in choice

   (These two components are related to the selection of system boundaries, the functional unit and processes).
3. The uncertainty in the parameters.

In order to assess the uncertain-data-in-the-parameters option, a sensitivity analysis and uncertainty data should be jointly examined to give comparative results; at this point, the parameters that are creating the critical (uncertainty) results can be determined. Hence, in this thesis, the uncertainty in the data is scrutinised using the mean (average) value, the standard deviation and the coefficient of variation (CV), so that it can be decided whether the data is close to the mean value or if there is a vast deviation. The standard deviation is defined as a number that is used to indicate how the measurements within a group are spread out from the average (mean or expected value), and it is calculated as the square root of variance by determining each data point's deviation relative to the mean value. Meanwhile, the CV is defined as a statistical measure of the relative dispersion of data points in a dataset and is calculated in the following manner: coefficient of variation = (standard deviation/Mean) * 100. Multiplying the coefficient by 100 is an optional step to get a percentage as opposed to merely obtaining a decimal number.

## 3.9 Sensitivity Analysis Modelling in SimaPro Software

Finding the most important assumptions is typically something that is undertaken in the objective and scope phase of a study and then later during data collection. SimaPro software provides an efficient way to build in parameters that can be used, especially when there are doubts about which parameters have a significant impact on the overall outputs during the life-cycle modelling. The LCA SimaPro software can use global data from the likes of the United States or Europe, or it can utilise domestic data from Australia. This way of modelling is particularly useful when this method is applied throughout the entire LCA and changing one parameter can automatically alter the parameters everywhere (Sustainability, 2018).

Meanwhile, sensitivity analysis is a tool that is used to check and assess the output data (results), or it can be a technique employed to ascertain the impact of certain independent variables on a single dependent variable. In addition, it evaluates the influence that the most important parameters have on an LCA's results (Goedkoop et al., 2016), meaning it will check and help to assess the reliability of the whole assessment's findings and verify whether they have been affected by uncertainties in the data, model builds, the fuel pathway phase, the vehicle's operation phase and the vehicle's manufacturing phase. Furthermore, sensitivity analysis can flag up significant issues with any parameters and is used to examine the effects of an LCA's GHG emissions on energy demand, particulate matter (PM), human health (cancer and non-cancerous diseases) and transportation over its entire lifetime. The parameters that play significant roles in an LCA’s results are the occupancy rate of passengers, fuel consumption, electricity mix consumption and production, kilometres travelled, average load, fraction load factor, crude oil extraction and production, liquified petroleum gas (LPG) production and processing, natural gas production and processing, hydrogen production and processing, vehicle manufacture, maintenance and disposal. There is a knowledge gap in previous studies in that they used too few parameters and only applied them to one or two case studies. Consequently, in this thesis, 15 parameters have been employed across three case studies.

This move allows for a base case to be identified that represents a reasonable current value (reference value). Also, in relation to all of the parameters, it highlights a low and high value, which offers up plausible boundaries on the likely variations of each one based on the assumption that almost all parameters can have a reach of approximately +10% to -10% of the total of the LCA’s results. Thus, the selection of case A (a decrease of 10%) and case B (an increase of 10%) allows for the creation of a reference value. Furthermore, the analysis consisted of a modification to the assumptions that were made during the development of the model. Table 3.7 shows the parameters that affect the LCA’s overall energy use and the emissions during transportation over the course of the vehicle’s entire lifetime.

| **Parameters** | **Passenger Vehicles** | **Public Transport Buses** | **Heavy-duty Truck Vehicles** |
|---|---|---|---|
| **Fuel consumption (use)** | x | x | x |
| **Electricity grid consumption** | x | x | x |
| **Electricity grid production** | x | x | x |
| **Passenger occupancy rate** | x | x | - |
| **Kilometre travelled** | x | x | x |
| **Average load** | - | - | x |
| **Fraction load** | - | - | x |
| **Crude oil extraction and refining** | x | x | x |
| **LPG production and processing** | x | x | - |
| **Natural gas production and processing** | x | x | - |
| **Biofuel production and processing** | x | x | - |
| **Hydrogen production and processing** | x | x | - |
| **Vehicle manufacture** | x | x | x |
| **Vehicle maintenance** | x | x | x |
| **Vehicle disposal** | x | x | x |

**Table 3.7: Parameters that Impact the Overall LCA Results**

## 3.10 Modelling the Environmental Rating Scores of Vehicles

An environmental rating scheme for vehicles is very important because it informs consumers about different vehicles and their impacts on the environment. There are three common methods used to determine the environmental rating scores of vehicles:

1. the Australian Green Vehicle Guide (GVG), which uses the European driving cycle and follows Australian Design Rules (ADRs) (ADR 81)
2. the European Ecotest, which uses the NEDC to determine vehicles' rating scores
3. the US EPA GVG, which uses the Smart Way program to measure vehicles' rating scores.

### 3.10.1 The Australian Green Vehicle Guide

All vehicles in Australia should be within the national Australian emission standard or their environmental rating scores should be within standard ranges. These national standards are known as ADRs. They are adopted from Europe and other countries, such as Japan and the USA, who are the major importers of vehicles into Australia. The information used in the GVG is supplied directly by vehicle manufacturers. A vehicle's environmental rating score is based on the vehicle operation phase (tailpipe emissions). The fuel consumption and emissions of all new vehicles are provided by the manufacturers on the GVG website, which ranks vehicles according to the follow (An Australian Government Initiative, 2020):

1. urban tailpipe emissions (lowest to highest)
2. rural tailpipe emissions (lowest to highest)
3. the combination of urban and rural tailpipe emissions (lowest to highest)
4. energy consumption (lowest to highest)
5. electric range (highest to lowest)
6. air pollution standard (highest to lowest)

7. noise (lowest to highest)
8. alphabetical order (A–Z by make, model and variant).

### 3.10.2 The European Ecotest

The Eco Test is considered an important test that measures vehicles' environmental rating scores. It is based on the European driving cycle that applies to most cars in Europe. Vehicle manufacture companies can use the Eco Test to establish a car's performance and efficiency. The Eco Test includes all the necessary tests related to a vehicle's environmental impact for two reasons (ADAC, 2020):

1. It covers all the key emissions, including GHGs and air pollutants.
2. The tests are realistic, covering many driving conditions, including motorway driving, and considering the impact of air conditioning on vehicle features when compared to standard tests.

### 3.10.3 The US EPA GVG

This is one of the necessary tests applied to passenger vehicles in the USA, and it includes the Smart Way program, which lowers emissions by 20%, if used. It considers two types of emissions, which are detailed below (EPA, 2020):

#### *3.10.3.1 GHG Emissions Rating*

Vehicles that score a ten are considered the cleanest vehicles. However, this rating only represents the emissions during the vehicle operation phase (tailpipe emissions), ignoring the many emissions produced during the vehicle operation phase (maintenance), the fuel cycle (fuel production and electricity generation) and the vehicle non-operational phase (vehicle manufacture and disposal).

#### *3.10.3.2 Smog Rating*

This rating reflects vehicle tailpipe emissions that contribute to local and regional air pollution, creating problems, such as smog, haze and health issues. Vehicles that score a ten are the cleanest. Light-duty cars and trucks must meet either federal (EPA) or Californian (CARB) emission requirements. Motor vehicle emissions contribute to ambient levels of air toxins that are known or are suspected to be human and/or animal carcinogens. Exposure to air toxins can also cause non-cancerous health effects, such as neurological, cardiovascular, respiratory, reproductive and immune system damage. Classifications of vehicle exhaust emissions are listed below:

1. nonmethane organic gas or other carbon-containing compounds, including hydrocarbons (HCs)
2. NOx, which combines with HCs to create smog
3. PM, which are tiny particles of solid matter that lodge in the lungs and deposit on buildings
4. CO.

### 3.10.4 Vehicle Rating Scores and Life Cycle Emissions

Generally, a vehicle’s rating score is estimated based only on the emissions during the vehicle operation phase (tailpipe emissions). However, it is important to cover all stages of emissions – including upstream and downstream, such as the fuel cycle (fuel pathway), vehicle operation phase (vehicle maintenance) and the vehicle non-operational phase (vehicle manufacture and disposal) – so that the environmental rating score is more accurate. Unlike many studies, this study combines tailpipe emissions with two major life cycles associated with vehicles:

1. the fuel cycle (fuel pathway) – the vehicles' environmental rating scores will consider the LCA GHG emissions during fuel production and electricity generation
2. the vehicle operation and non-operational phases.

By considering these stages, the vehicles' environmental rating scores will estimate the emissions during cradle-to-grave vehicle manufacture, maintenance and disposal.

Similarly, the environmental rating scheme for heavy vehicles (vehicles that have a gross mass of 3.5 tonnes or more) is very important because it provide users with information about fuel consumption, road condition, drive behaviour, vehicle components, vehicle service and maintenance, as well as the initial cost. The light vehicle rating scheme is a good method for collecting data and is easily understood by consumers, so the framework for light-duty vehicles' environmental rating scores can also be applied to heavy-duty vehicles. The rating of GHG emissions can be determined by using the following practical tests (Dr Rocco Zito, 2007):

1. the Composite Urban Emissions Drive Cycle (CUEDC), where fuel consumption is derived from LSD.
2. heavy vehicle simulation software.
3. in-house testing/operation.

In this study, heavy-duty vehicles are rated by estimating the whole life cycle energy consumption, GHG emissions, PM, HTc and HTnc over the vehicles' lifetimes.

In summary, this chapter formulated an approach to estimate the total life cycle assessment of vehicles over their lifetimes, based on the AusLCI database. The approach considers all the stages of life cycle energy use and emissions, including the fuel pathway, tailpipe emissions, vehicle manufacture, maintenance and disposal. Moreover, the approach accounts for all types of vehicle, including conventional, alternative and advanced. All the data used in the modelling was quality checked using uncertainty analysis, and for further accuracy, the LCA results underwent a sensitivity analysis, which also shows whether individual parameters have a positive or negative impact on the outcome. Lastly, a theory was presented to estimate vehicles' environmental rating scores.

# CHAPTER 4: PASSENGER, BUS AND HEAVY VEHICLES LCA

## 4.1 Results and Findings

Life cycle assessment (LCA) is a means of assessing the varying impacts of the factors associated with all stages of vehicle lifespan, from production to disposal. One of the aims of this thesis is to identify the most important parameters that contribute to the environmental impact of transport in the context of LCA, hence why consideration is given to the mining of raw materials and manufacturing, operating and disposing of the vehicles. Unlike many studies on the LCA of transportation, this study considers LCA to comprise:

1. the vehicle manufacturing phase (estimating the energy used and emissions produced during the materials production and vehicle assembly)
2. the vehicle maintenance phase (estimating the energy used and emissions produced during the vehicle operation phase over a vehicle's lifetime)
3. the vehicle disposal phase (estimating the energy used and emissions produced when dismantling a vehicle).

The LCA results obtained as part of this thesis are estimated by using different input sources. Most of these sources are from the SimaPro software (AusLCI database) or are adapted and linked to other Australian databases. Others are from vehicle manufacturers. Listed below are the specific database resources:

1. AusLCI found within the SimaPro software
2. Australian National Greenhouse Account Factor (NGAF)
3. Australian National Pollution Inventory (NPI)
4. Australian Survey of Motor Vehicle Use (ABS)
5. Australian Government, Department of Planning and Transport Infrastructure (DPTI) and Australian Transport Assessment and Planning

6. the manufacturer companies' websites of the Toyota Prius, Nissan Leaf, Miev, Toyota Mirai and EMOSS.

The study assumes that the GHG emissions are the sum of the emissions of CO2, CH4 and N2O, and it focuses on air pollutants, including particulate matter (PM), human toxicity, cancer (HTc) and human toxicity, non-cancer (HTnc). The results of the environmental impact assessment of vehicles during their lifetimes are presented separately for each impact category. This section is divided into three categories, which are discussed in the following sections.

### 4.1.1 Global Warming Potential

GHG emissions are considered the main cause of global warming, with a significant proportion contributed by transportation. Regarding passenger vehicles, Table 4.1 and Figure 4.1 indicate that vehicles powered by alternative fuel have lower GHG emissions than conventional vehicles. Furthermore, compressed natural gas (CNG) vehicles produce significantly fewer GHG emissions compared to conventional and advanced vehicles, followed by fuel cell vehicles (FCVs). This is because both CNG and FCVs have lower fuel economy, which directly affects vehicle exhaust emissions. Added to that, hydrogen fuels are derived from renewable energy sources rather than fossil fuels. In addition, although battery electric vehicles (BEVs) have zero tailpipe emissions, they produce more GHG emissions during the vehicle manufacture stage and from power supply (if the electricity is derived from non-renewable energy sources). Like BEVs, FCVs have zero tailpipe emissions; however, their contribution to GHG emissions is higher due to the emissions released during the vehicle manufacture and maintenance phases. This finding leads to the conclusion that although the FCV is considered a more expensive car, its contribution to climate change is lower.

Another finding shown in the figures is that conventional vehicles release more tailpipe emissions (operation phase) than they do upstream emissions (the fuel pathway) and during the vehicle manufacture phases. Conversely, advanced vehicle technologies have a greater environmental impact during their power supply and vehicle manufacture phases. Added to that, due to the production of lithium batteries, BEVs emit considerable GHG emissions to the environment. Due to electricity generation from non-renewable energy sources in Australia, the BEV has a small effect on the environment, much the same as conventional vehicles. Although conventional vehicles release more GHG emissions (in tonnes) to the environment, they are the most popular mode of vehicle because of reasons related to the availability of fuels and their reasonable prices.

| **Passenger Vehicle Model** | **Fuel Cycle (kg/pkm)** | **Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture (kg/pkm)** | **Vehicle Maintenance (kg/pkm)** | **Vehicle Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|---|---|---|
| **Petrol Baseline** | 0.0412 | 0.1808 | 0.029 | 0.00602 | 0.00212 | 0.259 |
| **LSDV** | 0.0306 | 0.1744 | 0.029 | 0.00602 | 0.00212 | 0.242 |
| **LPGV** | 0.028 | 0.137 | 0.029 | 0.00602 | 0.00212 | 0.202 |
| **PHEV** | 0.0723 | 0.0437 | 0.0329 | 0.00906 | 0.00379 | 0.162 |
| **BEV** | 0.0973 | 0 | 0.0363 | 0.0204 | 0.00426 | 0.158 |
| **HEV** | 0.0164 | 0.0748 | 0.0298 | 0.00625 | 0.00225 | 0.13 |
| **FCV** | 0.00915 | 0 | 0.0306 | 0.00602 | 0.00212 | 0.0479 |
| **CNGV** | 0.000379 | 0.0021 | 0.029 | 0.00602 | 0.00212 | 0.0397 |

**Table 4.1: LCA GHG Emissions (kg/pkm) of Passenger Vehicles**

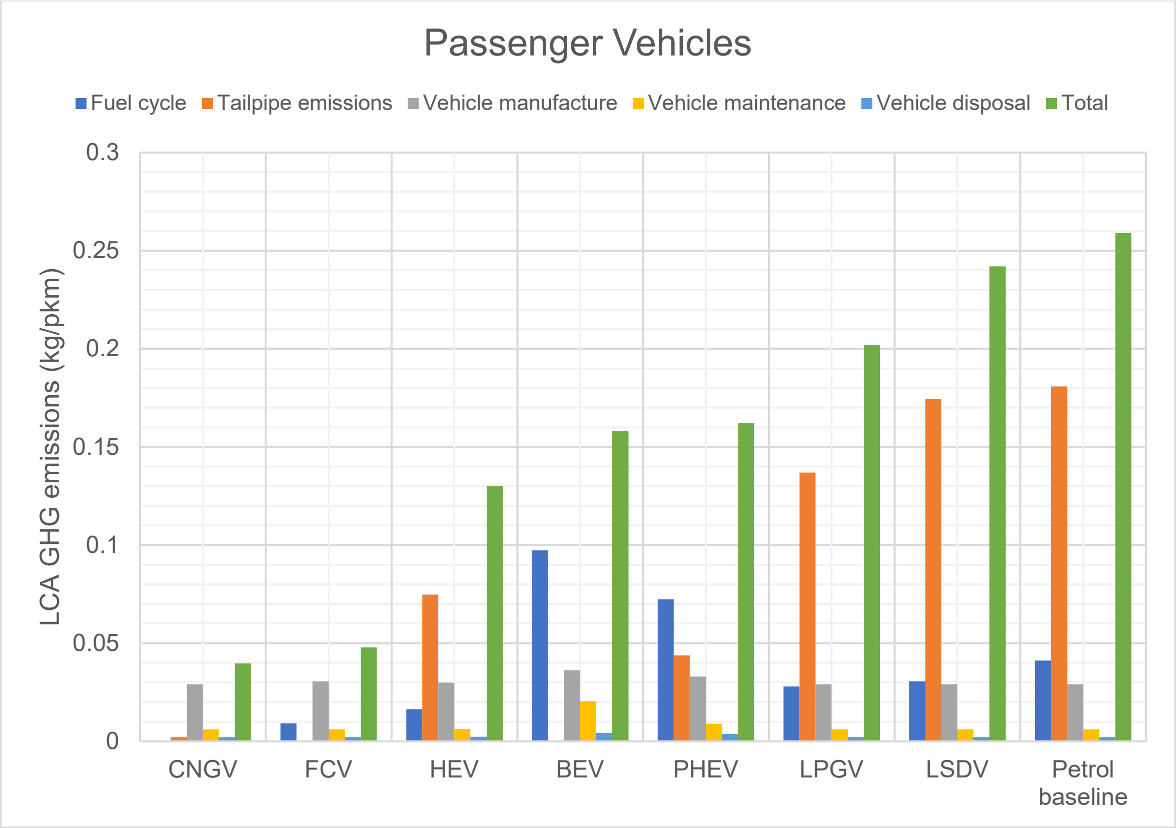


**Figure 4.1: LCA GHG Emissions (kg/pkm) of Passenger Vehicles**

In the case of the LCA GHG emission for public transport buses, the results in Table 4.2 and Figure 4.2 show that both CNG and fuel cell buses can deliver significant GHG emissions savings compared to conventional and battery electric buses. Moreover, it was observed that the bus cradle-to-grave ($C_2G$) (from manufacture and disposal) GHG emissions are higher for battery electric buses than conventional LSD buses. Additionally, the fuel pathway (electricity supply) for battery electric buses emits significant GHGs because the electricity used is produced from coal (fossil energy) instead of renewable energy sources. This point may make battery electric buses an undesirable public transport option in Australia. Furthermore, although the use of liquified petroleum gas (LPG) buses can reduce the volume of GHG emissions to the environment, it is still classified as non-sustainable because LPG is produced from fossil fuel. Consequently, LPG buses are not preferred over conventional LSD buses. Similar to LPG buses, hybrid buses are comparable to conventional buses in terms of exhaust emissions.

| Bus Model | Fuel Cycle (kg/pkm) | Tailpipe Emissions (kg/pkm) | Vehicle Manufacture (kg/pkm) | Vehicle Maintenance (kg/pkm) | Vehicle Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|---|---|---|
| **Battery Electric** | 0.0713 | 0 | 0.0109 | 0.0148 | 0.000484 | 0.0974 |
| **Hybrid** | 0.00857 | 0.04883 | 0.00901 | 0.0128 | 0.000259 | 0.0795 |
| **LSD Baseline** | 0.00686 | 0.03904 | 0.00885 | 0.0133 | 0.000233 | 0.0682 |
| **LPG** | 0.00707 | 0.03443 | 0.00881 | 0.0128 | 0.000233 | 0.0634 |
| **Fuel cell** | 0.00231 | 0 | 0.00915 | 0.0128 | 0.000233 | 0.0245 |
| **CNG** | 9.57E-05 | 0.0000473 | 0.00885 | 0.0133 | 0.000233 | 0.0225 |

**Table 4.2: LCA GHG Emissions (kg/pkm) of Public Transport Buses**

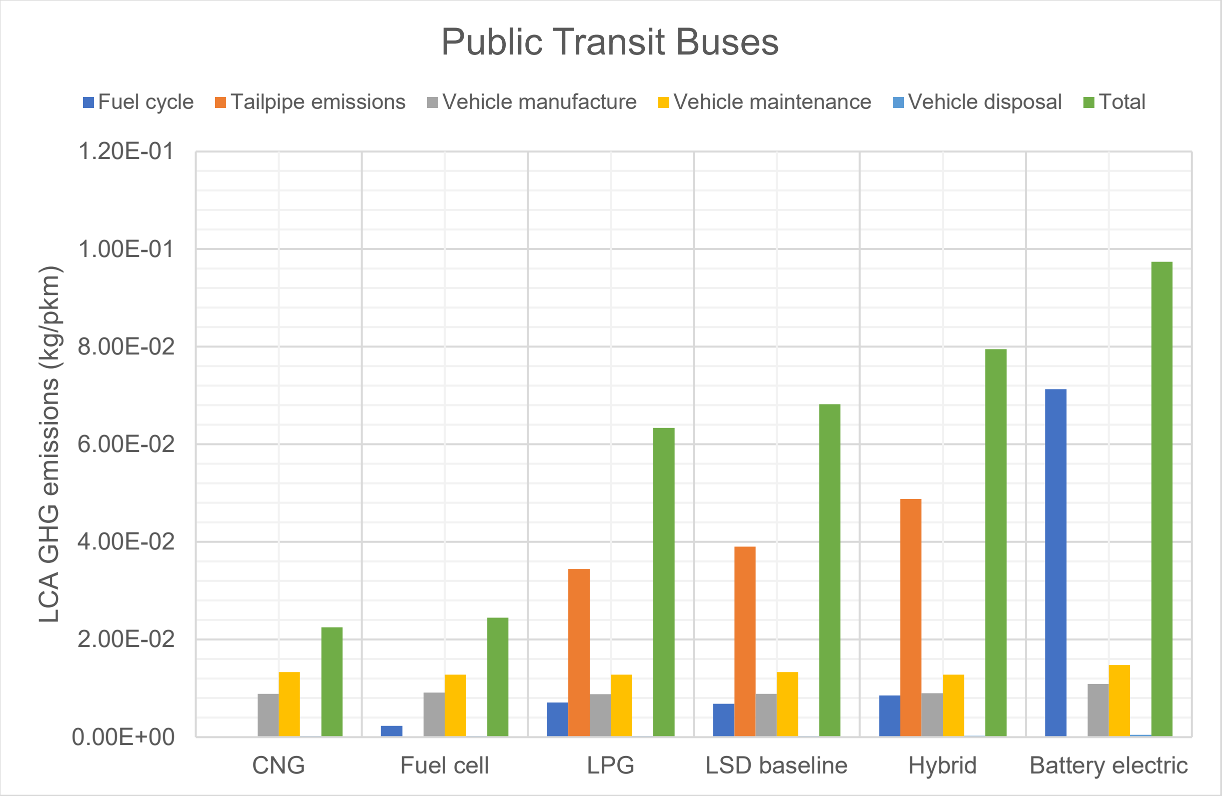


**Figure 4.2: LCA GHG Emissions (kg/pkm) of Public Transport Buses**

Regarding heavy-duty truck vehicles' LCA GHG emissions, two types of trucks were examined: rigid and articulated because, according to the Australian Bureau of Statistics, the two types of trucks have different levels of fuel consumption and different kilometres travelled. The results shown in Tables 4.3 and 4.4 and Figures 4.3 and 4.4 indicate that battery electric articulated trucks produce significantly fewer GHG emissions compared to other types of truck, including conventional and hybrid, because battery electric articulated trucks have zero tailpipe emissions. Lastly, it was noted that the contribution to LCA GHG emissions made by heavy-duty truck vehicle tailpipe emissions (operation phase) is much higher compared to the fuel pathway, manufacture, maintenance and disposal phases due to the fact that heavy-duty truck vehicles travel more kilometres and have much longer operation phases than other types of transportation.

| Rigid Truck Model | Fuel Cycle (kg/tkm) | Tailpipe Emissions (kg/tkm) | Vehicle Manufacture (kg/tkm) | Vehicle Maintenance (kg/tkm) | Vehicle Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|---|---|---|
| **Hybrid** | 0.0668 | 0.3792 | 0.0207 | 0.0133 | 0.000615 | 0.48 |
| **LSD Baseline** | 0.0418 | 0.2382 | 0.02 | 0.0133 | 0.000586 | 0.314 |
| **Battery Electric** | 0.231 | 0 | 0.0297 | 0.0207 | 0.00183 | 0.283 |

**Table 4.3: LCA GHG Emissions (kg/tkm) of Rigid Trucks**

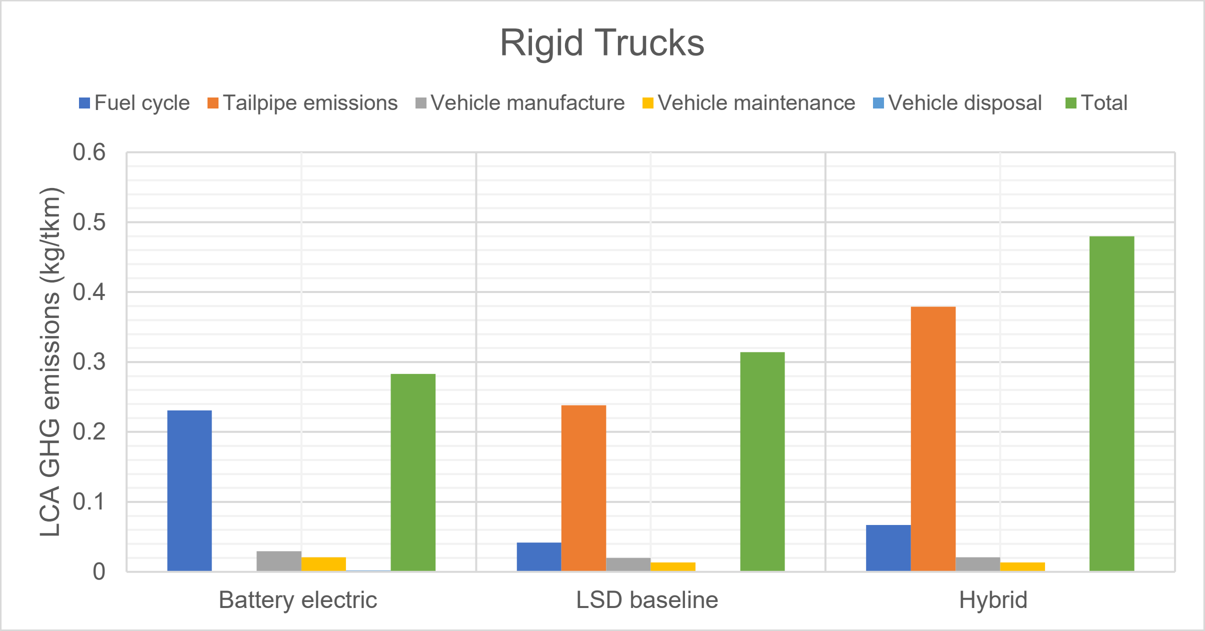


**Figure 4.3: LCA GHG Emissions (kg/tkm) of Rigid Trucks**

| Articulated Truck Model | Fuel Cycle (kg/tkm) | Tailpipe Emissions (kg/tkm) | Vehicle Manufacture (kg/tkm) | Vehicle Maintenance (kg/tkm) | Vehicle Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|---|---|---|
| **Hybrid** | 0.0203 | 0.1157 | 0.00246 | 0.00184 | 8.57E-05 | 0.14 |
| **LSD Baseline** | 0.0178 | 0.1022 | 0.00307 | 0.0014 | 8.40E-05 | 0.124 |
| **Battery Electric** | 0.0687 | 0 | 0.00307 | 0.0014 | 8.40E-05 | 0.0732 |

**Table 4.4: LCA GHG Emissions (kg/tkm) of Articulated Trucks**

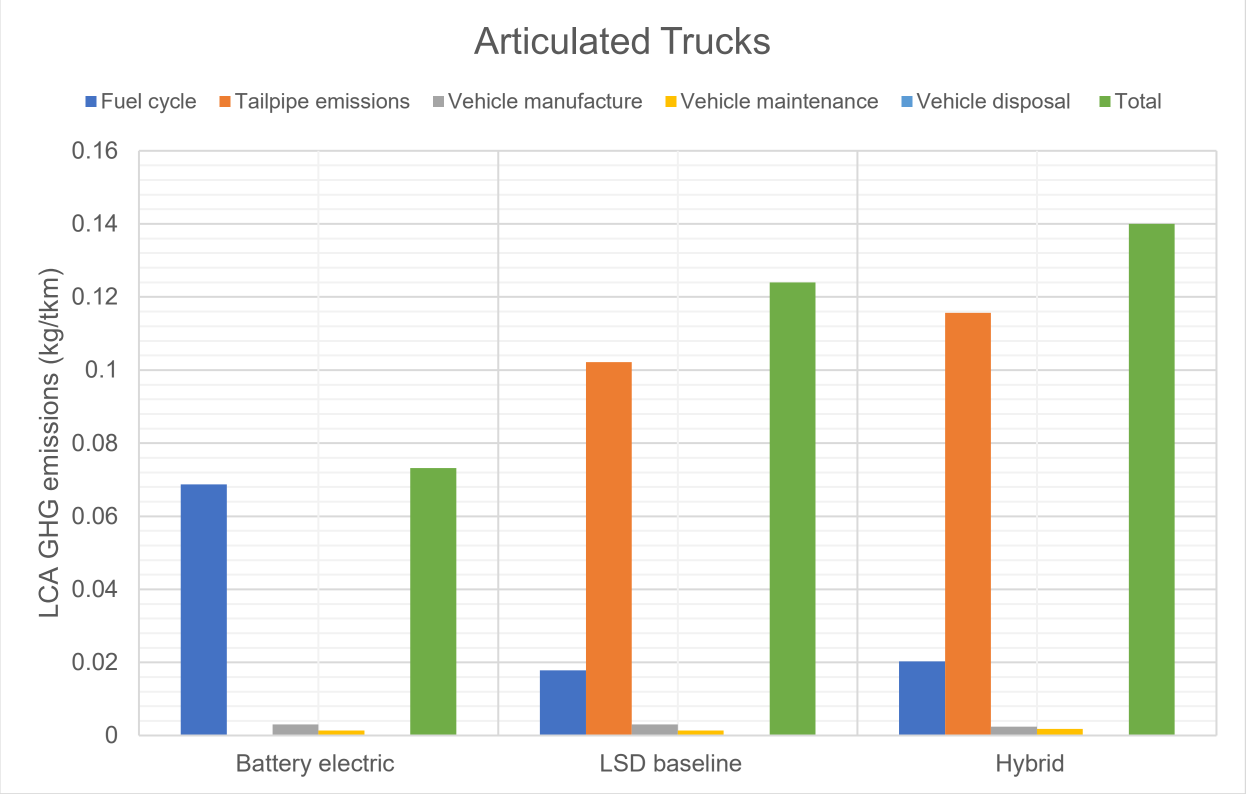


**Figure 4.4: LCA GHG Emissions (kg/tkm) of Articulated Trucks**

### 4.1.2 Cumulative Energy Demand

The life cycle energy use of transportation is considered the most important factor in deciding whether the vehicle is sustainable (posing little or no threat to both human health and the environment). As can be seen from the results of LCA energy use for passenger vehicles in Table 4.5 and Figure 4.5, CNG vehicles and FCVs consume less energy than conventional and advanced vehicle technologies because alternative fuel and hydrogen-powered fuel cells are derived from low carbon feedstock. Moreover, the results indicate that conventional vehicles still consume more energy than both advanced vehicles and vehicles powered by alternative fuels because conventional vehicles have a high compression ratio causing high energy use and poor fuel economy. Interestingly, the results illustrate that energy use during vehicle manufacture, maintenance and disposal are similar across all types of vehicle. Energy use during the production of BEVs is higher than for diesel and advanced vehicles.

| **Passenger Vehicle Model** | **Fuel Cycle and Tailpipe Emissions (MJ/pkm)** | **Vehicle Manufacture (MJ/pkm)** | **Vehicle Maintenance (MJ/pkm)** | **Vehicle Disposal (MJ/pkm)** | **Total (MJ/pkm)** |
|---|---|---|---|---|---|
| **Petrol Baseline** | 2.84 | 0.404 | 0.113 | 0.017 | 3.37 |
| **LSDV** | 2.41 | 0.404 | 0.113 | 0.017 | 2.9 |
| **LPGV** | 1.96 | 0.404 | 0.113 | 0.0117 | 2.49 |
| **Electric** | 1.11 | 0.503 | 0.292 | 0.0302 | 1.93 |
| **PHEV** | 0.923 | 0.472 | 0.173 | 0.0261 | 1.59 |
| **HEV** | 0.21 | 0.415 | 0.118 | 0.0128 | 0.755 |
| **FCV** | 0.104 | 0.422 | 0.113 | 0.0117 | 0.652 |
| **CNGV** | 0.0585 | 0.404 | 0.113 | 0.0117 | 0.588 |

**Table 4.5: LCA Energy Use (MJ/pkm) of Passenger Vehicles**

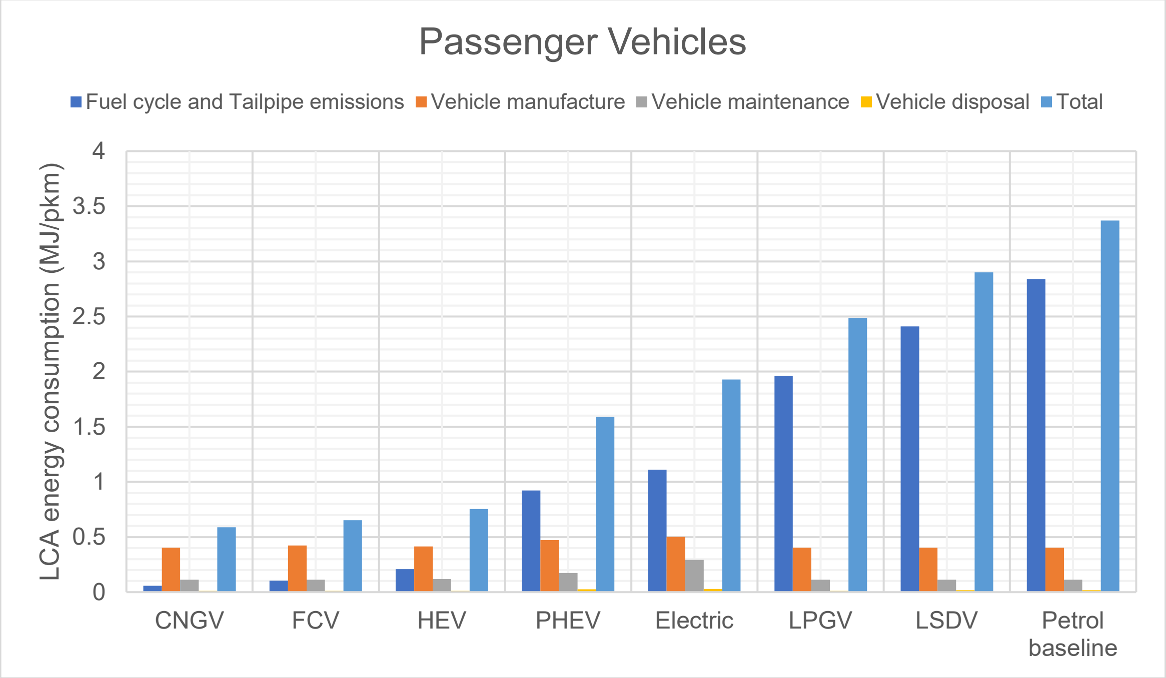


**Figure 4.5: LCA Energy Use (MJ/pkm) of Passenger Vehicles**

Regarding public transport buses' LCA energy use, the results in Table 4.6 and Figure 4.6 show that the use of both CNG and fuel cell buses can achieve a significant reduction in energy use over the buses' lifetimes. Battery electric buses consume much more energy than other types of bus, with most of the energy use occurring during the power generation phase. Similarly, conventional LSD buses also consume much more energy during their lifetimes because the powertrain/conventional LSD bus has a high compression ratio (large combustion chamber) meaning the fuel economy is much lower compared to other vehicles' powertrains.

| **Bus Model** | **Fuel Cycle and Tailpipe Emissions (MJ/pkm)** | **Vehicle Manufacture (MJ/pkm)** | **Vehicle Maintenance (MJ/pkm)** | **Vehicle Disposal (MJ/pkm)** | **Total (MJ/pkm)** |
|---|---|---|---|---|---|
| **Battery Electric** | 0.812 | 0.138 | 0.179 | 0.00225 | 1.13 |
| **Hybrid** | 0.676 | 0.113 | 0.16 | 4.09E-10 | 0.949 |
| **LSD Baseline** | 0.541 | 0.112 | 0.16 | 8.61E-05 | 0.812 |
| **LPG** | 0.495 | 0.111 | 0.16 | 8.61E-05 | 0.765 |
| **Fuel cell** | 0.0263 | 0.115 | 0.16 | 8.61E-05 | 0.301 |
| **CNG** | 0.0148 | 0.112 | 0.16 | 8.61E-05 | 0.287 |

**Table 4.6: LCA Energy Use (MJ/pkm) of Public Transport Buses**

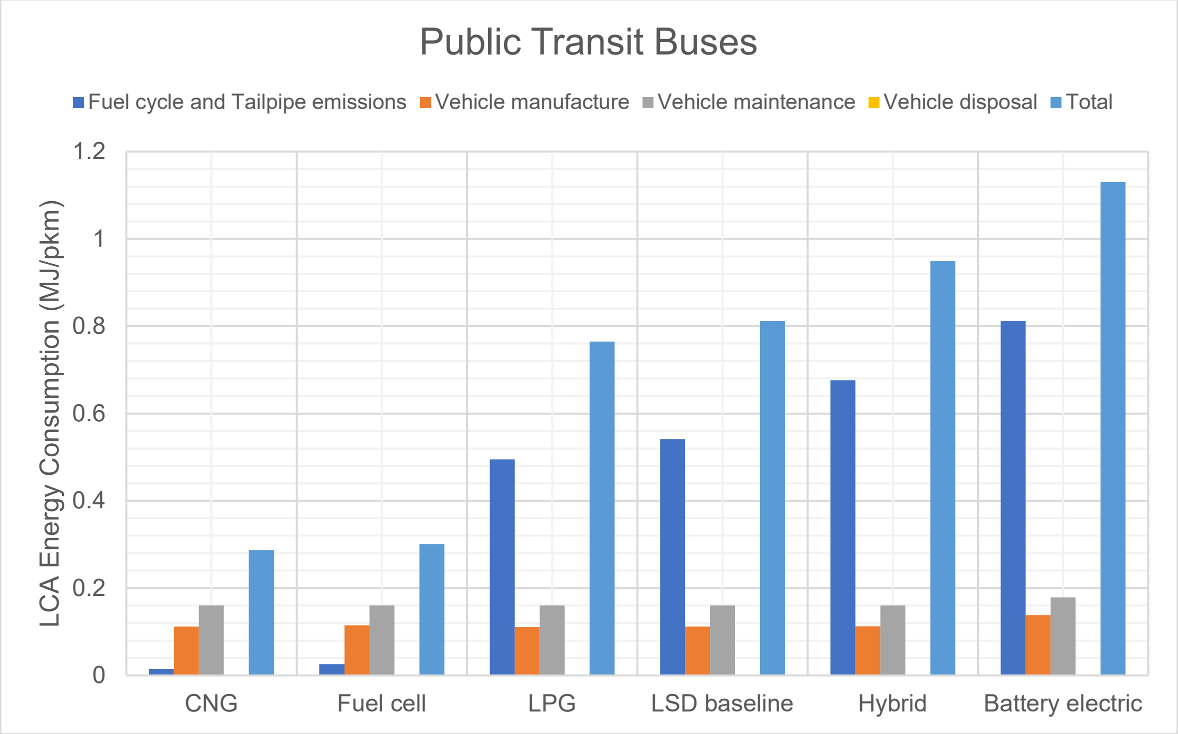


**Figure 4.6: LCA Energy Use (MJ/pkm) of Public Transport Buses**

Regarding heavy-duty truck vehicles' LCA energy demands, the results in Table 4.7 and Figure 4.8 illustrate that battery electric articulated trucks consume less energy relative to LSD and hybrid heavy-duty truck vehicles. This is because the LCA results are affected by many factors, such as fuel economy, load capacity, average weight and kilometres travelled. The use of fossil fuels is another factor that directly affects the results. Advanced-technology heavy-duty trucks, both rigid and articulated, are the best option in Australia because they consume less energy than conventional trucks.

| Rigid Truck Model | Fuel cycle and Tailpipe Emissions (MJ/tkm) | Vehicle Manufacture (MJ/tkm) | Vehicle Maintenance (MJ/tkm) | Vehicle Disposal (MJ/tkm) | Total (MJ/tkm) |
|---|---|---|---|---|---|
| **Hybrid** | 5.26 | 0.285 | 0.264 | 0.001 | 5.82 |
| **LSD Baseline** | 3.3 | 0.278 | 0.264 | 0.000756 | 3.84 |
| **Battery Electric** | 2.63 | 0.401 | 0.361 | 0.0115 | 3.41 |

**Table 4.7: LCA Energy Use (MJ/tkm) of Rigid Trucks**

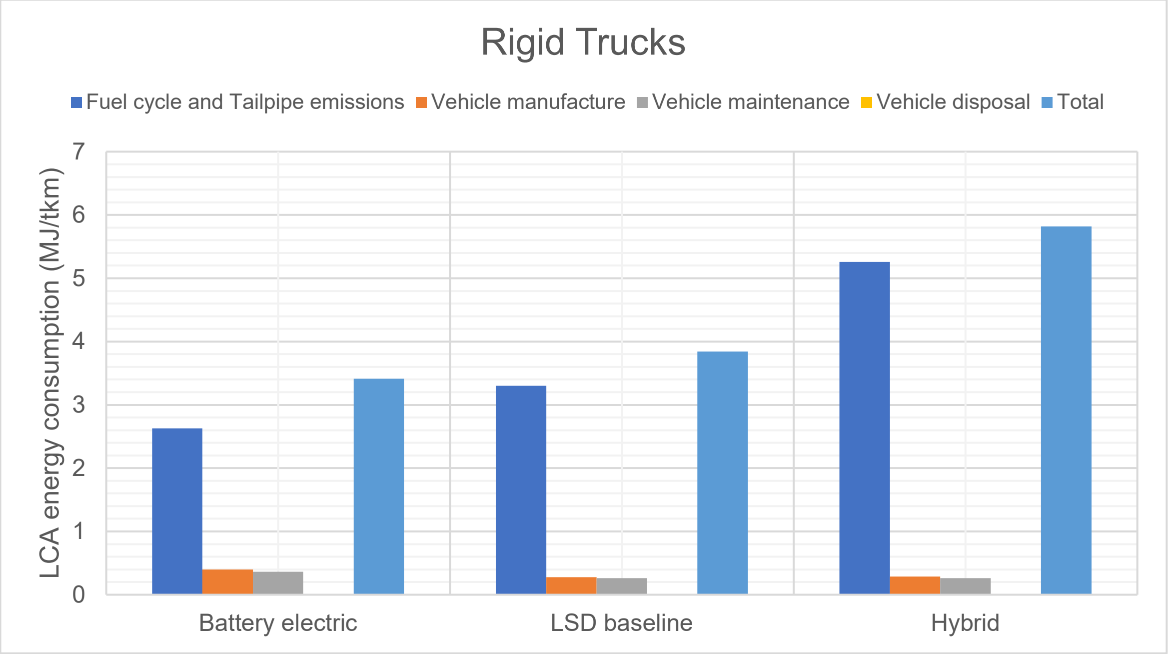


**Figure 4.7: LCA Energy Use (MJ/tkm) of Rigid Trucks**

| **Articulated Truck Model** | **Fuel Cycle and Tailpipe Emissions (MJ/tkm)** | **Vehicle Manufacture (MJ/tkm)** | **Vehicle Maintenance (MJ/tkm)** | **Vehicle Disposal (MJ/tkm)** | **Total (MJ/tkm)** |
|---|---|---|---|---|---|
| **Hybrid** | 1.6 | 0.0344 | 0.0362 | 0.000121 | 1.67 |
| **LSD Baseline** | 1.41 | 0.0422 | 0.0321 | 0.000107 | 1.48 |
| **Battery Electric** | 0.782 | 0.0422 | 0.0321 | 0.000107 | 0.857 |

**Table 4.8: LCA Energy Use (MJ/tkm) of Articulated Trucks**

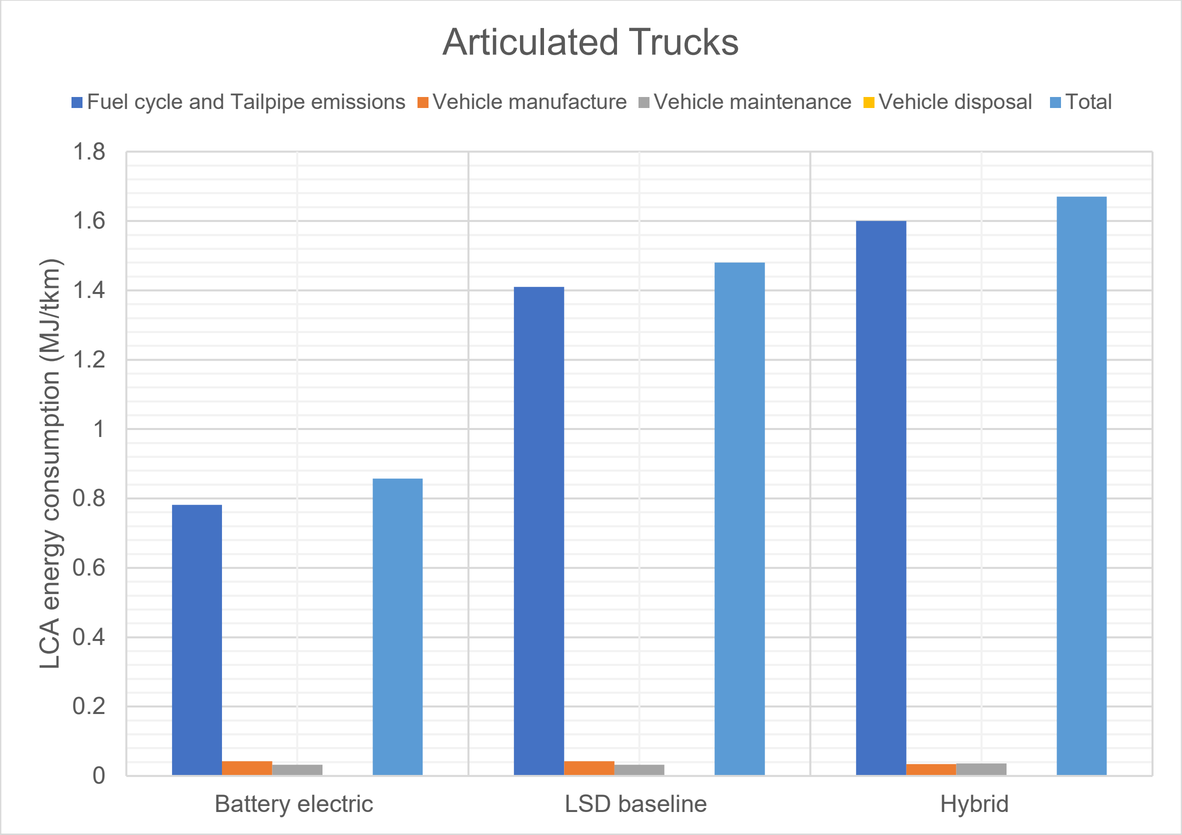


**Figure 4.8: LCA Energy Use (MJ/tkm) of Articulated Trucks**

### 4.1.3 Influence of Human Health

Human impact on the environment includes impacts on biophysical environments, biodiversity and other resources. The term is used in the context of pollution emissions produced as a result of human activities, but it also applies broadly to all major human impacts on the environment. Chemicals can be emitted to the environment (air, water, soil) during all products', services' and systems' life cycle stages. Emission inventories of different products may contain hundreds of chemicals, many of which will have a potentially toxic impact on humans, including causing both cancerous and non-cancerous diseases, leading to damage to human health. The impact pathways for human toxicity combine the following four factors: an environmental factor, a human exposure factor, a human toxicity effect factor and a toxicity damage factor. An environmental factor indicates the distribution and transformation of chemicals in the environment. The exposure factor relates the chemical mass in the environment to human exposure. The effect factor indicates the potential human toxicity effects per unit of chemical exposure and lastly, the damage factor relates the potential effects to damage to human health (LC-IMPACT, 2020). This study focuses on three kinds of gases – PM, HTc and HTnc – due to their direct impact on human health (and, therefore, human life). The results are presented in tables and figures showing how PM, HTc and HTnc vary according to the mode of transportation. Regarding passenger vehicles, Tables and Figures 4.9, 4.10 and 4.11 show that the largest contribution of PM comes from conventional vehicles, followed by advanced vehicle technologies. For conventional vehicles, the fuel pathway and vehicle operation phase (tailpipe emissions) are when most PM is released, while for advanced vehicles and vehicles powered by alternative fuel, most of their life cycle PM is released during vehicle manufacture, maintenance and disposal. The vehicle manufacture phase contributes the majority of LCA HTc and HTnc for all passenger vehicles, although alternative vehicles have reduced HTc and HTnc compared to advanced vehicle technologies.

| Passenger Vehicle Model | Fuel cycle and Tailpipe Emissions (kg/pkm) | Vehicle Manufacture, Maintenance and Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|
| **LSDV** | 0.000215 | 0.000012 | 0.000227 |
| **Petrol Baseline** | 8.52E-05 | 1.22E-05 | 9.74E-05 |
| **PHEV** | 2.39E-05 | 3.29E-05 | 5.67E-05 |
| **HEV** | 3.43E-05 | 1.45E-05 | 4.88E-05 |
| **BEV** | 1.03E-05 | 2.62E-05 | 3.65E-05 |
| **LPGV** | 1.26E-05 | 1.22E-05 | 2.49E-05 |
| **FCV** | 1.22E-06 | 1.32E-05 | 1.44E-05 |
| **CNGV** | 1.19E-06 | 1.22E-05 | 1.34E-05 |

**Table 4.9: LCA PM (kg/pkm) of Passenger Vehicles**

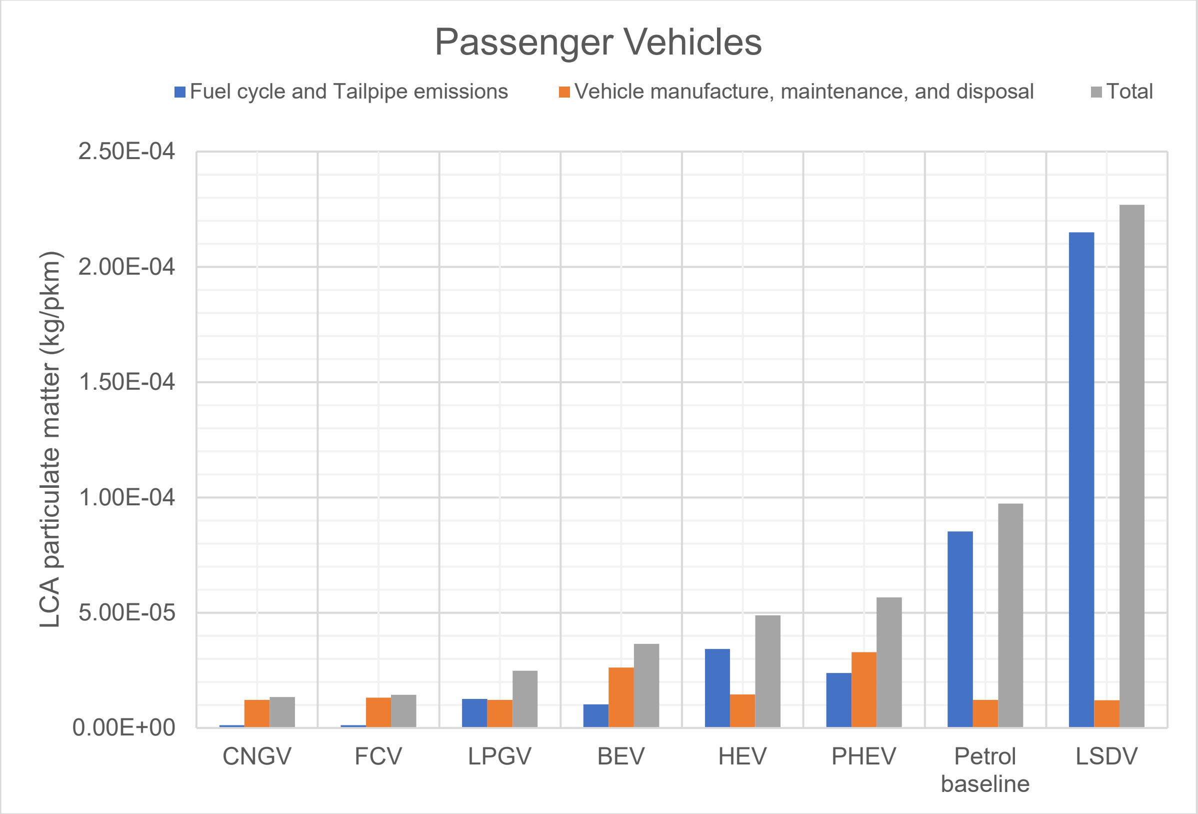


**Figure 4.9: LCA PM (kg/pkm) of Passenger Vehicles**

| **Passenger Vehicle Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **PHEV** | 1.74E-10 | 2.16E-09 | 2.33E-09 |
| **BEV** | 1.94E-10 | 2.01E-09 | 2.20E-09 |
| **HEV** | 6.43E-11 | 1.52E-09 | 1.58E-09 |
| **Petrol Baseline** | 1.60E-10 | 1.41E-09 | 1.57E-09 |
| **FCV** | 4.39E-11 | 1.51E-09 | 1.56E-09 |
| **LSDV** | 1.39E-10 | 1.41E-09 | 1.55E-09 |
| **LPGV** | 7.55E-11 | 1.41E-09 | 1.49E-09 |
| **CNGV** | 7.05E-13 | 1.41E-09 | 1.41E-09 |

**Table 4.10: LCA HTc (kg/pkm) of Passenger Vehicles**

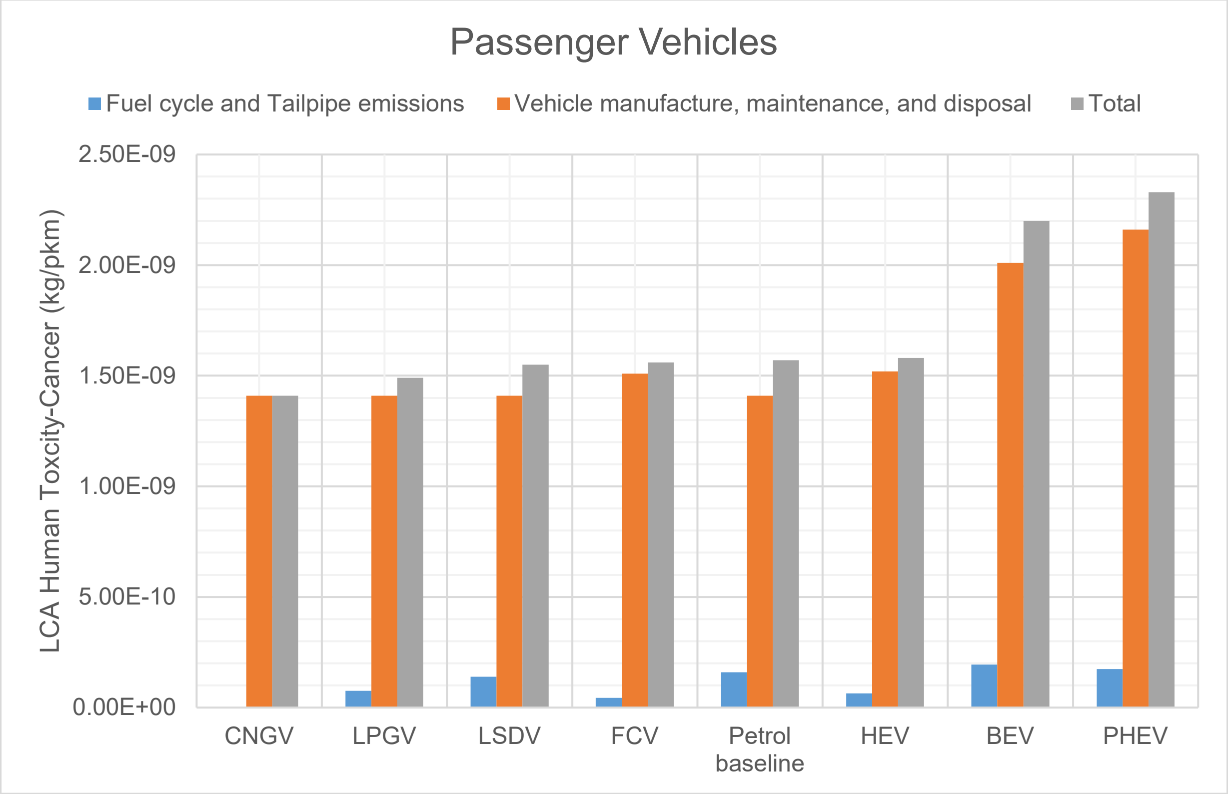


**Figure 4.10: LCA HTc (kg/pkm) of Passenger Vehicles**

| Passenger Vehicle Model | Fuel Cycle and Tailpipe Emissions (kg/pkm) | Vehicle Manufacture, Maintenance and Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|
| **PHEV** | 3.08E-09 | 2.30E-08 | 2.61E-08 |
| **BEV** | 3.66E-09 | 1.52E-08 | 1.89E-08 |
| **FCV** | 1.96E-09 | 6.08E-09 | 8.03E-09 |
| **HEV** | 7.56E-10 | 7.08E-09 | 7.83E-09 |
| **Petrol Baseline** | 1.47E-09 | 5.45E-09 | 6.92E-09 |
| **LSDV** | 1.18E-09 | 5.45E-09 | 6.63E-09 |
| **LPGV** | 9.90E-10 | 5.45E-09 | 6.44E-09 |
| **CNGV** | 4.56E-11 | 5.40E-09 | 5.50E-09 |

**Table 4.11: LCA HTnc (kg/pkm) of Passenger Vehicles**

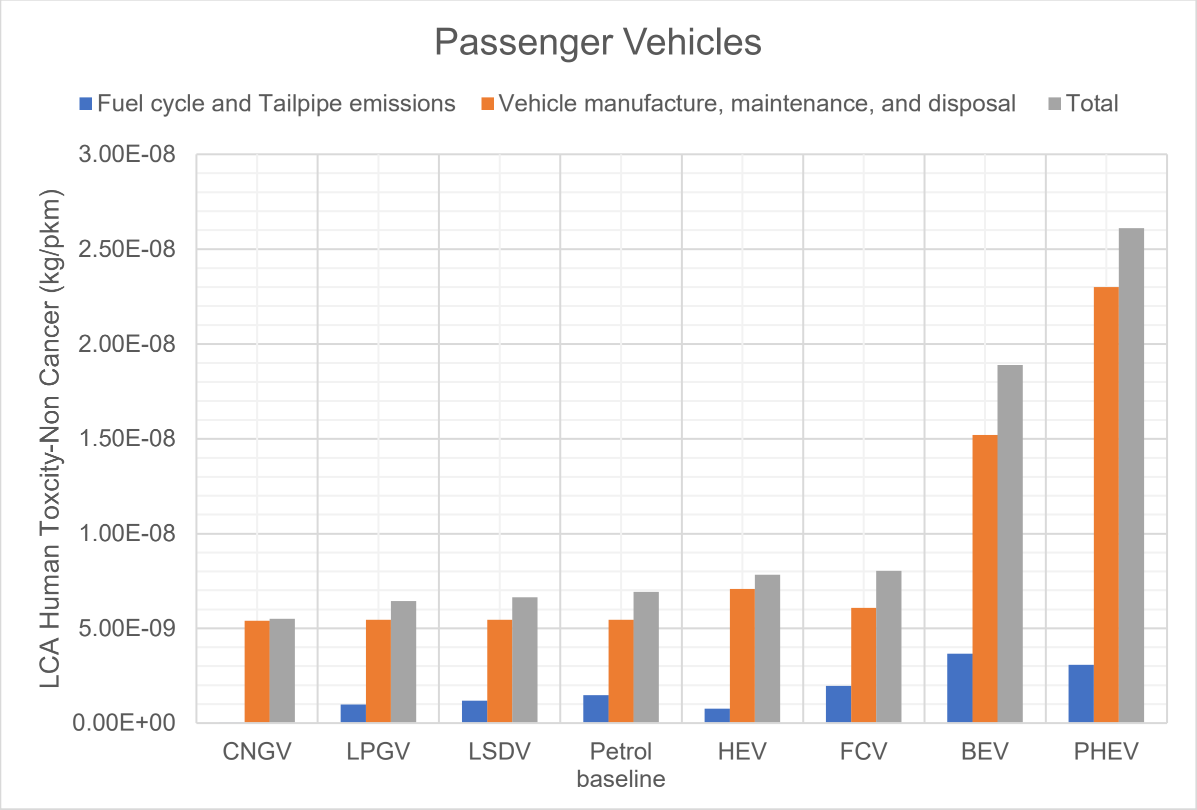


**Figure 4.11: LCA HTnc (kg/pkm) of Passenger Vehicles**

In the case of public transport buses, the results in Tables and Figures 4.12, 4.13 and 4.14 indicate that CNG buses produce much less PM, followed by fuel cell buses, then LPG buses compared to other types of bus. Battery electric buses emit approximately the same volume of PM during the fuel cycle as their vehicle manufacture phase. However, the largest contribution of LCA PM emissions occurs during the vehicle $C_2G$ phase for most types of bus. The results also show that CNG, fuel cell and LPG buses contribute much less to HTc than advanced-technology and conventional buses. Notably, fuel cell buses emit much more HTnc while LPG buses have much lower emissions. The final observation is that the main contribution of LCA HTc and HTnc occurs during vehicle manufacture, maintenance and disposal.

| **Bus Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Bus Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **Hybrid** | 6.07E-05 | 5.04E-06 | 6.57E-05 |
| **LSD Baseline** | 4.86E-05 | 4.84E-06 | 5.34E-05 |
| **Battery Electric** | 7.53E-06 | 7.13E-06 | 1.47E-05 |
| **LPG** | 3.18E-06 | 4.73E-06 | 7.92E-06 |
| **Fuel cell** | 3.07E-07 | 4.93E-06 | 5.24E-06 |
| **CNG** | 2.98E-07 | 4.84E-06 | 5.14E-06 |

**Table 4.12: LCA PM (kg/pkm) of Public Transport Buses**

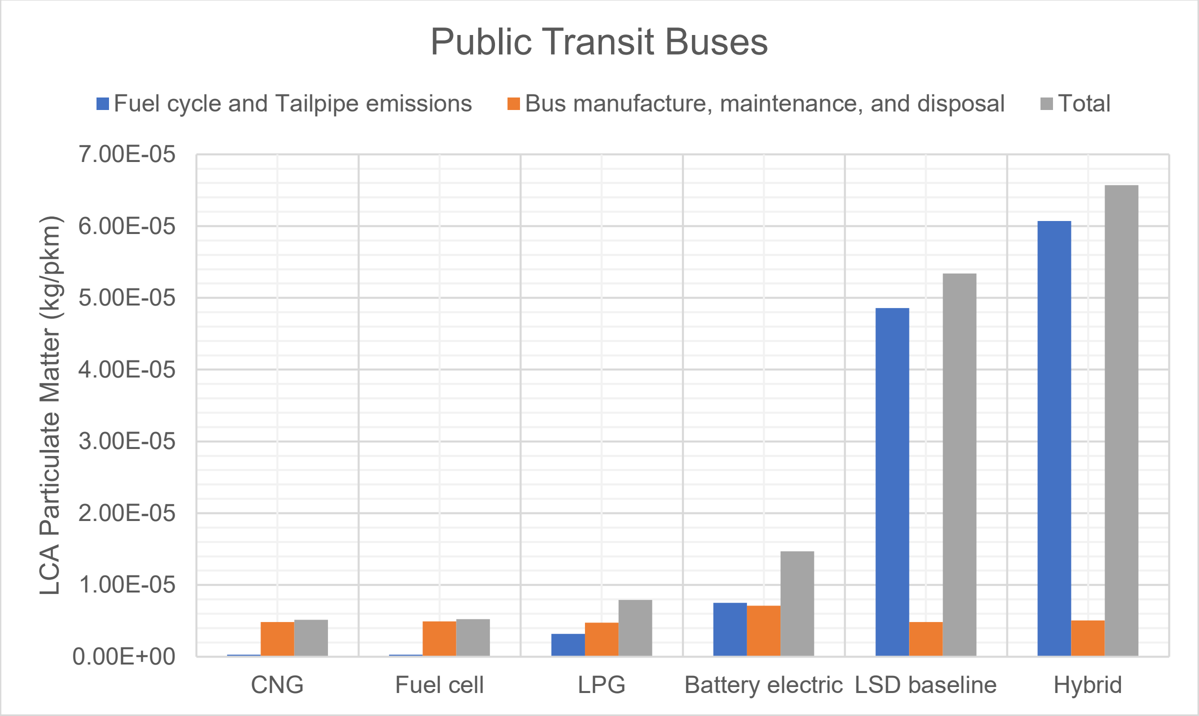


**Figure 4.12: LCA PM (kg/pkm) of Public Transport Buses**

| Bus Model | Fuel Cycle and Tailpipe Emissions (kg/pkm) | Bus manufacture, Maintenance and Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|
| **Battery Electric** | 1.42E-10 | 5.32E-10 | 6.73E-10 |
| **Hybrid** | 3.90E-11 | 4.23E-10 | 4.62E-10 |
| **LSD Baseline** | 3.12E-11 | 4.09E-10 | 4.41E-10 |
| **Fuel cell** | 1.11E-10 | 4.27E-10 | 4.38E-10 |
| **LPG** | 1.90E-11 | 4.06E-10 | 4.25E-10 |
| **CNG** | 1.78E-13 | 4.09E-10 | 4.10E-10 |

**Table 4.13: LCA HTc (kg/pkm) of Public Transport Buses**

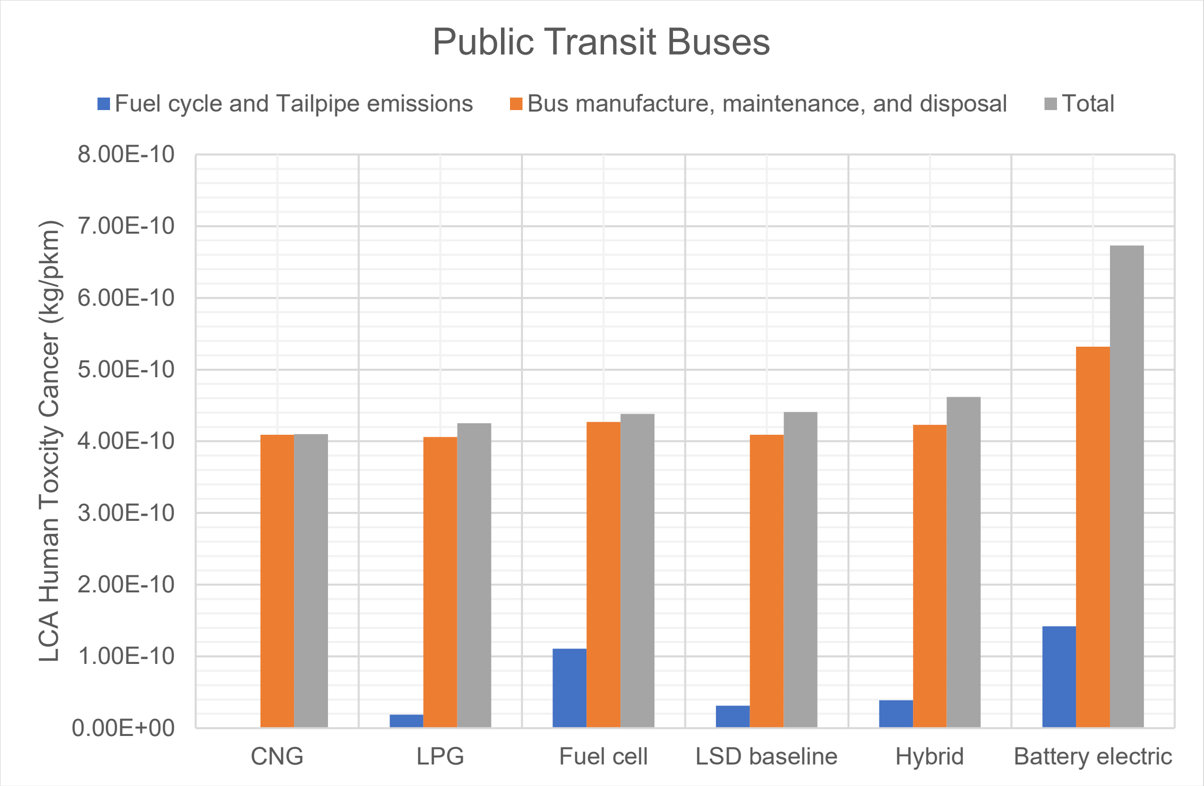


Figure 4.13: LCA HTc (kg/pkm) of Public Transport Buses

| **Bus Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Bus Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **Battery Electric** | 2.68E-09 | 3.46E-09 | 6.14E-09 |
| **Fuel cell** | 4.93E-10 | 1.87E-09 | 2.36E-09 |
| **LSD Baseline** | 2.64E-10 | 2.00E-09 | 2.26E-09 |
| **Hybrid** | 3.30E-10 | 1.87E-09 | 2.20E-09 |
| **CNG** | 1.15E-11 | 2.00E-09 | 2.01E-09 |
| **LPG** | 2.50E-10 | 1.73E-09 | 1.98E-09 |

Table 4.14: LCA HTnc (kg/pkm) of Public Transport Buses

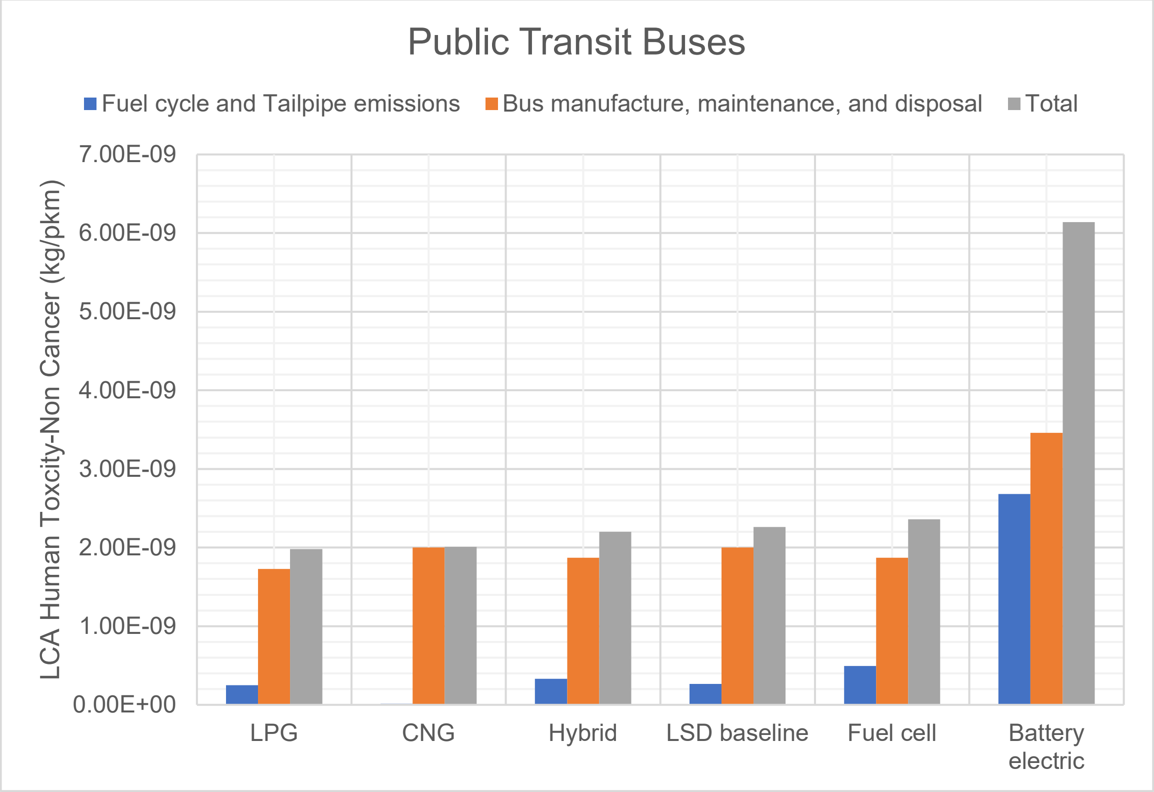


**Figure 4.14: LCA HTnc (kg/pkm) of Public Transport Buses**

For heavy-duty truck vehicles, the results in Tables and Figures 4.15, 4.16, 4.17, 4.18 and 4.19 show that the battery electric truck has lower LCA PM emissions than other types of truck, and, for most trucks, the majority of LCA PM emissions occur from the fuel cycle and tailpipe emissions. However, for the battery electric rigid truck, it appears that LCA PM emissions are approximately equal for both the fuel pathway and vehicle $C_2G$ phase. Furthermore, the results indicate that LCA HTc and HTnc emissions of conventional trucks are much smaller when compared to both hybrid and battery electric trucks. In other words, conventional LSD heavy-duty truck vehicles release more HTc and HTnc than other types of truck because the power supply is derived from non-renewable energy sources (fossil fuels), which results in much higher emissions in the environment.

| Rigid Truck Model | Fuel Cycle and Tailpipe Emissions (kg/tkm) | Bus Manufacture, Maintenance and Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|
| **Hybrid** | 3.95E-04 | 1.18E-05 | 4.07E-04 |
| **LSD Baseline** | 2.46E-04 | 1.07E-05 | 2.57E-04 |
| **Battery Electric** | 2.44E-05 | 2.18E-05 | 4.63E-05 |

**Table 4.15: LCA PM (kg/tkm) of Rigid Trucks**

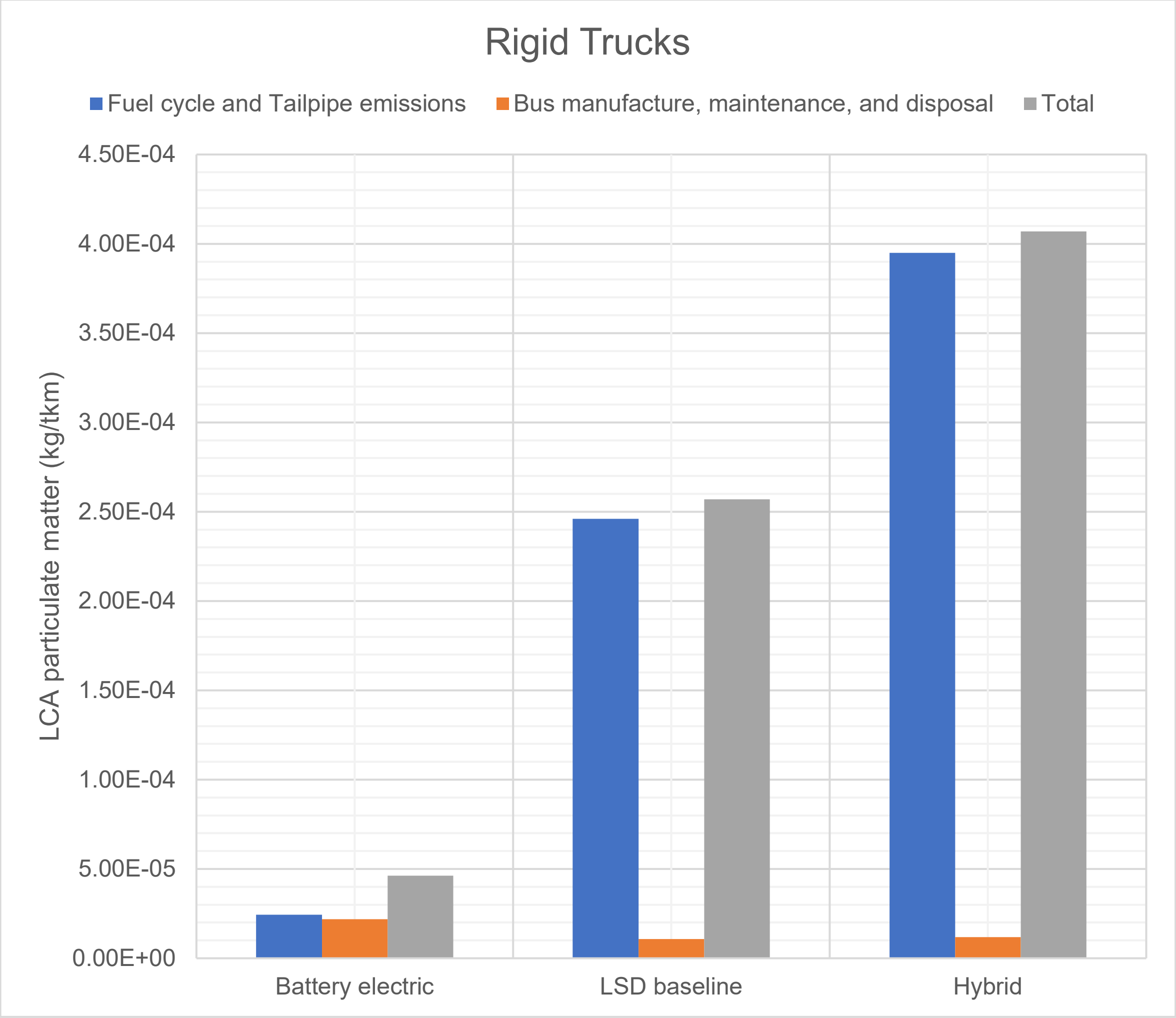


**Figure 4.15: LCA PM (kg/tkm) of Rigid Trucks**

| **Articulated Truck Model** | **Fuel Cycle and Tailpipe Emissions (kg/tkm)** | **Bus Manufacture, Maintenance and Disposal (kg/tkm)** | **Total (kg/tkm)** |
|---|---|---|---|
| **Hybrid** | 8.36E-05 | 2.20E-06 | 8.58E-05 |
| **LSD baseline** | 7.35E-05 | 1.89E-06 | 7.54E-05 |
| **Battery Electric** | 7.26E-06 | 1.89E-06 | 9.15E-06 |

**Table 4.16: LCA PM (kg/tkm) of Articulated Trucks**

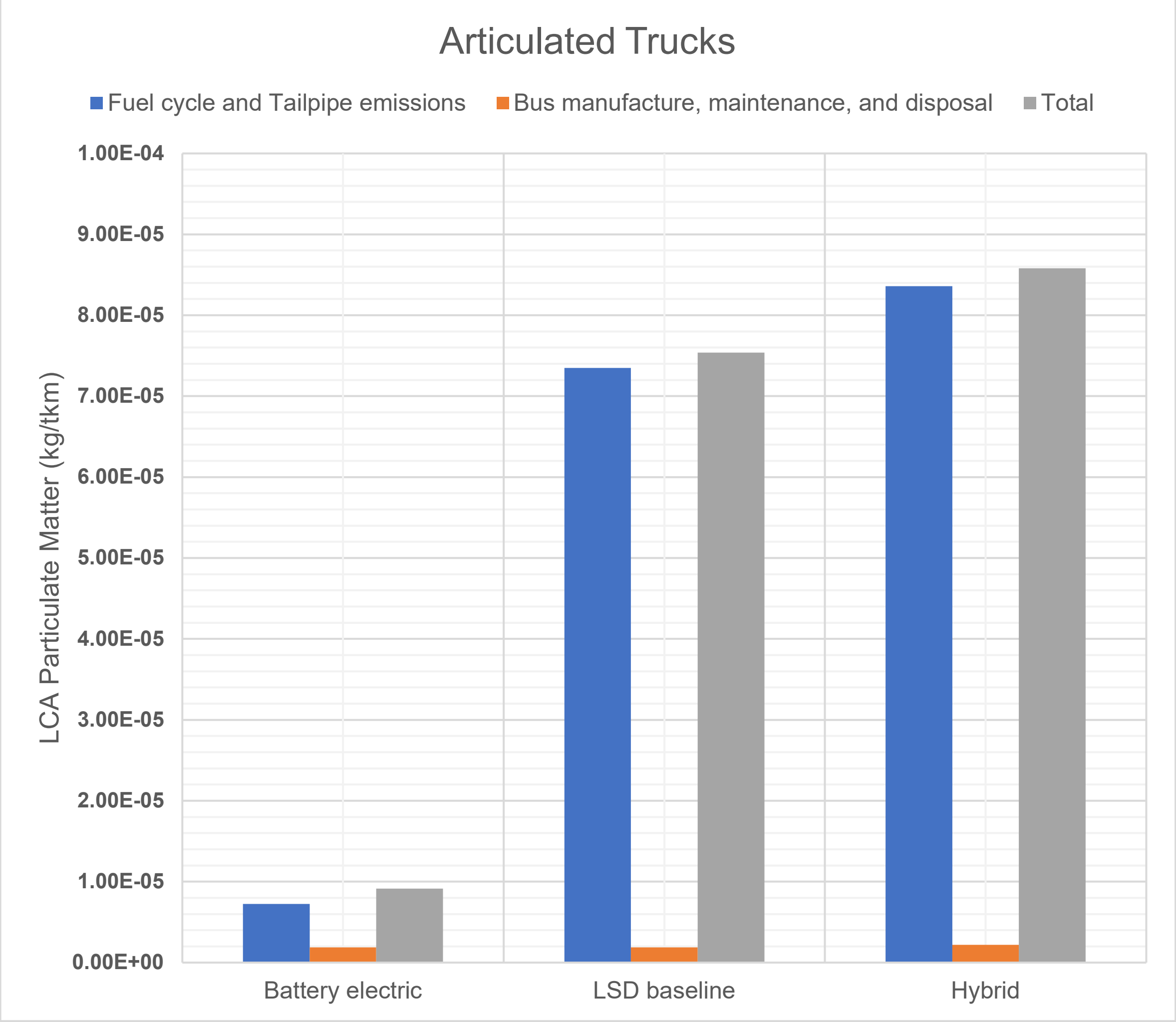


**Figure 4.16: LCA PM (kg/tkm) of Articulated Trucks**

| Rigid Truck Model | Fuel Cycle and Tailpipe Emissions (kg/tkm) | Bus Manufacture, Maintenance and Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|
| **Battery Electric** | 4.60E-10 | 1.74E-09 | 2.20E-09 |
| **Hybrid** | 3.04E-10 | 1.25E-09 | 1.55E-09 |
| **LSD Baseline** | 1.90E-10 | 1.18E-09 | 1.38E-09 |

**Table 4.17: LCA HTc (kg/tkm) of Rigid Trucks**

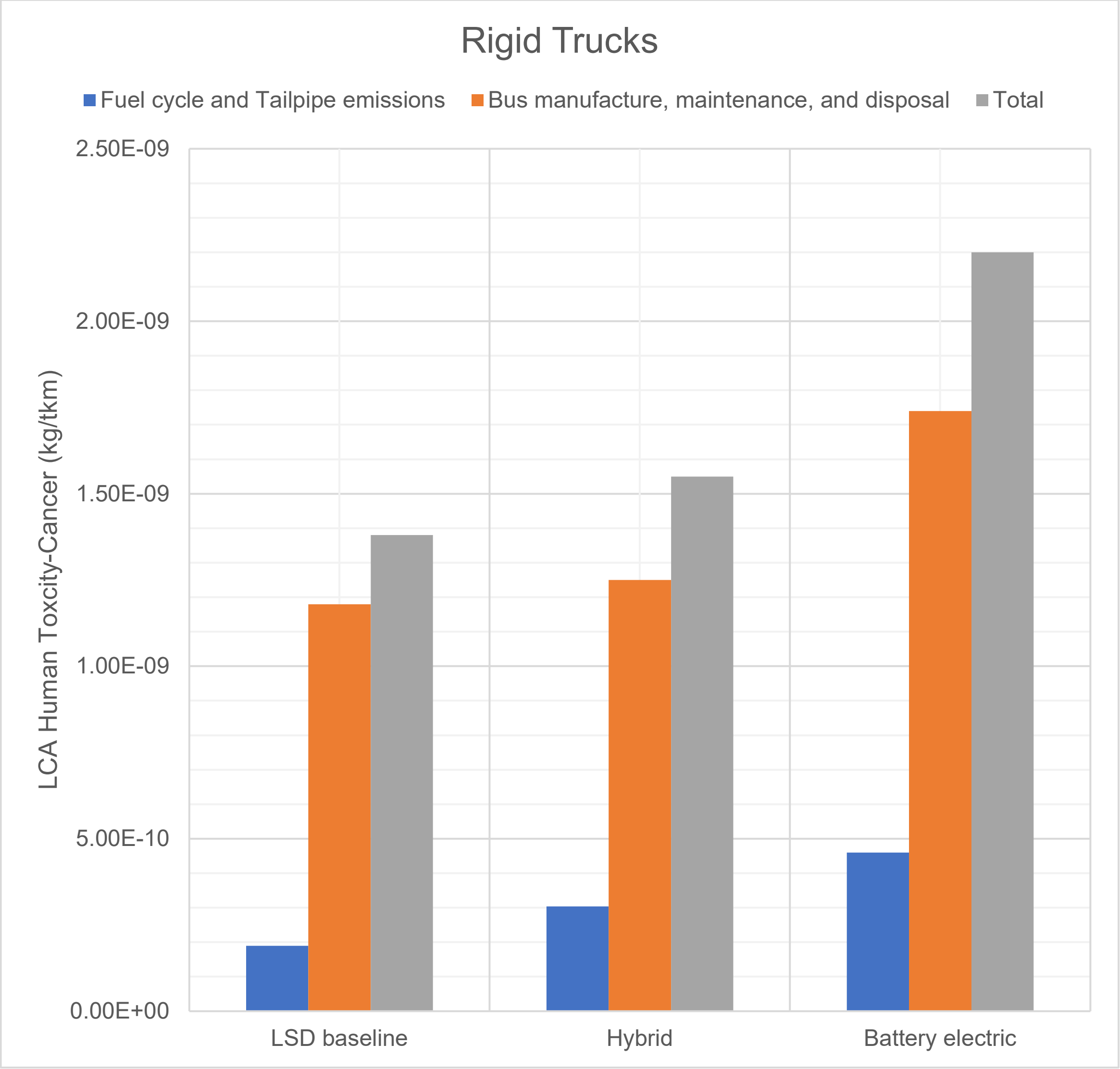


**Figure 4.17: LCA HTc (kg/tkm) of Rigid Trucks**

| Articulated Truck Model | Fuel Cycle and Tailpipe Emissions (kg/tkm) | Bus Manufacture, Maintenance and Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|
| **Battery Electric** | 1.37E-10 | 1.86E-10 | 3.23E-10 |
| **Hybrid** | 9.24E-11 | 1.88E-10 | 2.80E-10 |
| **LSD Baseline** | 8.13E-11 | 1.86E-10 | 2.67E-10 |

**Table 4.18: LCA HTc (kg/tkm) of Articulated Trucks**

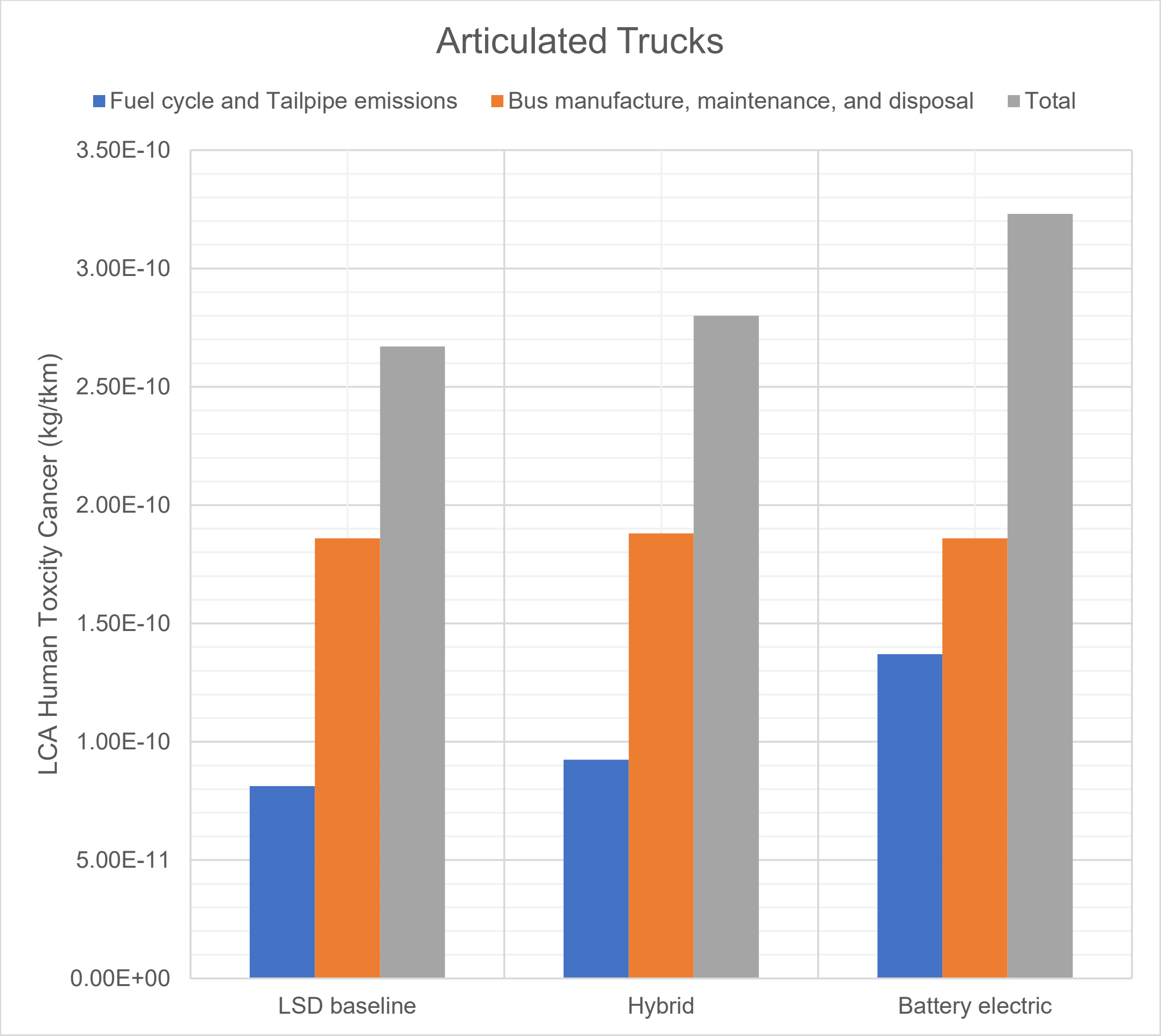


**Figure 4.18: LCA HTc (kg/tkm) of Articulated Trucks**

| Rigid Truck Model | Fuel Cycle and Tailpipe Emissions (kg/tkm) | Bus Manufacture, Maintenance and Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|
| **Battery Electric** | 8.70E-09 | 1.22E-08 | 2.09E-08 |
| **Hybrid** | 2.57E-09 | 5.81E-09 | 8.38E-09 |
| **LSD Baseline** | 1.61E-09 | 5.29E-09 | 6.90E-09 |

**Table 4.19: LCA HTnc (kg/tkm) of Rigid Trucks**

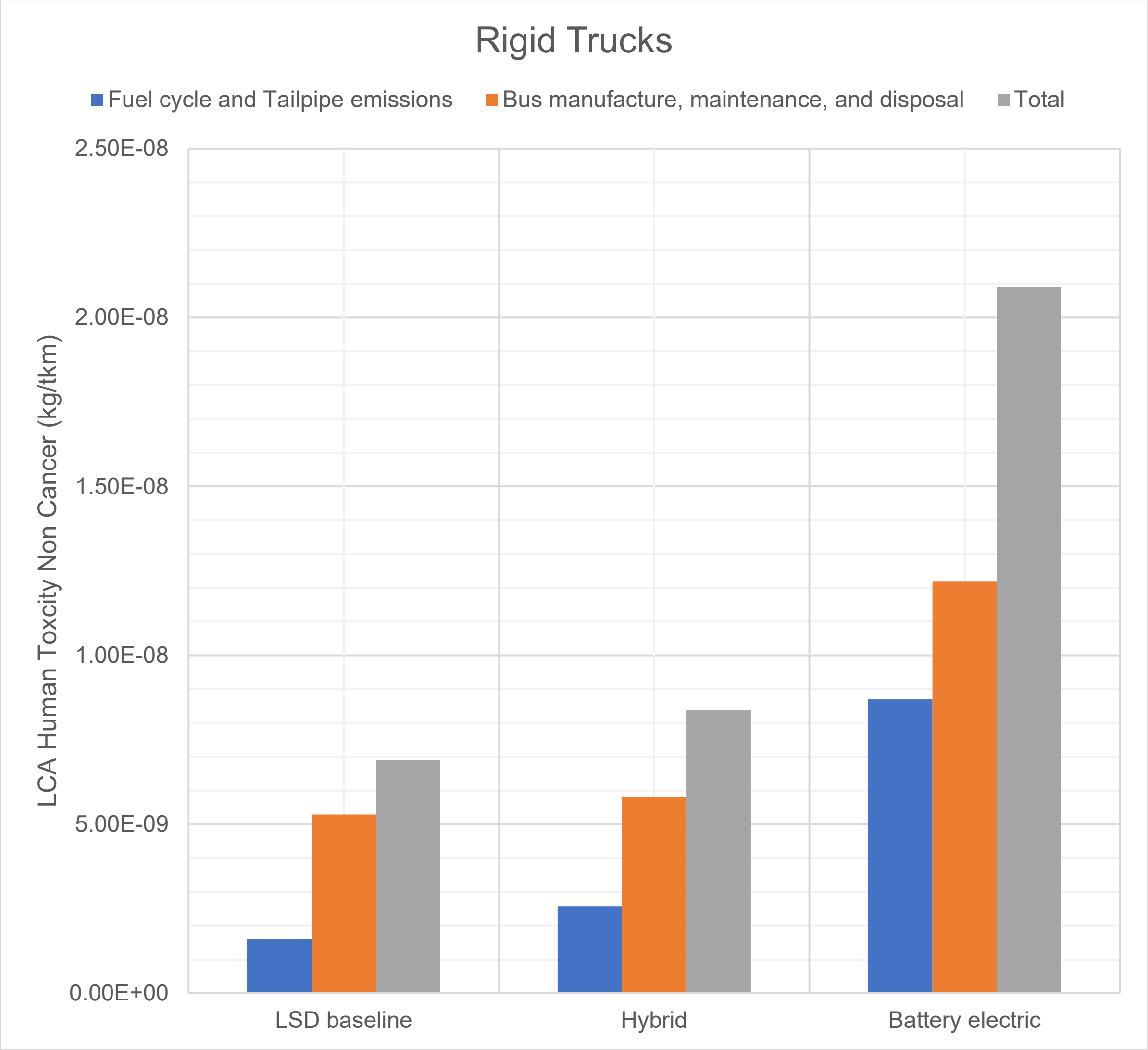


**Table 4.19: LCA HTnc (kg/tkm) of Rigid Trucks**

| Articulated Truck Model | Fuel Cycle and Tailpipe Emissions (kg/tkm) | Bus Manufacture, Maintenance and Disposal (kg/tkm) | Total (kg/tkm) |
|---|---|---|---|
| **Battery Electric** | 2.59E-09 | 9.52E-10 | 3.54E-09 |
| **Hybrid** | 7.81E-10 | 9.77E-10 | 1.75E-09 |
| **LSD Baseline** | 6.87E-10 | 9.52E-10 | 1.64E-09 |

**Table 4.20: LCA HTc (kg/tkm) of Articulated Trucks**

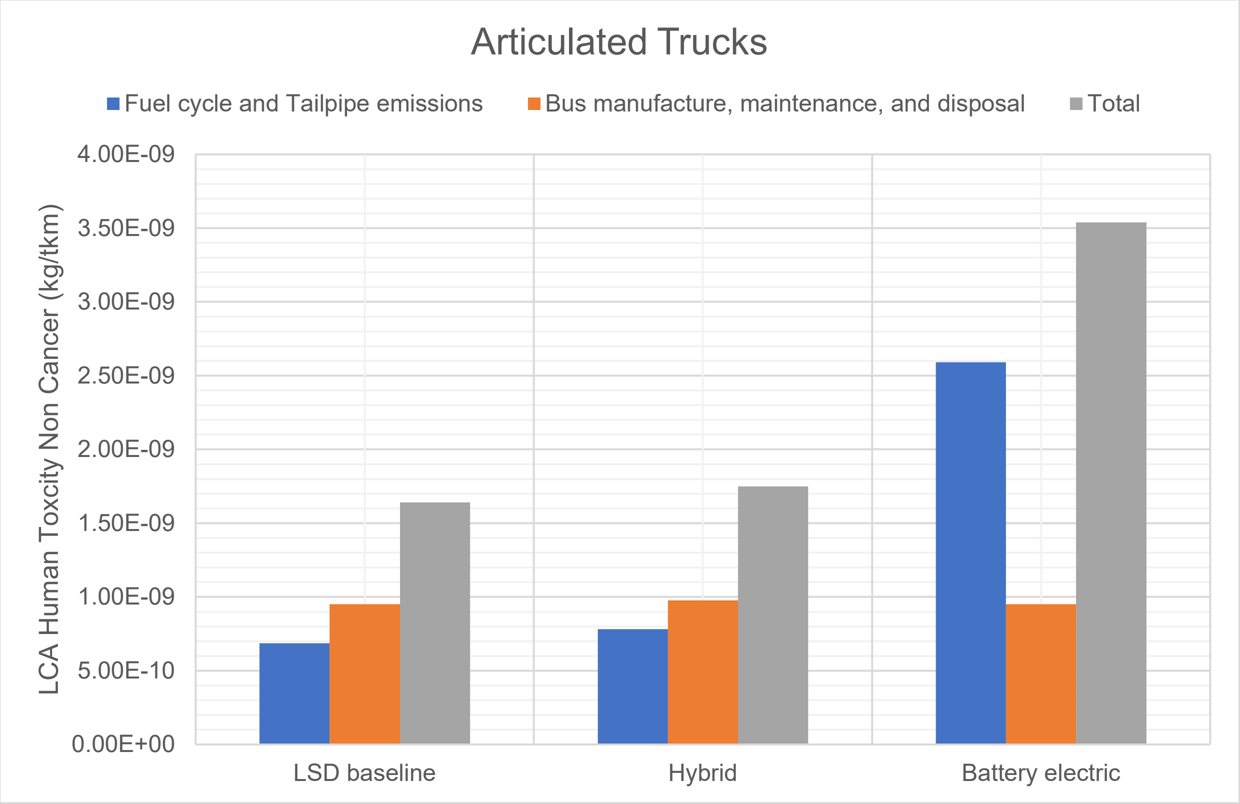


**Figure 4.20: LCA HTnc (kg/tkm) of Articulated Trucks**

## 4.2 Discussion of Results

The objective of this thesis has been to analyse and assess the environmental impact and performance of the road-based transport sector in Australia; therefore, life-cycle inventories for different modes of Australian road vehicles were compiled. Life-cycle impact results were also produced, and energy use and emissions were assessed in the context of passenger vehicles, public transport buses and heavy-duty trucks. However, it is difficult to make comparisons when examining vehicle exhaust emissions per kilometre travelled in relation to different types of fuels (e.g. petroleum and electric) and with regard to different types of road vehicles (e.g. heavy road vehicle and light passenger vehicles). In terms of there being different types of fuels, there are conventional and alternative energy sources, and different types of road vehicles encompass both traditional and advanced technologies. This means that there is extreme variability in the available emissions data.

An LCA has been performed on eight different types of passenger vehicles (petrol, diesel, CNG, LPG, plug in, hybrid, fuel cell and battery electric), six different types of public transport buses (diesel, CNG, LPG, hybrid, fuel cell and battery electric) and six divergent modes of heavy-duty trucks (LSD rigid, hybrid rigid, battery electric rigid, LSD articulated, hybrid articulated, and battery electric articulated). The performed LCA was mostly conducted using modelled inventories of the vehicles that were assembled using data from the AusLCI and, where appropriate, other Australian vehicle emission data.

### 4.2.1 Passenger Vehicles

This research considered the whole LCA of the vehicle, including its operational phase (tailpipe emissions and maintenance), its fuel pathway phase and the non-operational phase (manufacture and disposal), while the LCAs of automobiles in earlier studies only considered vehicular tailpipe emissions and upstream emissions (fuel pathway). As reported by Williams (Williams, 2009), a full life-cycle assessment is needed in order to complete a successful LCA. This is consistent with the obtained results that are presented in section 4.1 as covering all stages of the assessment produces more information and details about the LCA, meaning the findings will be more accurate and reliable.

In the present study, the operation phase (tailpipe emissions) of the passenger vehicle was found to be the most significant factor and accounted for 70%–80% of the total LCA emissions. As can be seen in Tables 4.1 and 4.5 and Figures 4.1 and 4.5, this finding does not comply with the results reported by Castro et al. (Castro et al., 2003) – they asserted that there was a higher proportion of GHG emissions and energy consumption during the vehicle's operational phase (up to 90%) when compared to both the fuel pathway and the non-operational phase. This disparity can be explained by the fact that this thesis also analysed alternative fuels, such as CNG and LPG, rather than conventional fuels like petrol and diesel in isolation. However, the literature review is based on an examination of conventional fuels rather than their renewable counterparts, so this could have led to differing LCA results among various studies. Leading on from this, the fuel pathway is thought to be the second-largest contributor to energy use and emissions. A study by Jochem et al. (Jochem et al., 2015) underscored that it is very important to analyse the fuel feedstock, make comparisons and select the best way to achieve low carbon intensity and reduce GHG emissions. This is consistent with the results that we presented in section 4.1. When a fuel source has a lower level of carbon intensity, there is a significant saving of GHG emissions in terms of the exhaust's output.

Meanwhile, the third-largest contributor to energy use and emissions is the vehicle manufacturing phase. Nealer and Hendrickson (2015) argued that this stage contributes 10%–22% of the total life cycle with regard to GHG emissions, yet in relation to advanced vehicle technologies, including battery and plug-in, the manufacturing phases only accounted for 1%–8% of the same total. This does not tally with the level of GHG emissions discovered and presented in Table 4.1 and Figure 4.1, which indicated that the contribution of the manufacturing phase for a petrol vehicle is 11% and 20% for a plug-in automobile. This is explained by the fact that lower vehicle emissions arise from advanced vehicle technologies that have been examined in this thesis, while earlier studies were based on an older generation of vehicles.

Indeed, one study by Messagie et al. (Messagie et al., 2014) highlighted that alternative fuel-powered vehicles produce 18%–24% fewer emissions during their total LCA compared to baseline petrol vehicles. This is not consistent with our LCA-based GHG emissions, which are presented in Table 4.1 and Figure 4.1 and show that the LCA's GHG emissions in relation to alternative vehicles were found to be lower by 84% in comparison with baseline petrol vehicles. After some research was completed, it was found that the differing LCA databases used by the aforementioned scholars and in this thesis contributed to this large discrepancy; the critical parameter was the emission factor used for electricity generation in Europe and Australia, respectively. An investigation by Nealer and Hendrickson (Nealer and Hendrickson, 2015) also identified that battery production and disposal are large contributors to GHG emissions, which is a similar finding to the level of GHG emissions illustrated in Table 4.1 and Figure 4.1. Both battery production and vehicle disposal have an impact on the environment; hence, the impact they have should not be ignored.

Electricity produced from renewable fuel improves the driving and the recharge cycle, meaning it is a good option for making a vehicle sustainable (Nigro and Jiang, 2013). Moreover, Lucas et al. (Lucas et al., 2012) demonstrated that if the electricity is generated from renewable sources, battery electric vehicles (BEVs) can be considered a sustainable form of transportation. Both of these assertions are consistent with our results in section 4.1. When electricity is produced from non-fossil fuel, LCA GHG emissions will be lower; however, these emissions will increase when electricity is derived from non-renewable energy. Nevertheless, Granovskii et al. (Granovskii et al., 2006) showed that vehicle maintenance and the disposal phases of BEVs involves higher energy consumption and emissions relative to conventional vehicles. This is consistent with the LCA's energy use data and the GHG emissions reported in sections 4.1.1 and 4.1.2. Advanced vehicle technologies, including BEVs, encompass much more energy consumption and emissions during the maintenance and disposal phases.

Furthermore, Joseck and Ward (Joseck and Ward, 2014) argued that fuel cell vehicles can significantly reduce GHG and air pollution emissions; their findings are equivocal to the air pollution results presented in Tables 4.10 and 4.11 and Figures 4.10 and 4.11. When hydrogen is produced from renewable energy sources, the emissions will be decreased. The challenge facing hydrogen FCVs is how to store enough high-pressure hydrogen for/in on-board vehicle systems. Finally, the LCA study of passenger vehicles showed the environmental effects of the vehicle's operational phase (70%–80%), its fuel cycle (10%–15%) and its non-operational phase (10%–15%). The operational phase was identified as the most vital part of the vehicle's lifespan in terms of its environmental impact – this result is consistent with other national and international literature (Huo et al., 2015, Jochem et al., 2015, Nealer and Hendrickson, 2015, Nigro and Jiang, 2013, Hawkins et al., 2013, Lucas et al., 2012, Aguirre et al., 2012, Gao and Winfield, 2012, Baptista et al., 2009).

### 4.2.2 Public Transport Buses

Few data points exist in the literature in terms of public transport buses that can be compared to this thesis' results. However, a study by Ally and Pryor (Ally and Pryor, 2007) found that hydrogen-powered versions of this particular vehicle produce 50% fewer GHG emissions in comparison with conventional and advanced buses. This is a lower figure than we uncovered (see Table 4.2 and Figure 4.2), which indicates that the fuel-cell bus puts out lower 64% lower emissions than LSD buses. This could be explained if the hydrogen-based fuel is produced from renewable fuel as the emissions will be lower, but they will significantly increase if this element is derived from fossil fuels. In relation to this, Williamson (Williamson, 2012) highlighted the importance of modifying the spark ignition engine by using dual-cycle heat to increase engine efficiency in order to reduce air pollution and GHG emissions; these findings match up with the results illustrated in section 4.1.1.

Furthermore, a study by Cooper et al. (Cooper et al., 2012) demonstrated that public transit buses powered by natural gas produce fewer PM and NOx emissions than diesel buses because the former uses the spark ignition from gas engines. The case is similar to the LCA of PM (see Table 4.12 and Figure 4.12). PM levels are quite low and lower than LSD buses; if CNG is produced from renewable sources, emissions will be even lower. However, if it is derived from fossil fuels, emissions will be exacerbated. Meanwhile, McKenzie and Durango-Cohen (McKenzie and Durango-Cohen, 2012) identified that in order to reduce emissions, battery manufacturing and recycling must be improved. They also underlined that vehicle size, loading, electricity production and driving behaviour are all factors that significantly influence vehicle exhaust emissions, which concurs with our own findings in sections 4.1.1 and 4.1.3. Elements like electricity production and the number of passengers have a significant impact on the environment. Indeed, one study found that there are many factors that dramatically influence vehicle exhaust emissions, including fuel-cell-stack manufacturing, recycling and hydrogen infrastructures (Cuéllar et al., 2016). This is consistent with our own results in section 4.1.2, and these factors have a direct impact on human health and the environment.

Conversely, this study's findings are in disagreement with related discoveries by Beer et al. (Beer et al., 2001b) whose research is currently the only Australian reference point for LCAs on vehicles of this type when using conventional and alternative fuels. They asserted that LCA GHG emissions for LSD buses are 1.29 kg/pkm and 0.595 kg/pkm for their LPG counterparts, while our results in Table 4.2 showcase LCA GHG emissions of 0.0682 kg/pkm for LSD buses and 0.0225 kg/pkm for LPG buses. This is probably because this thesis included all of the LCA phases while the Australian Greenhouse Office (AGO) report only took tailpipe emissions and fuel cycle phases into account. Finally, section 4.1.1 highlights that the life-cycle emissions of public transport buses are quite low and lower than one would suspect. For many reasons, the use of public transport is more environmentally friendly than private transport, particularly in the context of emissions per passenger kilometre travelled.

### 4.2.3 Heavy-Duty Truck Vehicles

Few data points exist in the literature that offer appropriate comparisons to this study's LCA results. Moreover, all of them only analyse one type of heavy-duty truck, while the present study has scrutinised two types: rigid and articulated. Fulton et al. (2009) underlined that the energy consumption of heavy-duty truck vehicles is predicted to increase by 50% by 2050, which concurs with our findings in section 4.1.2. In response to this, advanced technology heavy-duty truck vehicles are the best option as they deliver significant savings in terms of energy use compared to conventional trucks. Furthermore, Hao et al. (2012) stated that if improvements are made to the fuel consumption rate, level of mileage utilisation and use of liquefied natural gas, fuel consumption and GHG emissions will be meaningfully reduced. This is consistent with the results found and presented in section 4.1.1. Low-carbon-intensity fuel could significantly decrease LCA GHG emissions.

Facanha and Horvath (Facanha and Horvath, 2007) indicated that NOx emissions are correlated to fuel consumption, while PM10 emissions are affected by both the fuel cycle and the vehicle's manufacturing phase, which echoed our findings (see section 4.1.3). Fuel consumption has a direct impact on vehicle exhaust emissions, while vehicle manufacturing has much more of an effect on PM emissions. An investigation by Kamakate and Schipper (Kamakate and Schipper, 2009) also showed that heavy-duty trucks will become a sustainable means of transportation if the driving cycle, load factor and truck capacity are improved, which is in accordance with our own findings in section 4.1. The average load factor is considered to be important and has a noticeable effect on the LCA's results.

At the same time, Beer et al. (Beer et al., 2001b) argued that the LCA of PM is 4.47E-4 kg/tkm for an LSD rigid truck during the use phase. This amount is twice as large as the results presented in Table 4.15, which illustrated that the same assessment for the same type of vehicle is 2.46E-4 kg/tkm during the fuel pathway and tailpipe emission phases. The present study drew information from the AusLCI, including data about the Australian driving cycle, while the aforementioned study employed different sources of data, such as information about a divergent driving cycle. Ultimately, this thesis' findings illustrate that advanced heavy-duty trucks are more environmentally efficient than their conventional and hybrid counterparts. Additionally, the articulated truck is more environmentally friendly than the rigid truck in the context of its reduction in energy use per tonne per kilometre travelled, GHG emissions per tonne per kilometre travelled and air pollution per tonne per kilometre.

## 4.3 Conclusion of Results

Overall, when comparing the LCA results obtained during this study with related national and international literature, there seems to be a general level of consistency across all vehicle and fuel types. Indeed, any discrepancies can usually be explained by the use of different data sets and/or the differing respective scopes of the LCA. Hence, in the following chapters, the uncertainty and sensitivity of the input data will be investigated in order to determine the accuracy and reliability of the inputs and outputs of the LCA and how they could affect the overall results.

# CHAPTER 5: UNCERTAINTY ANALYSIS OF LCA

## 5.1 Results and Findings

Uncertainty analysis aims to quantify the variability of the output that results from the variability of the input, and it is used to show the range of possible values wherein the true measurement value lies. The quantification is most often performed by estimating statistical quantities, such as the mean, the median, standard deviation (SD) and coefficient of variation (CV). An SD is a statistic that measures the dispersion of a dataset relative to its mean (average) value. If the data points are further from the mean, there is higher deviation within the dataset. The CV is the ratio of the SD to the mean. The higher the CV, the greater the level of dispersion around the mean. The lower the CV, the more precise the estimate. In this study, Monte Carlo analysis in the LCA SimaPro software was used to model uncertainty analysis in the LCA database to reveal the absolute uncertainty.

Uncertainty analyses of LCA for the transport sector, including passenger vehicles, public transport buses and heavy-duty truck vehicles, were performed. The results of the uncertainty analysis of the LCA for passenger vehicles illustrate that the data used to model LCA energy use, GHG emissions and particulate matter (PM) is certain; however, there is uncertainty in the data related to human toxicity, cancer and non-cancer (HTc and HTnc). Table 5.1 and Figure 5.1 show the results of the uncertainty analysis for petrol vehicles. The CV (%) is relatively small for the categories of energy use, global warming potential (GWP) and PM (5%, 1% and 11%, respectively). On the other hand, the results indicate that the CV (%) is relatively large for both HTc (37%) and HTnc (39%). Therefore, it can be said that most of the uncertainty in the LCA for petrol vehicles arises from the lack of available data in Australia about HTc and HTnc.

| Impact Category | Mean | SD | CV% |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3220257 | 0.16665015 | 5 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.25638771 | 0.00381514 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 5.74E-10 | 37 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.70E-09 | 2.58E-09 | 39 |
| **Particulate Matter (kg/pkm)** | 9.69E-05 | 1.03E-05 | 11 |

**Table 5.1: Uncertainty Analysis of Petrol Vehicles' LCA**

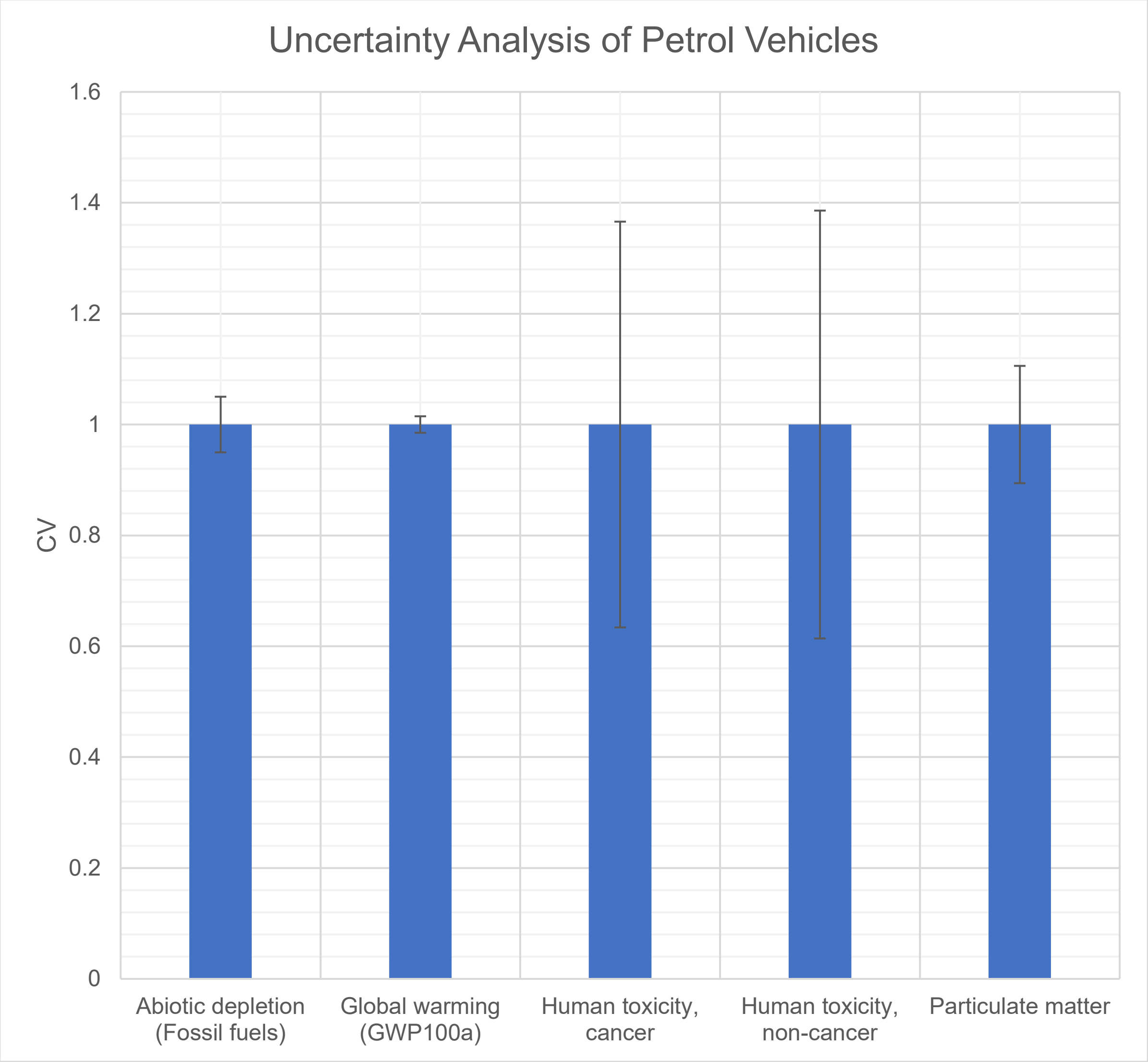


**Figure 5.1: Uncertainty Analysis of Petrol Vehicles' LCA**

In regard to the uncertainty analysis of public transport buses' LCA results, the results summarised that most types of bus have reliable data because the CV is close to the mean value. For instance, for LSD buses (shown in Table and Figure 5.2) the data related to energy depletion resources, GHG emissions, HTc and PM are reliable because the uncertainty analysis shows that the CV is close to the mean value for energy use (6%), global warming (5%), HTc (3%) and particulate matter (3%). However, the CV of LCA HTnc is high and spread out from the average (mean) value, which significantly contributes to the uncertainty analysis by 15%.

| **Impact Category** | **Mean** | **SD** | **CV %** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.80811081 | 0.046274356 | 6 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.067729206 | 0.003072434 | 5 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.36E-10 | 1.47E-11 | 3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 3.46E-10 | 15 |
| **Particulate Matter (kg/pkm)** | 5.33E-05 | 1.59E-06 | 3 |

**Table 5.2: Uncertainty Analysis of LSD Buses' LCA**

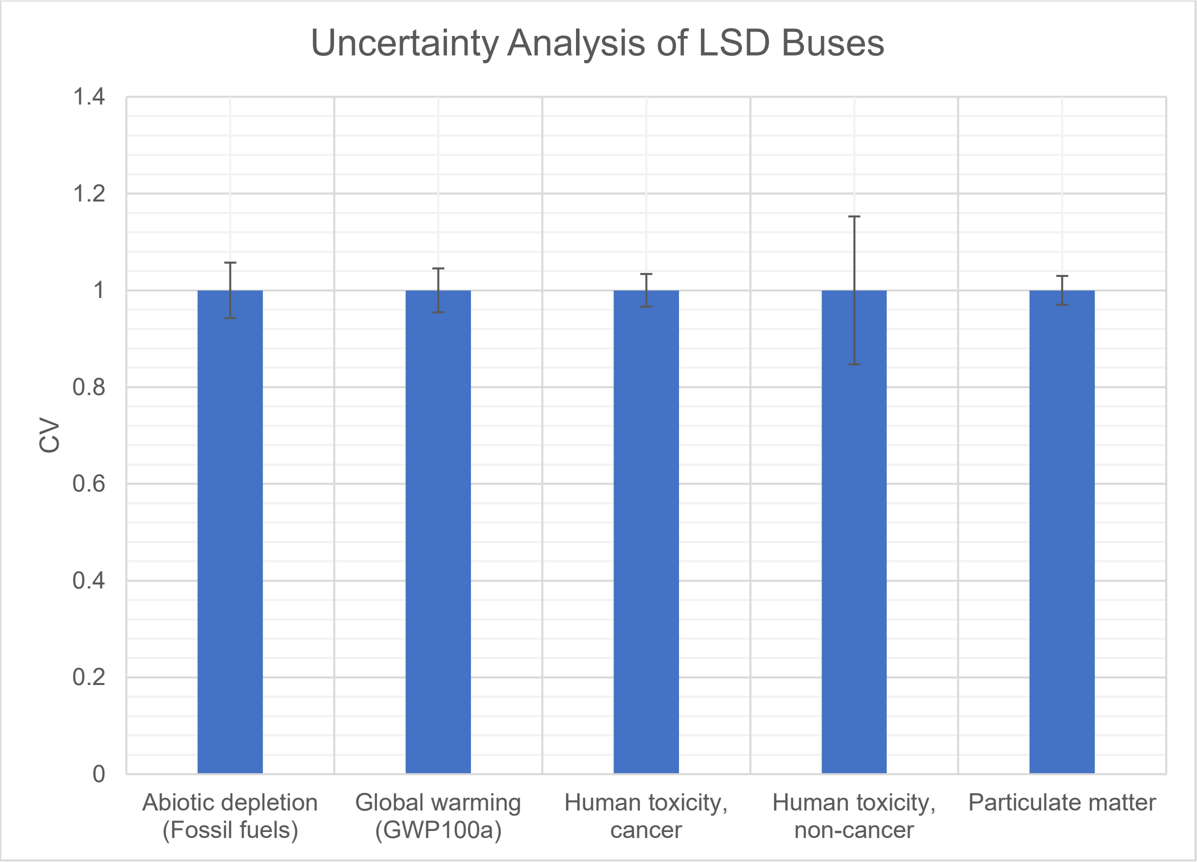


**Figure 5.2: Uncertainty Analysis of LSD Buses' LCA**

On the other hand, some types of bus, including compressed natural gas (CNG) and fuel cell buses, have higher degrees of uncertainty in their LCA results. For instance, for CNG buses (shown in Table and Figure 5.3) the CV (%) is approximately close to the mean value for energy use (16%), global warming (19%) and PM (19%), while the CV is further from the mean value for HTc (27%) and HTnc (33%). Notably, there is a higher deviation within the dataset – the more spread out the data, the higher the SD. These situations can be explained because the data related to human health is unreliable, and it is difficult to adapt human health (life) databases.

| **Impact Category** | **Mean** | **SD** | **CV%** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.25671891 | 0.04221874 | 16 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.019702923 | 0.003698962 | 19 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.27E-10 | 1.17E-10 | 27 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.96E-09 | 6.52E-10 | 33 |
| **Particulate Matter (kg/pkm)** | 5.02E-06 | 9.40E-07 | 19 |

**Table 5.3: Uncertainty Analysis of CNG Buses' LCA**

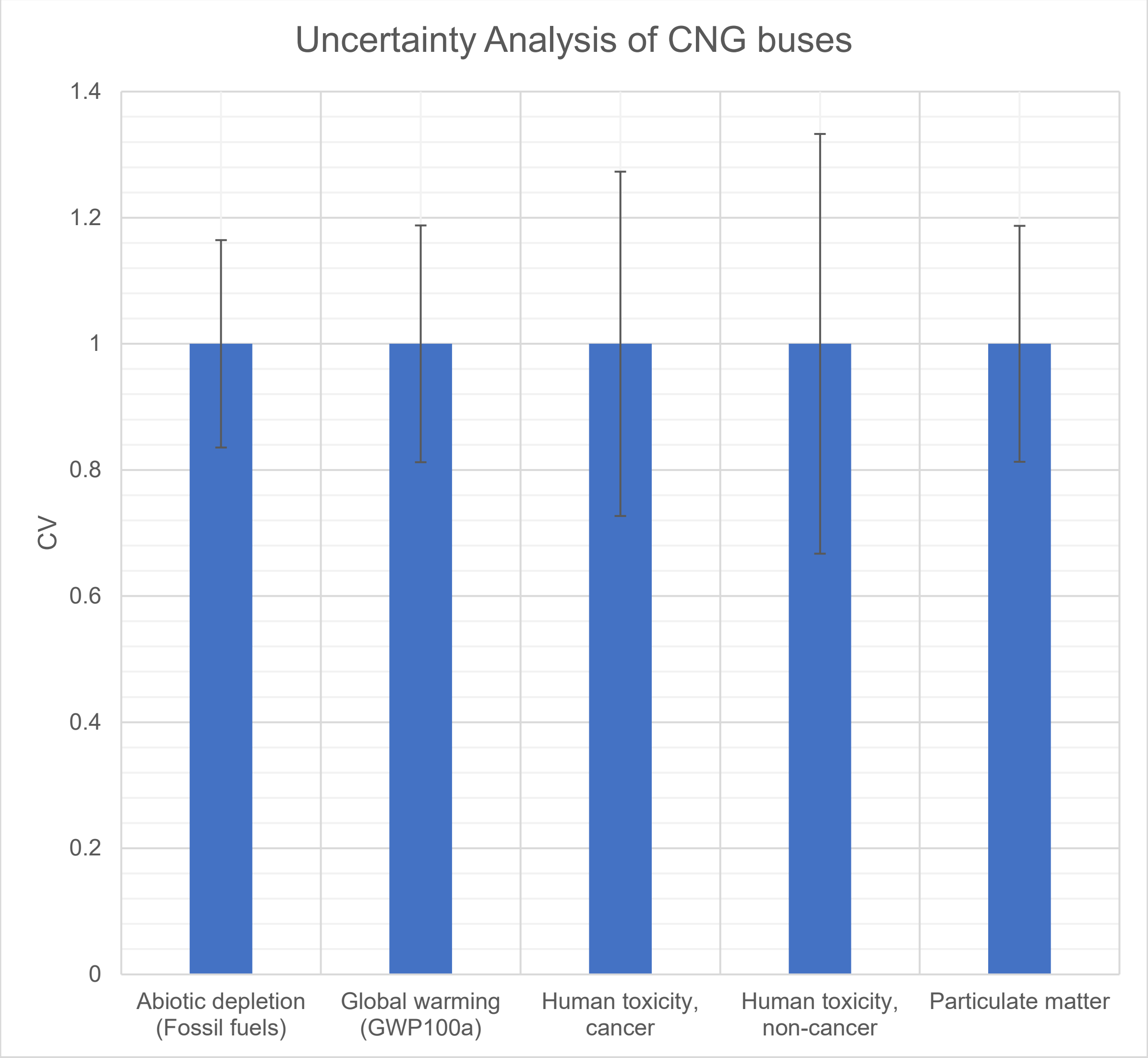


**Figure 5.3: Uncertainty Analysis of CNG Buses' LCA**

The results of the uncertainty analysis for heavy-duty truck vehicles demonstrate that heavy-duty truck vehicles have a low degree of uncertainty in the categories of LCA GWP, depletion in energy use and human health influences compared to both passenger vehicles and public transport buses. Curiously, the degrees of uncertainty for these three categories – LCA GWP, energy use and PM – are almost (90%–99%) identical. Furthermore, once again, the principal causes of uncertainty in the LCA results are the HTc and HTnc values due to the lack of available data in Australia. Table and Figure 5.4 present the results of the uncertainty analysis for LSD rigid trucks. The CV (%) is close to the average (mean) value for energy use, GWP and PM (5%, 2% and 4%, respectively). In contrast, the results indicate that the data points are further from the mean, and there is a higher deviation within the dataset for both HTc (42%) and HTnc (29%). Furthermore, the uncertainty analysis indicates a 95% confidence interval for each category, and the range is considerable.

| **Impact Category** | **Mean** | **SD** | **CV%** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | 3.8297621 | 0.19343318 | 5 |
| **Global Warming (GWP100a) (kg/tkm)** | 0.31212415 | 0.005733702 | 2 |
| **Human Toxicity, Cancer (kg/tkm)** | 1.38E-09 | 5.72E-10 | 42 |
| **Human Toxicity, Non-Cancer (kg/tkm)** | 6.87E-09 | 1.99E-09 | 29 |
| **Particulate Matter (kg/tkm)** | 0.000256426 | 1.00E-05 | 4 |

**Table 5.4: Uncertainty Analysis of LSD Rigid Trucks' LCA**

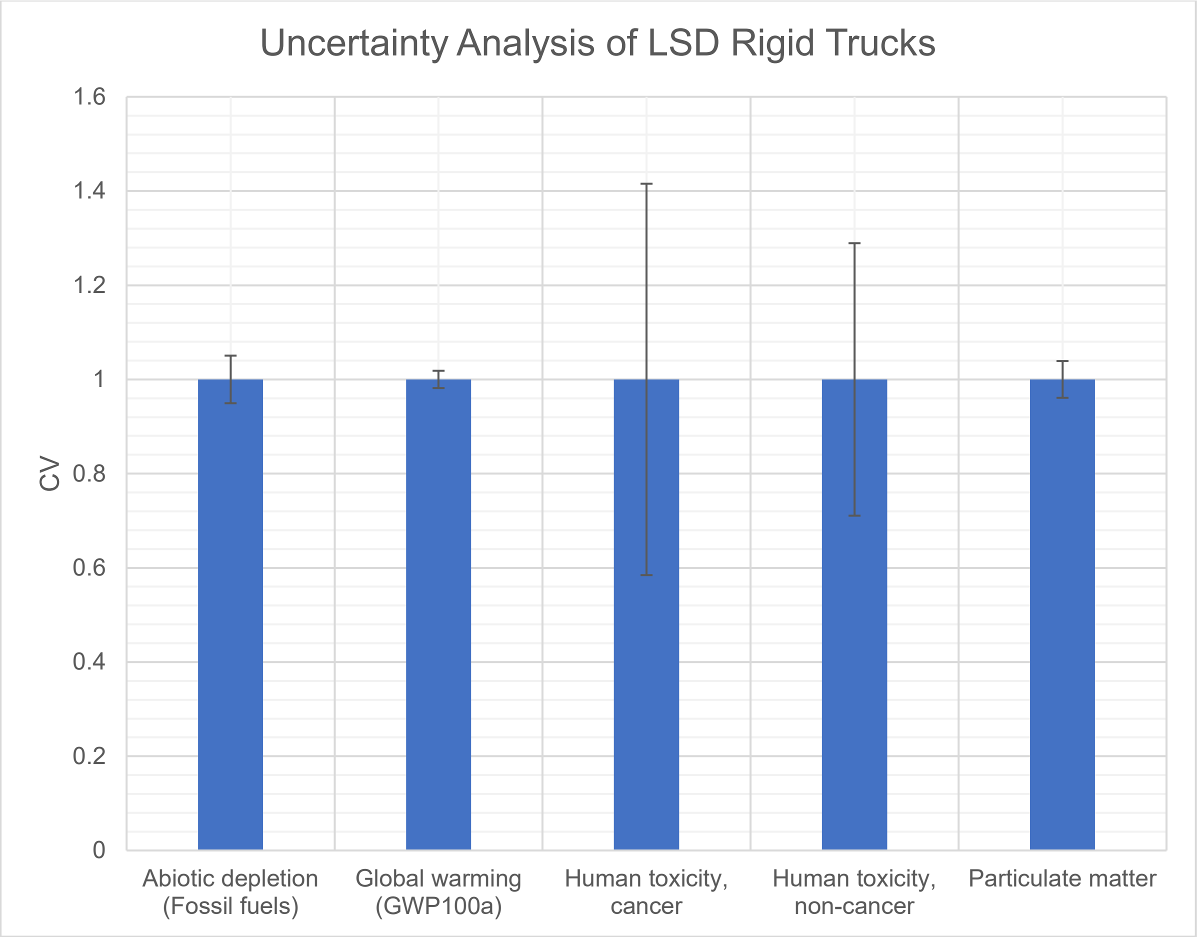


**Figure 5.4: Uncertainty Analysis of LSD Rigid Trucks' LCA**

This uncertainty analysis has been performed for all vehicles, and the results can be found in Appendix F.

## 5.2 Discussion of Results

When performing an LCA, the available data will not always be satisfactory. Such information is often gathered from a variety of sources, and some data will not always be available. This thesis used the AusLCI's data and other Australian vehicle emission data sources where it was appropriate, while previous studies referred to information from a variety of other sources. In relation to this, Noshadravan et al. (Noshadravan et al., 2015) focused on the uncertainty analysis of the data used to build the life cycle modelling during the vehicle's operational phase. They stated that the parameters can affect the overall LCA results, which is not consistent with our results in section 5.1. This is explained by the fact that this thesis utilised the AusLCI and other Australian vehicle emission data when it was apt to do so, and it examined the information that is used to model the assessment during all of the LCA phases, while earlier studies only examined the data during the use phase.

Furthermore, Seager et al. (Seager et al., 2008) examined the uncertainty data in the LCA for Li-ion batteries when used in BEVs. The sources/reliability of battery production and the results of the study showed that in order to reduce the uncertainty in the LCA's results, it is important to assess the types and properties of materials, which is counter to our own findings in section 5.1. This is likely because this study did not consider the types and properties of material manufacturing. A material's efficiency has the potential to reduce LCA GHG emissions that are connected to material-intensive systems, including light-duty vehicles. Indeed, there is significant potential to reduce the substantial emissions connected to producing the materials that are used in vehicles (Hertwich et al., 2019).

Meanwhile, Cellura et al. (Cellura et al., 2011) indicated that the uncertainty-analysis method needs to develop a sensitivity analysis to strengthen the reliability of the results, which was a similar finding to our own (see section 5.1), indicating that this paper is both rigorous in its approach and sound in terms of its findings.  Work by Groen et al. (2017) also showed that the sensitivity-analysis method should be chosen according to the magnitude of the uncertainty and the degree of correlation, agreeing with our own assertions in section 5.1. The sensitivity analysis is used to quantify the uncertainty of the data in order to give a high level of confidence regarding the veracity of the LCA's results.

The uncertainty analysis' findings in this thesis are also similar to those from a study by Wei et al. (Wei et al., 2015) who stated that in order to produce more accurate LCA results and to investigate the data used in the LCA model, the CV would have to be employed in relation to all types of transportation as a means of checking all of the data used for modelling. Indeed, this thesis adopted the approaches of Wei et al. (2015), Groen et al. (2017) and Cellura et al. (2011) with regard to their uncertainty analyses. However, our study went into greater depth by assessing all of the data used to build an LCA of the vehicles during their operational, fuel pathway and non-operational phases. This is inconsistent with the findings of earlier studies by (Noshadravan et al., 2015) and (Seager et al., 2008) who only examined the data during the use phase. The incongruity is due to our employment of AusLCI data and other appropriate Australian vehicle emission information, which allowed a wider and more rigorous approach to the uncertainty analysis to be undertaken. As a result, this thesis is more reliable in terms of the data used to model an LCA.

Moreover, Beer et al. (Beer et al., 2001a) indicated that the CV of PM is estimated to be 50% for LSD buses and 39% for LSD rigid trucks, which is not consistent with the results presented in Tables 5.2 and 5.4; they suggest that the CV of PM is much lower – 3% for LSD buses and 4% for rigid trucks. This disparity is apparent because the specified study used a variety of input sources of data and only examined this information during the operational phase; conversely, this thesis utilised AusLCI data and other appropriate Australian vehicle emission information in relation to the entire LCA, which gave much better results due to the consistency of the input data.

Consequently, the results of the uncertainty analysis showed that for almost all of the types of transportation analysed, the CV is relatively small – in fact, less than 11% (see Tables 5.1 and

5.2 and Figures 5.1 and 5.2). This means that all of the data used to model the life cycles is reliable. That said, some LCA categories, including HTc and HTnc display more variation with regard to the CV, meaning that the data has a greater spread from the mean and is uncertain. In addition, the analyses showed that heavy-duty trucks make lower contributions to uncertainty in terms of the LCA's global warming potential, its depletion in energy use and its influence on human health when compared with both passenger vehicles and public transport buses. Furthermore, it has been noted that values relating to human toxicity (cancerous and non-cancerous) were the biggest contributor to uncertainty in the LCA results (see Tables 5.3 and 5.4 and Figures 5.3 and 5.4) because of the lack of Australian databases. Thus, closer investigation of the databases will be an important process when addressing and minimising the uncertainty in the data that is used to build LCAs of vehicles.

# CHAPTER 6: SENSITIVITY ANALYSIS OF LCA

## 6.1 Results and Findings

Sensitivity analysis is a valuable tool for studying the robustness of results and their sensitivity to uncertainty factors in the life cycle assessment. Sensitivity analysis highlights the most important parameters to determine whether the data quality needs to be improved, and it also enhances the interpretation of the LCA results. This study used 15 parameters and undertook sensitivity analyses of three case studies – base value, case A and case B – representing the reference value and variations of that parameter. Sensitivity analyses of vehicle LCA results are performed according to several major parameters, factors and assumptions relating LCA global warming potential (GWP), depletion in energy use and human health influences. The results include GWP; depletion in energy; particulate matter (PM) and human toxicity, cancer and non-cancer (HTc and HTnc, respectively) that are affected by particular assumptions, parameters and factors when input into the life cycle model.

### 6.1.1 Global Warming Potential

#### *6.1.1.1 Passenger Vehicles*

GWP (in kg/pkm) is affected by most assumptions, parameters and factors directly, especially the passenger occupancy rate, which is considered an important factor that has a large effect on the overall LCA results. For instance, for **petrol passenger vehicles,** if the occupancy rate value decreases by 10% (1.44) from the reference value (1.6), the GHG emissions increase by 11.1% (0.287 kg/pkm) from the reference value (0.2591 kg/pkm). Conversely, if the occupancy rate increases by 10% (1.76) from the reference value, the GHG emissions decrease by 9.1% (0.2355 kg/pkm), as shown in Tables 6.1 and 6.2 and Figure 6.1. This occurs without any change in fuel consumption. Although this particular parameter (passenger occupancy rate) has a considerable impact on LCA GHG emissions, there are many other factors, including using fossil fuels instead of renewable energy, that directly affect the LCA results.

| Impact Category | Reference Value (Base) | Case A (−10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.28791779 | 0.2355691 | 11.1 | − 9.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.7423326 | 3.0619085 | 11 | −9 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 0.000108216 | 8.85E-05 | 11 | −9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.75E-09 | 1.43E-09 | 11 | −9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 7.69E-09 | 6.29E-09 | 11 | −9 |

**Table 6.1: Sensitivity Analysis for LCA of Petrol Vehicles (occupancy rate parameter)**

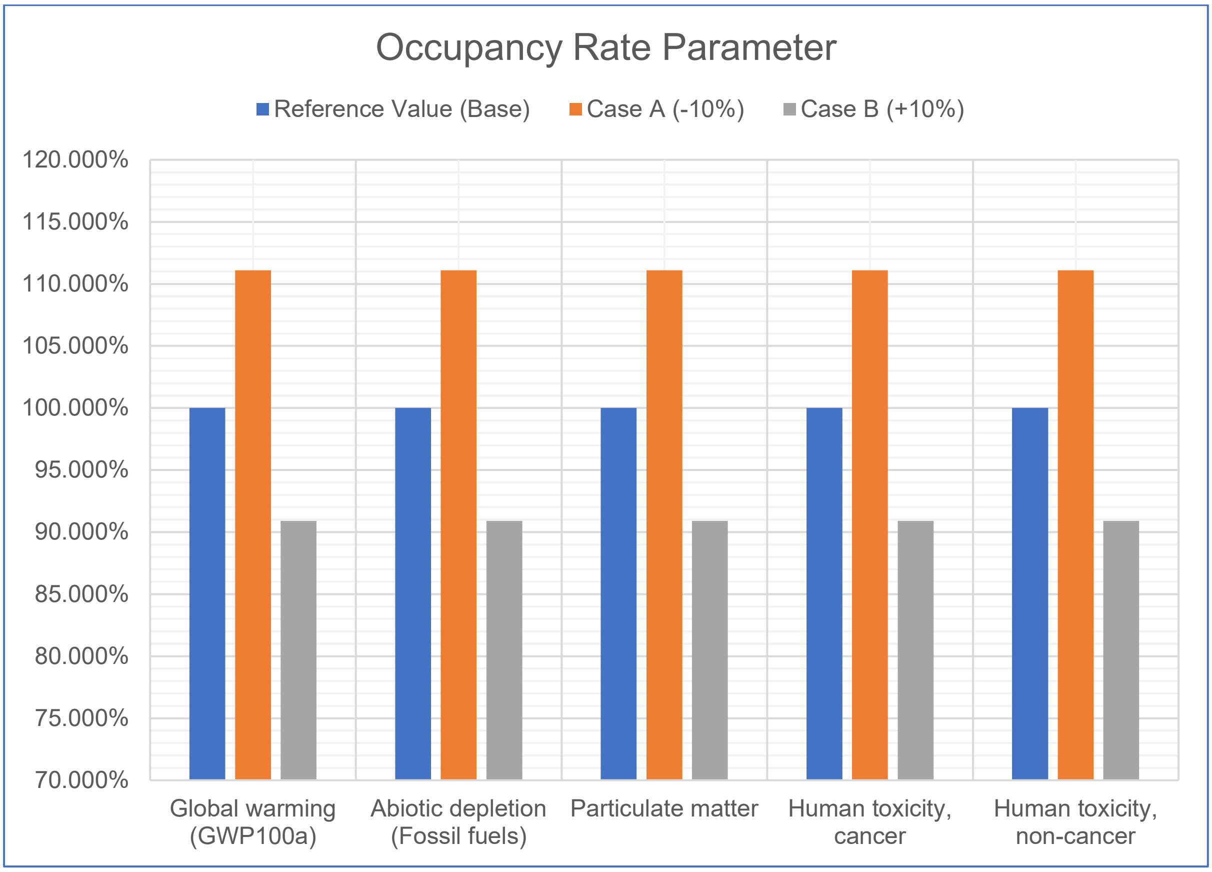


**Figure 6.1: Sensitivity Analysis for LCA of Petrol Vehicles (occupancy rate parameter)**

This analysis has been performed for all the other vehicle and fuel types, and the complete results are shown in Appendix G since they are too extensive for inclusion here. Below is a summary of the sensitivity analyses performed for the various vehicle and fuel types, with only the parameters highlighted in the tables described in the main body sections.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.25912601 | 0 | 0 | |
| **Occupancy Rate** | 0.28791779 | 11.1 | 0.2355691 | 9.1 |
| **Kilometres Travelled** | 0.28378924 | 9.5 | 0.23894701 | 7.8 |
| **Fuel Consumption** | 0.23692911 | 8.6 | 0.28132291 | 8.6 |
| **Vehicle Manufacture** | 0.25622509 | 1.1 | 0.26202694 | 1.1 |
| **Vehicle Maintenance** | 0.25852358 | 0.23 | 0.25972844 | 0.23 |
| **Crude Oil Refining** | 0.25878923 | 0.13 | 0.25946279 | 0.13 |
| **Vehicle Disposal** | 0.25891367 | 0.08 | 0.25933836 | 0.08 |
| **Crude Oil Extraction** | 0.25895912 | 0.06 | 0.25929291 | 0.06 |

**Table 6.2: Summary of Sensitivity Analysis for Petrol Passenger Vehicles LCA (GWP) (Note: the parameters are presented in order of most to least significant (most to least sensitive to change)**

The kilometres travelled factor has a noticeable effect on the total LCA results. For instance, for **fuel cell vehicles (FCVs),** when the kilometres travelled value varies by 10% from the base value (129280 km), the GHG emissions (in kg/pkm) either increase by 2.1% (0.048929 kg/pkm) from reference value (0.047913 kg/pkm) or decrease by 1.7% (0.047082 kg/pkm), as shown in Table 6.3. This is because although the parameter (kilometres travelled) influences the LCA GHG emissions results, the fuel resources use also have an impact on the results.

|  | 10% Decrease |  | 10% Increase |  |
|---|---|---|---|---|
|  | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.047913 | 0 | 0 |  |
| **Occupancy Rate** | 0.053237 | 11.1 | 0.043557 | 9.1 |
| **Vehicle Manufacture** | 0.044851168 | 6.39 | 0.050974969 | 6.39 |
| **Kilometres Travelled** | 0.048929 | 2.1 | 0.047082 | 1.7 |
| **Fuel Consumption** | 0.046998 | 1.9 | 0.048828 | 1.9 |
| **Hydrogen Production** | 0.046998 | 1.91 | 0.048828 | 1.91 |
| **Vehicle Maintenance** | 0.047310638 | 1.26 | 0.048515499 | 1.26 |
| **Vehicle Disposal** | 0.047701 | 0.44 | 0.048125 | 0.44 |
| **Hydrogen Processing** | 0.047913056 | 0.00 | 0.04791308 | 0.00 |

**Table 6.3: Summary of Sensitivity Analysis for LCA of FCVs (GWP)**

Moreover, LCA GWP (in kg/pkm) is affected by the fuel use parameter (in L/100 km or kg/km), but the effect varies between passenger vehicle types. For instance, for **conventional vehicles**, the effect on LCA GHG emissions is permanent when fuel use parameter increases or decreases by 10% from the reference value, while for **advanced vehicle technologies**, the effect is low and much smaller when fuel usage is low for both fuel cell and compressed natural gas (CNG) vehicles. For instance, for **CNG vehicles,** when fuel consumption increases by 10% (9.4E-05 kg/km) from the reference value (8.6E-05 kg/km), LCA GWP increases by 0.6% (0.039927 kg/pkm) from the reference value (0.039675 kg/pkm). Vice versa, when the fuel economy value decreases by 10% (7.74E-05 kg/pkm), LCA GWP decreases by 0.65% (0.039424 kg/pkm), as shown in Table 6.4. This is because the fuel consumption is so low that the CNG vehicle emissions will be lower compared to other types of vehicle.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.039675 | 0 | 0 | |
| **Occupancy Rate** | 0.044084 | 11.1 | 0.036069 | 9.1 |
| **Vehicle Manufacture** | 0.036774 | 7.3 | 0.042576 | 7.3 |
| **Vehicle Maintenance** | 0.039073 | 1.52 | 0.040278 | 1.52 |
| **Kilometres Travelled** | 0.039955 | 0.7 | 0.039446 | 0.6 |
| **Fuel Consumption** | 0.039424 | 0.65 | 0.039927 | 0.6 |
| **Vehicle Disposal** | 0.039463 | 0.53 | 0.039888 | 0.54 |
| **Natural Gas Processing** | 0.039672185 | 0.01 | 0.03967853 | 0.01 |
| **Natural Gas Production** | 0.039675357 | 0.001 | 0.039675357 | 0.001 |

**Table 6.4: Summary of Sensitivity Analysis for LCA of CNG Vehicles (GWP)**

In addition, the two parameters electricity mix grid consumption (in kwh/km) and electricity production (in kwh/MJ) have a much greater impact on total LCA results for advanced vehicle technologies. For instance, **for battery electric vehicles (BEVs),** when the electricity consumption (kwh/km) and production (kwh/MJ) parameters increase or decrease by 10% from the base values, LCA GWP increases by 6.1% (0.167957 kg/pkm) and 6.1% (0.167893 kg/pkm), respectively, from the reference value (0.158228 kg/pkm) and decreases by 6.1% (0.148498) and 6.1% (0.148562 kg/pkm) from the reference value (0.158228 kg/pkm), respectively, as shown in Table 6.5. The effect is caused not just by the two parameters, electricity consumption and production, but also from fuel resources (fuel derived from fossil fuel).

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.158228 | 0 | 0 | |
| **Occupancy Rate** | 0.175808 | 11.1 | 0.143843 | 9.1 |
| **Kilometres Travelled** | 0.169038 | 6.8 | 0.149382 | 5.6 |
| **Electricity Mix Consumption** | 0.148498 | 6.1 | 0.167957 | 6.1 |
| **Vehicle Manufacture** | 0.148498 | 6.15 | 0.167957 | 6.15 |
| **Electricity Mix Production** | 0.148562 | 6.1 | 0.167893 | 6.1 |
| **Vehicle Maintenance** | 0.156191 | 1.29 | 0.160264 | 1.29 |
| **Vehicle Disposal** | 0.157801 | 0.27 | 0.158654 | 0.27 |

**Table 6.5: Summary of Sensitivity Analysis for LCA of BEVs (GWP)**

In addition, the parameter of vehicle manufacture (in volumetric measurement unit) has less of an effect for conventional vehicles' LCA results than for alternative fuel-powered advanced vehicle technologies. For instance, for liquified petroleum gas (**LPG) vehicles,** when the vehicle manufacture value deviates from the reference value by plus or minus 10%, GWP will decrease by 1.4% (0.198831 kg/pkm) and increase by 1.4% (0.204633 kg/pkm) from the base value (0.201732 kg/pkm), as shown in Table 6.6. Although the vehicle manufacture phase has the biggest impact on LCA GHG emissions, other factors, such as the fuel resources and electricity generation for advanced vehicles, also impact the LCA results.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.201732 | 0 | 0 | |
| **Occupancy Rate** | 0.224147 | 11.1 | 0.183393 | 9.1 |
| **Kilometres Travelled** | 0.220018 | 9.1 | 0.186771 | 7.4 |
| **Fuel Consumption** | 0.185274 | 8.2 | 0.218189 | 8.2 |
| **Vehicle Manufacture** | 0.198831 | 1.4 | 0.204633 | 1.4 |
| **LPG Production** | 0.19903393 | 1.34 | 0.20442992 | 1.34 |
| **Vehicle Maintenance** | 0.201129 | 0.30 | 0.202334 | 0.30 |
| **Vehicle Disposal** | 0.20152 | 0.11 | 0.201944 | 0.11 |
| **LPG Processing** | 0.20173192 | 0.00 | 0.20173193 | 0.00 |

**Table 6.6: Summary of Sensitivity Analysis for LCA of LPG vehicles (GWP)**

Additionally, the parameter of vehicle maintenance has a small effect on the outcomes (LCA results). For instance, low sulphur diesel (**LSD) vehicles'** LCA GHG emissions decrease by 0.25% (0.241819 kg/pkm) from the base value (0.242422 kg/pkm) when vehicle maintenance (in MJ) decreases by 10% from the reference value, while the parameter vehicle maintenance increases by 0.25% (0.243024 kg/pkm) when the vehicle maintenance value increases by 10%, as shown in Table 6.7. Although vehicle servicing and maintenance can have an impact on LCA results, this depends on the vehicle mode, such as advanced or alternative.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.242422 | 0 | 0 | |
| **Occupancy Rate** | 0.269358 | 11.1 | 0.220384 | 9.1 |
| **Kilometres Travelled** | 0.265229 | 9.4 | 0.223761 | 7.7 |
| **Fuel Consumption** | 0.221895 | 8.5 | 0.262948 | 8.5 |
| **Vehicle Manufacture** | 0.239521 | 1.2 | 0.245323 | 1.2 |
| **Crude Oil Refining** | 0.240959 | 0.60 | 0.243885 | 0.60 |
| **Vehicle Maintenance** | 0.241819 | 0.25 | 0.243024 | 0.25 |
| **Vehicle Disposal** | 0.24221 | 0.09 | 0.242634 | 0.09 |
| **Crude Oil Extraction** | 0.242239 | 0.08 | 0.242605 | 0.08 |

**Table 6.7: Summary of Sensitivity Analysis for LCA of LSD Vehicles (GWP)**

The parameter of vehicle disposal (in volumetric measurement unit) has a very small effect on the LCA outcome for conventional vehicles, yet it has a great impact on the outcomes for both advanced vehicle technologies and vehicles powered by alternative fuels. Although the effect of the vehicle disposal parameter on LCA GHG emissions is very small, their impact should not be ignored. For instance, for plug-in vehicles (PEHVs), when the vehicle disposal parameter value deviates from the reference value (0.161683 kg/pkm) by plus or minus 10%, LCA GWP increases by 0.23% (0.162062 kg/pkm) or decreases by 0.23% (0.161304 kg/pkm), respectively, as shown in Table 6.8.

The vehicle end-of-life phase can impact LCA outcomes for advanced vehicle technologies, more so than for conventional vehicles because advanced vehicles have more components and parts that need to be shredded and dismantled during the disposal phase.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.161683 | 0 | 0 | |
| **Occupancy Rate** | 0.179648 | 11.1 | 0.146985 | 9.1 |
| **Kilometres Travelled** | 0.174568 | 8.0 | 0.151141 | 6.5 |
| **Electricity Grid Consumption** | 0.154455 | 4.47 | 0.168911 | 4.47 |
| **Electricity Grid Mix Production** | 0.15450212 | 4.44 | 0.16886227 | 4.44 |
| **Fuel Consumption** | 0.157315 | 2.7 | 0.166052 | 2.7 |
| **Vehicle Manufacture** | 0.158396 | 2.0 | 0.16497 | 2.0 |
| **Vehicle Maintenance** | 0.16077643 | 0.56 | 0.16258795 | 0.56 |
| **Vehicle Disposal** | 0.161304 | 0.23 | 0.162062 | 0.23 |
| **Crude Oil Refining** | 0.161794 | 0.07 | 0.161593 | 0.06 |
| **Crude Oil Extraction** | 0.161583 | 0.06 | 0.161783 | 0.06 |

**Table 6.8: Summary of Sensitivity Analysis for LCA of PHEVs (GWP)**

Lastly, other parameters, including crude oil extraction and refining, natural gas production and processing, LPG production and processing and hydrogen production and processing, have much smaller effects on LCA results; however, for some types of vehicle, their effects are more apparent. For instance:

1. When the crude oil extraction and refining value (kg) decreases by 10% from the reference value, LCA GHG emissions **for petrol passenger vehicles** decrease by 0.06% (0.25895912 kg/pkm) and 0.13% (0.25878923 kg/pkm), respectively, from the reference value (0.25912601 kg/pkm). However, LCA GHG emissions increase by 0.06% (0.25929291 kg/pkm) and 0.13% (0.25946279 kg/pkm) when these parameters increase by 10% from the base value, as shown in Table 6.2 above.

2. The parameters of natural gas production and processing parameters (in kg) do not have greatly influence the results. When these parameters are increased or decreased by 10% from the reference value for **CNG vehicles,** LCA GWP decreases by 0.001% (0.039675357 kg/pkm) and 0.01% (0.039672185 kg/pkm) from the reference value (0.039675357 kg/pkm), respectively, and increases by 0.001% (0.039675357 kg/pkm) and 0.01% (0.03967853 kg/pkm), as shown in Table 6.4 above.
3. The impact of LPG production and processing on **LPG vehicle** LCA results can be seen. For instance, when these values decrease from the base value by 10%, LCA GWP decreases by 1.34% (0.19903393 kg/pkm) and 0.00% (0.20173192 kg/pkm), respectively. Vice versa, LCA GWP increases by 1.34% (0.20442992 kg/pkm) and 0.00% (0.20173193 kg/pkm), respectively, when LPG production and processing parameters increase by 10%, as shown in Table 6.6 above.
4. Hydrogen production and processing parameters have considerable effects on LCA GHG emissions results. For instance, for FCVs**,** LCA GHG emissions vary between case A (0.046998 kg/pkm and 0.047913056 kg/pkm) from the base value (0.047913 kg/pkm) and case B (0.048828 kg/pkm and 0.04791308 kg/pkm), as shown in Table 6.3.

#### *6.1.1.2 Public Transport Buses*

Passenger occupancy rate has a higher effect on the GWP impact of public transport buses. For instance, **for LSD buses,** when the passenger occupancy rate (in P) decreases or increases by 10% from the base value (0.068235326 kg/pkm), LCA GWP increases by 11.1% (0.075817029 kg/pkm) and decreases by 9.1% (0.062032115 kg/pkm), as shown in Table 6.9. However, the effect on the LCA results might be not just be from the passenger occupancy rate, but also from fuel production.

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.068235326 | 0 | 0 | |
| **Occupancy Rate** | 0.075817029 | 11.1 | 0.062032115 | 9.1 |
| **Kilometre Travelled** | 0.073333086 | 7.3 | 0.064064432 | 6.3 |
| **Fuel Consumption** | 0.063647343 | 6.7 | 0.07282331 | 6.7 |
| **Vehicle Maintenance** | 0.066907686 | 1.95 | 0.069562967 | 1.95 |
| **Vehicle Manufacture** | 0.067350757 | 1.3 | 0.069119895 | 1.3 |
| **Crude Oil Refining** | 0.067907528 | 0.48 | 0.068563124 | 0.48 |
| **Crude Oil Extraction** | 0.068194307 | 0.06 | 0.068276345 | 0.06 |
| **Vehicle Disposal** | 0.068211987 | 0.03 | 0.068258666 | 0.03 |

**Table 6.9: Summary of Sensitivity Analysis for LCA of LSD Buses (GWP)**

Similarly, the kilometres travelled parameter has a noticeable effect on outcome. For instance, if the kilometre travelled value for **LSD buses** deviates by plus or minus 10% from the base value (0.068235326 kg/pkm), LCA GWP increases by 7.3% (0.073333086 kg/pkm) and decreases by 6.3% (0.064064432 kg/pkm), as shown in Table 6.9 above. The fuel consumption parameter also has a considerable effect on life cycle modelling. For instance, for **hybrid electric buses,** when the fuel economy value decreases by 10%, GWP decreases by 7.2% (0.073728048 kg/pkm) from the base value (0.07946759 kg/pkm). In contrast, GWP increases by 7.2% (0.085207132 kg/pkm) from the reference value when fuel consumption increases by 10%, as shown in Table 6.10. Although the hybrid bus has a lower fuel consumption, it has a significant impact on LCA GHG emissions because the fuel is produced from fossil fuel sources.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.07946759 | 0 | 0 | |
| **Occupancy Rate** | 0.088297323 | 11.1 | 0.072243264 | 9.1 |
| **Kilometres Travelled** | 0.085844859 | 8.0 | 0.074249825 | 6.6 |
| **Fuel Consumption** | 0.073728048 | 7.2 | 0.085207132 | 7.2 |
| **Vehicle Maintenance** | 0.078187702 | 1.61 | 0.080747478 | 1.61 |
| **Vehicle Manufacture** | 0.078566209 | 1.1 | 0.080368971 | 1.1 |
| **Crude Oil Refining** | 0.079057842 | 0.52 | 0.079877338 | 0.52 |
| **Crude Oil Extraction** | 0.079416316 | 0.06 | 0.079518864 | 0.06 |
| **Vehicle Disposal** | 0.079441642 | 0.03 | 0.079493539 | 0.03 |

**Table 6.10: Summary of Sensitivity Analysis for LCA of Hybrid Electric Buses (GWP)**

The bus manufacture parameter has a very small effect on LCA GHG emissions in conventional buses, while the impact is much bigger in CNG fuel-powered buses. For instance, for **CNG buses,** when the bus manufacture parameter (in volumetric measurement unit) deviates by either plus or minus 10% from the base value (0.022501538 kg/pkm), LCA GWP decreases by 3.9% (0.021616636 kg/pkm) and will increase by 3.9% (0.023386441 kg/pkm), as shown in Table 6.11. This is because CNG buses can be affected by other factors, including fuel production, advanced and alternative vehicles.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.022501538 | 0 | 0 | |
| **Occupancy Rate** | 0.025001709 | 11.1 | 0.020455944 | 9.1 |
| **Vehicle Maintenance** | 0.021173898 | 5.90 | 0.023829179 | 5.90 |
| **Vehicle Manufacture** | 0.021616636 | 3.9 | 0.023386441 | 3.9 |
| **Vehicle Disposal** | 0.022478199 | 0.10 | 0.022524878 | 0.10 |
| **Kilometres Travelled** | 0.022517395 | 0.1 | 0.022488564 | 0.1 |
| **Fuel Consumption** | 0.022487267 | 0.1 | 0.022515809 | 0.1 |
| **Natural Gas Production** | 0.022491971 | 0.04 | 0.022511106 | 0.04 |
| **Natural Gas Processing** | 0.022500738 | 0.001 | 0.022502338 | 0.001 |

**Table 6.11: Summary of Sensitivity Analysis for LCA of CNG Bus (GWP)**

Further, electricity grid mix impact can be considered as having a higher effect on output results regarding **battery electric buses**. For instance, when both electricity mix consumption and production are increased and decreased by 10% from the base value (0.09743295 kg/pkm), LCA GWP increases by 7.3% (0.10455961 kg/pkm) and 7.27% (0.1045126 kg/pkm), respectively, and will decrease by 7.3% (0.090306287 kg/pkm) and 7.27% (0.090353298 kg/pkm), respectively, as shown in Table 6.12. These two parameters have significant impacts on LCA GHG emissions because the electricity is generated from fossil fuels rather than renewable energy sources.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.09743295 | 0 | 0 | |
| **Occupancy Rate** | 0.10825883 | 11.1 | 0.088575409 | 9.1 |
| **Kilometres Travelled** | 0.10535146 | 8.1 | 0.090954165 | 6.6 |
| **Electricity Mix Consumption** | 0.090306287 | 7.3 | 0.10455961 | 7.3 |
| **Electricity Mix Production** | 0.090353298 | 7.27 | 0.1045126 | 7.27 |
| **Vehicle Maintenance** | 0.095956888 | 1.51 | 0.098909011 | 1.51 |
| **Vehicle Manufacture** | 0.096340749 | 1.1 | 0.09852515 | 1.1 |
| **Vehicle Disposal** | 0.09738458 | 0.05 | 0.09748132 | 0.05 |

**Table 6.12: Summary of Sensitivity Analysis for LCA of Battery Electric Buses (GWP)**

The impact of the bus maintenance parameter can be seen on **CNG buses** LCA GHG emissions. For instance, when the value deviates from the base value (0.022501538 kg/pkm) by plus or minus 10%, LCA GHG emissions decrease by 5.9% (0.021173898 kg/pkm) and increase by 5.9% (0.023829179 kg/pkm), as shown in Table 6.11 above. This is because the impact is not just from this parameter but also from other factors, such as fuel resources. Finally, other parameters, including crude oil extraction, LPG production and processing, natural gas production and processing and bus disposal, have much smaller impacts on the overall LCA results, so the effects of these parameters can be ignored.

#### *6.1.1.3 Heavy-duty Truck Vehicles*

The average load parameter is considered to have a significant effect on LCA GHG emissions results for heavy-duty truck vehicles, followed by the fraction load parameter, then the kilometres travelled parameter. For instance, **for rigid LSD trucks**, when the average load value varies from the base value (0.31364184) by plus or minus 10%, LCA GHG emissions (in kg/tkm) increase by 11.1% (0.34849093) and decrease by 9.1% (0.28512894), while LCA GHG emissions increase by 9.9% (0.34471929) and decrease by 7.91% (0.28821483) from the base value. Lastly, the GWP will increase by 9.9% (0.34471929) and decrease by 7.9% (0.28821483) from the base value when the kilometres travelled value for **conventional rigid LSD trucks** varies by plus or minus 10% from the base value, as shown in Table 6.13. Although these parameters have significant impacts on the LCA results, other impacts, such as fuel production and driving behaviour, might also affect the LCA outcome.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/tkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.31364184 | 0 | 0 | |
| **Average Load** | 0.34849093 | 11.1 | 0.28512894 | 9.1 |
| **Kilometres Travelled** | 0.34471929 | 9.9 | 0.28821483 | 7.9 |
| **Fraction Load Factor** | 0.34471929 | 9.9 | 0.28821483 | 7.91 |
| **Fuel Consumption** | 0.28567213 | 8.9 | 0.34161154 | 8.9 |
| **Vehicle Manufacture** | 0.31163828 | 0.6 | 0.3156454 | 0.6 |
| **Crude Oil Refining** | 0.31164246 | 0.64 | 0.31564122 | 0.64 |
| **Vehicle Maintenance** | 0.31230954 | 0.42 | 0.31497414 | 0.42 |
| **Crude Oil Extraction** | 0.31339164 | 0.08 | 0.31389203 | 0.08 |
| **Vehicle Disposal** | 0.31358322 | 0.02 | 0.31370045 | 0.02 |

**Table 6.13: Summary of Sensitivity Analysis for LCA of LSD Rigid Trucks (GWP)**

In addition, for **advanced heavy vehicle technologies**, both electricity mix consumption and electricity mix production parameters have much higher effects on output results. For instance, regarding **battery electric articulated trucks,** when these parameters decrease and increase by 10% from the reference value (0.073240527), LCA GHG emissions (in kg/tkm) decrease by 9.4% (0.066371308) and 9.32% (0.066416621) and increase by 9.38% (0.080109745) and 9.32% (0.080064432), respectively, as shown in Table 6.14. This is because the electricity is generated from non-renewable energy sources (fossil fuels), so more emissions are produced. In addition, there are other impacts on the LCA results for advanced vehicles.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/tkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.073240527 | 0 | 0 | |
| **Average Load** | 0.081378363 | 11.1 | 0.066582297 | 9.1 |
| **Kilometres Travelled** | 0.080872992 | 10.4 | 0.066995783 | 8.5 |
| **Fraction Load Factor** | 0.080872992 | 10.42 | 0.066995783 | 8.53 |
| **Electricity Mix Consumption** | 0.066371308 | 9.4 | 0.080109745 | 9.38 |
| **Electricity Mix Production** | 0.066416621 | 9.32 | 0.080064432 | 9.32 |
| **Vehicle Manufacture** | 0.072933954 | 0.4 | 0.0735471 | 0.4 |
| **Vehicle Maintenance** | 0.073100669 | 0.19 | 0.073380385 | 0.19 |
| **Vehicle Disposal** | 0.073232123 | 0.01 | 0.07324893 | 0.01 |

**Table 6.14: Summary of Sensitivity Analysis for LCA of Electric Articulated Trucks (GWP)**

Moreover, the fuel economy parameter can also have a considerable impact on LCA GHG emissions results. For instance, for **hybrid articulated trucks,** when the fuel consumption parameter is deviates from the base value (0.14031212 kg/tkm) by plus or minus 10%, LCA

GWP decreases by 9.7% (0.12671997 kg/tkm) and increases by 9.7% (0.15390428 kg/tkm), as shown in Table 6.15. The effect on the LCA results is not just from this parameter (fuel economy) but also from other factors, such as fuel production.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/tkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.14031212 | 0 | 0 | |
| **Average Load** | 0.15590236 | 11.1 | 0.12755648 | 9.1 |
| **Kilometres Travelled** | 0.15541452 | 10.8 | 0.12795562 | 8.8 |
| **Fraction Load Factor** | 0.15541452 | 10.76 | 0.12795562 | 8.81 |
| **Fuel Consumption** | 0.12671997 | 9.7 | 0.15390428 | 9.7 |
| **Crude Oil Refining** | 0.13934233 | 0.69 | 0.14128192 | 0.69 |
| **Vehicle Manufacture** | 0.14006587 | 0.2 | 0.14055838 | 0.2 |
| **Vehicle Maintenance** | 0.14012789 | 0.13 | 0.14049635 | 0.13 |
| **Crude Oil Extraction** | 0.14019077 | 0.09 | 0.14043348 | 0.09 |
| **Vehicle Disposal** | 0.14030355 | 0.01 | 0.1403207 | 0.01 |

**Table 6.15: Summary of Sensitivity Analysis for LCA of Hybrid Articulated Trucks (GWP)**

Furthermore, the parameters truck manufacture and crude oil refining have limited impact on global warming potential. Lastly, the impacts of other parameters including crude oil extraction, truck manufacture and truck disposal can be ignored their impact due to their much small effect on LCA GHG emissions results.

### 6.1.2 Abiotic Depletion (Fossil Fuels) (MJ/pkm)

#### *6.1.2.1 Passenger Vehicles*

There is a similarity between the effect of factors, assumptions and parameters, as mentioned above, on LCA GWP and on LCA energy use. For instance, for **LSD vehicles,** when the passenger occupancy rate (in P) decreases or increases by 10% from the reference value (2.942879 MJ/pkm), the change of LCA energy use (in MJ/pkm) varies from case A (11.1%, 3.269865 MJ/pkm) to case B (9.1%, 2.675344 MJ/pkm), as shown in Table 6.16. So, although the passenger occupancy rate has a large impact on LCA energy use, the impact depends on both fuel resources and vehicle powertrain performance.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 2.942879 | 0 | 0 | |
| **Occupancy Rate** | 3.269865 | 11.1 | 2.675344 | 9.1 |
| **Kilometres Travelled** | 3.211054 | 9.1 | 2.723463 | 7.5 |
| **Fuel Consumption** | 2.701521 | 8.2 | 3.184236 | 8.2 |
| **Crude Oil Refining** | 2.733726 | 7.11 | 3.152031 | 7.11 |
| **Crude Oil Extraction** | 2.882091 | 2.07 | 3.003667 | 2.07 |
| **Vehicle Manufacture** | 2.902443 | 1.4 | 2.983314 | 1.4 |
| **Vehicle Maintenance** | 2.931555 | 0.38 | 2.954203 | 0.38 |
| **Vehicle Disposal** | 2.941708 | 0.04 | 2.94405 | 0.04 |

**Table 6.16: Summary of Sensitivity Analysis for LCA of LSD Vehicles (energy use)**

In addition, the influence of the kilometres travelled, and fuel economy parameters are connected. For instance, for **petrol vehicles,** when the kilometres travelled factor increases or decreases from the base value (3.3680994 MJ/pkm) by 10%, LCA energy use increases by

9.4% (3.6835211 MJ/pkm) and decreases by 7.7% (3.110027 MJ/pkm), respectively, and for **LPG vehicles,** when the fuel economy (fuel consumption) value decreases by 10% (0.050949 kg/km) from the reference value (0.05661 kg/km), LCA energy use decreases by 7.9% (2.293732 MJ/pkm) from the base value (2.489779 MJ/pkm). Vice versa, LCA energy demand for **LPG vehicles** increases by 7.9% (2.685827 MJ/pkm) from the reference value (2.489779 MJ/pkm) when the fuel economy factor increases by 10% (0.062271 kg/km), as shown in Tables 6.17 and 6.18, respectively. The effect of these parameters can be considerable, but there are also other factors that impact LCA energy use, namely, powertrain efficiency, fuel resources and advanced vehicle technology.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 3.3680994 | 0 | 0 | |
| **Occupancy Rate** | 3.7423326 | 11.1 | 3.0619085 | 9.1 |
| **Kilometres Travelled** | 3.6835211 | 9.4 | 3.110027 | 7.7 |
| **Fuel Consumption** | 3.0842198 | 8.4 | 3.6519789 | 8.4 |
| **Crude Oil Refining** | 3.3104404 | 1.71 | 3.4257583 | 1.71 |
| **Crude Oil Extraction** | 3.3126977 | 1.64 | 3.423501 | 1.64 |
| **Vehicle Manufacture** | 3.3276639 | 1.2 | 3.4085349 | 1.2 |
| **Vehicle Maintenance** | 3.3567754 | 0.34 | 3.3794233 | 0.34 |
| **Vehicle Disposal** | 3.3669284 | 0.03 | 3.3692703 | 0.03 |

**Table 6.17: Summary of Sensitivity Analysis for LCA of Petrol Passenger Vehicles (energy use)**

|  | 10% Decrease |  | 10% Increase |  |
|---|---|---|---|---|
|  | **Abiotic depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 2.489779 | 0 | 0 |  |
| **Occupancy Rate** | 2.766421 | 11.1 | 2.263436 | 9.1 |
| **Kilometres Travelled** | 2.70761 | 8.7 | 2.311554 | 7.2 |
| **Fuel Consumption** | 2.293732 | 7.9 | 2.685827 | 7.9 |
| **LPG Production** | 2.2952115 | 7.81 | 2.6843469 | 7.81 |
| **Vehicle Manufacture** | 2.449344 | 1.6 | 2.530215 | 1.6 |
| **Vehicle Maintenance** | 2.478455 | 0.45 | 2.501103 | 0.45 |
| **Vehicle Disposal** | 2.488608 | 0.05 | 2.49095 | 0.05 |
| **LPG Processing** | 2.4897791 | 0.001 | 2.4897793 | 0.001 |

**Table 6.18: Summary of Sensitivity Analysis for LCA of LPG Vehicles (energy use)**

Moreover, although the impact of the crude oil refining parameter on LCA results is generally minor, it has a significant effect on **conventional LSD vehicles**. For instance, when the value decreases by 10% from the reference value, LCA energy use decreases by 7.11% (2.733726 MJ/pkm); however, LCA energy use increases by 7.11% (3.152031 MJ/pkm) from the reference value when the value increases by 10%, as shown in Table 6.16 above. This is due to the complicated processes regarding crude oil refining that consume large amounts of energy. Furthermore, the vehicle manufacture parameter has a small impact on LCA energy use for most types of vehicle. However, its impact is more prominent for both advanced vehicle technologies and alternative fuel-powered vehicles. For instance, for **BEVs,** when vehicle manufacture (in volumetric measurement unit) decreases and increases by 10% from the reference value (1.933596 MJ/pkm), LCA energy demand decreases by 5.73% (1.822796

MJ/pkm) and increases by 5.73% (2.044395 MJ/pkm), respectively, as shown in Table 6.19. This is because the vehicle manufacture processes consume large amounts of energy. Added to that, the impact is not just from the vehicle manufacture parameter, but also from electricity generation and production for advanced vehicle technologies.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.933596 | 0 | 0 | |
| **Occupancy Rate** | 2.14844 | 11.1 | 1.757814 | 9.1 |
| **Kilometres Travelled** | 2.056707 | 6.4 | 1.832869 | 5.2 |
| **Electricity Mix Consumption** | 1.822796 | 5.73 | 2.044395 | 5.73 |
| **vehicle manufacture** | 1.822796 | 5.73 | 2.044395 | 5.73 |
| **Electricity Mix Production** | 1.823363 | 5.70 | 2.043829 | 5.70 |
| **Vehicle Maintenance** | 1.904379 | 1.51 | 1.962812 | 1.51 |
| **Vehicle Disposal** | 1.930572 | 0.16 | 1.936619 | 0.16 |

**Table 6.19: Summary of Sensitivity Analysis for LCA of BEVs (energy use)**

The electricity grid mix consumption parameter has a considerable effect on LCA results for both **BEVs and plug-in vehicles**. For instance, for BEVs, when the value decreases and increases by 10% from the reference value (1.933596 MJ/pkm), LCA energy use decreases by 5.73% (1.822796 MJ/pkm) and increases by 5.73% (2.044395 MJ/pkm), respectively, as do the electricity mix production parameter values, which has approximately the same impact on the overall LCA energy use results, as shown in Table 6.19 above. Lastly, other parameters, including crude oil extraction, LPG production and processing, natural gas production and processing, hydrogen production and processing, and vehicle maintenance and disposal, have much smaller effects on outcomes, so their effect on cumulative energy demand life cycle modelling can be ignored.

### *6.1.2.2 Public Transport Buses*

LCA energy use (in MJ/pkm) is greatly affected by three factors: passenger occupancy rate, kilometres travelled and fuel economy. For instance, for **LSD buses,** when the values of these three factors decrease and increase by 10% from the base value, LCA energy use (MJ/pkm) increases by 11.1% (0.90268177) and decreases by 9.1% (0.73855781) (passenger occupancy rate), increases by 7.6% (0.87248478) and decreases by 6.6% (0.76326443) (kilometres travelled), and decreases by 6.7% (0.75834951) and increases by 6.7% (0.86647767) (fuel economy), respectively, as shown in Table 6.20. This means that these parameters play significant roles with regard to LCA results. Other impacts arise from fuel production and driving behaviour.

| | **10% decrease** | | **10% increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.81241359 | 0 | 0 | |
| **Occupancy Rate** | 0.90268177 | 11.1 | 0.73855781 | 9.1 |
| **Kilometres Travelled** | 0.87248478 | 7.6 | 0.76326443 | 6.6 |
| **Fuel Consumption** | 0.75834951 | 6.7 | 0.86647767 | 6.7 |
| **Crude Oil Refining** | 0.76556345 | 5.77 | 0.85926373 | 5.77 |
| **Vehicle Maintenance** | 0.79641098 | 1.97 | 0.8284162 | 1.97 |
| **Crude Oil Extraction** | 0.79879704 | 1.68 | 0.82603014 | 1.68 |
| **Vehicle Manufacture** | 0.80124753 | 1.4 | 0.82357965 | 1.4 |
| **Vehicle Disposal** | 0.81240498 | 0.001 | 0.8124222 | 0.001 |

**Table 6.20: Summary of Sensitivity Analysis for LCA of LSD Buses (energy use)**

The parameter of LPG production significantly impacts LCA energy use results. For instance, for **LPG buses,** when the LPG production values fluctuates from the base value (0.76522557) by plus or minus 10%, LCA energy use (in MJ/pkm) decreases by 6.41% (0.71614542) and increases by 6.41% (0.81430572), respectively, as shown in Table 6.21. This significant impact on LCA energy use comes not just from the LPG production parameter but also from crude oil extraction and refining.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.76522557 | 0 | 0 | |
| **Occupancy Rate** | 0.85025064 | 11.1 | 0.69565961 | 9.1 |
| **Kilometres Travelled** | 0.82017383 | 7.2 | 0.72026791 | 5.9 |
| **Fuel Consumption** | 0.71577214 | 6.5 | 0.814679 | 6.5 |
| **LPG Production** | 0.71614542 | 6.41 | 0.81430572 | 6.41 |
| **Vehicle Maintenance** | 0.74927444 | 2.08 | 0.7811767 | 2.08 |
| **Vehicle Manufacture** | 0.75411618 | 1.5 | 0.77633496 | 1.5 |
| **Vehicle Disposal** | 0.76521696 | 0.001 | 0.76523418 | 0.001 |
| **LPG Processing** | 0.76522555 | 0.001 | 0.76522559 | 0.001 |

**Table 6.21: Summary of Sensitivity Analysis for LCA of LPG Buses (energy use)**

Added to that, the parameter of crude oil refining (in kg) also affects output results. For instance, for **hybrid electric buses,** when the value deviates from the base value (0.94870297) by plus or minus 10%, LCA energy use (MJ/pkm) decreases by 6.17% (0.89014029) and increases by 6.17% (1.0072656), respectively, as shown in Table 6.22. This is due to the complicated processes in crude oil refining, which make this parameter crucial to the LCA results.

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.94870297 | 0 | 0 |  |
| **Occupancy Rate** | 1.0541144 | 11.1 | 0.86245724 | 9.1 |
| **Kilometres Travelled** | 1.023792 | 7.9 | 0.88726651 | 6.5 |
| **Fuel Consumption** | 0.88112287 | 7.1 | 1.0162831 | 7.1 |
| **Crude Oil Refining** | 0.89014029 | 6.17 | 1.0072656 | 6.17 |
| **Crude Oil Extraction** | 0.93168228 | 1.79 | 0.96572365 | 1.79 |
| **Vehicle Maintenance** | 0.93275184 | 1.68 | 0.96465409 | 1.68 |
| **Vehicle Manufacture** | 0.93737643 | 1.2 | 0.9600295 | 1.2 |
| **Vehicle Disposal** | 0.94869042 | 0.001 | 0.94871551 | 0.001 |

**Table 6.22: Summary of Sensitivity Analysis for LCA of Hybrid Electric Buses (energy use)**

The impact on LCA energy use results from other parameters, including crude oil extraction, LPG processing and bus maintenance and disposal, can be ignored due to their much smaller effect on the overall life cycle modelling outcome.

### *6.1.1.3 Heavy-duty Truck Vehicles*

LCA energy use can be affected by many assumptions, factors and parameters in the case of heavy-duty truck vehicles. Some of the impacts pertain to conventional trucks, while others are relevant to advanced truck technologies. For instance, for LSD rigid trucks, when the average load, fraction load, kilometres travelled and fuel economy factors decrease and increase by

10% from the reference value, as shown in Table 6.23, LCA energy use (in MJ/tkm) changes as outlined below:

1. The average load value increases by 11.1% (4.2678149) and decreases by 9.1% (3.4918486) from the base value (3.8410334).
2. The fraction load value increases by 9.54% (4.2074329) and decreases by 7.8% (3.541252) from the base value (3.8410334).
3. The kilometres travelled value increases by 9.5% (4.2074329) and decreases by 7.8% (3.541252) from the base value (3.8410334).
4. The fuel consumption value decreases by 8.6% (3.5112739) and increases by 8.6% (4.1707929) from the base value (3.8410334).

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 3.8410334 | 0 | 0 | |
| **Average Load** | 4.2678149 | 11.1 | 3.4918486 | 9.1 |
| **Kilometres Travelled** | 4.2074329 | 9.5 | 3.541252 | 7.8 |
| **Fraction Load Factor** | 4.2074329 | 9.54 | 3.541252 | 7.80 |
| **Fuel Consumption** | 3.5112739 | 8.6 | 4.1707929 | 8.6 |
| **Crude Oil Refining** | 3.5552747 | 7.44 | 4.1267921 | 7.44 |
| **Crude Oil Extraction** | 3.7579803 | 2.16 | 3.9240865 | 2.16 |
| **Vehicle Manufacture** | 3.8131858 | 0.7 | 3.868881 | 0.7 |
| **Vehicle Maintenance** | 3.8146127 | 0.69 | 3.8674541 | 0.69 |
| **Vehicle Disposal** | 3.8409578 | 0.001 | 3.841109 | 0.001 |

**Table 6.23: Summary of Sensitivity Analysis for LCA of LSD Rigid Trucks (energy use)**

However, when the parameters electricity mix consumption and electricity mix production **in the case of battery electric articulated trucks** decrease and increase by 10% from the base value, as shown in Table 6.24, LCA energy use (in MJ/tkm) changes as explained below:

1. Electricity mix consumption decreases by 9.1% (0.77842609) and increases by 9.1% (0.93487705) from the base value (0.85665157).
2. Electricity mix production decreases by 9.08% (0.77882628) and increases by 9.08% (0.93447686) from the base value (0.85665157).

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.85665157 | 0 | 0 | |
| **Average Load** | 0.95183508 | 11.1 | 0.77877416 | 9.1 |
| **Kilometres Travelled** | 0.94356877 | 10.1 | 0.7855375 | 8.3 |
| **Fraction Load Factor** | 0.94356877 | 10.15 | 0.7855375 | 8.30 |
| **Electricity Mix Consumption** | 0.77842609 | 9.1 | 0.93487705 | 9.1 |
| **Electricity Mix Production** | 0.77882628 | 9.08 | 0.93447686 | 9.08 |
| **Vehicle Manufacture** | 0.85242871 | 0.5 | 0.86087444 | 0.5 |
| **Vehicle Maintenance** | 0.85344542 | 0.37 | 0.85985773 | 0.37 |
| **Vehicle Disposal** | 0.85664091 | 0.001 | 0.85666223 | 0.001 |

**Table 6.24: Summary of Sensitivity Analysis for LCA of Electric Articulated Trucks (energy use)**

In addition, the impact on the LCA energy use results from the crude oil refining parameter is also clearly observable. For instance, for **hybrid articulated trucks,** when the crude oil refining value varies from the reference value (1.6702337 MJ/tkm) by plus or minus 10%, LCA energy use decreases by 8.3% (1.5316271 MJ/tkm) and increases by 8.3% (1.8088403 MJ/tkm), respectively, as shown in Table 6.25. The LCA energy use results are not just influenced by the crude oil refining parameter but also from advanced vehicle technologies and fuel resources.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/Tkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/Tkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.6702337 | 0 | 0 | |
| **Average Load** | 1.8558152 | 11.1 | 1.5183943 | 9.1 |
| **Kilometres Travelled** | 1.8479549 | 10.6 | 1.5248255 | 8.7 |
| **Fraction Load Factor** | 1.8479549 | 10.64 | 1.5248255 | 8.71 |
| **Fuel Consumption** | 1.5102847 | 9.6 | 1.8301827 | 9.6 |
| **Crude Oil Refining** | 1.5316271 | 8.30 | 1.8088403 | 8.30 |
| **Crude Oil Extraction** | 1.629949 | 2.41 | 1.7105184 | 2.41 |
| **Vehicle Maintenance** | 1.6666144 | 0.22 | 1.673853 | 0.22 |
| **Vehicle Manufacture** | 1.6667908 | 0.2 | 1.6736766 | 0.2 |
| **Vehicle Disposal** | 1.6702216 | 0.001 | 1.6702458 | 0.001 |

**Table 6.25: Summary of Sensitivity Analysis for LCA of Hybrid Articulated Trucks (energy use)**

Other parameters, including crude oil extraction, truck manufacture, truck maintenance and disposal, can be ignored because they have little impact on the overall LCA energy use results.

### 6.1.3 Particulate Matter Category (kg/pkm)

#### *6.1.3.1 Passenger Vehicles*

The influence of assumptions, parameters and factors varies depending on vehicle types (whether they are conventional or alternative). The passenger occupancy rate and kilometres travelled factor significantly impact the LCA results of conventional vehicles, while the parameters of electricity mix consumption and production are more relevant to the LCA results of advanced vehicle technologies. For instance, for **petrol passenger vehicles**, when the values of passenger occupancy rate, kilometres travelled and fuel economy decrease and increase by 10% from the reference value, as shown in Table 6.26, LCA PM emissions change as outlined below:

1. Occupancy rate: LCA PM emissions increase by 11.1% (0.000108216 kg/pkm) and decrease by 9.1% (8.85E-05 kg/pkm) from the reference value (9.74E-05 kg/pkm).
2. Kilometres travelled: LCA PM emissions increase by 9.7% (0.000106857 kg/pkm) and decrease by 7.7% (8.97E-05kg/pkm) from the reference value (9.74E-05 kg/pkm).
3. Fuel consumption: LCA PM emissions decrease by 8.7% (8.89E-05 kg/pkm) and increase by 8.7% (0.000105911 kg/pkm) from the reference value (9.74E-05 kg/pkm).

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 9.74E-05 | 0 | 0 |  |
| **Occupancy Rate** | 0.000108216 | 11.1 | 8.85E-05 | 9.1 |
| **Kilometres Travelled** | 0.000106857 | 9.7 | 8.97E-05 | 7.7 |
| **Fuel Consumption** | 8.89E-05 | 8.7 | 0.000105911 | 8.7 |
| **Vehicle Manufacture** | 9.64E-05 | 1.0 | 9.84E-05 | 1.0 |
| **Crude Oil Refining** | 9.72E-05 | 0.21 | 9.76E-05 | 0.21 |
| **Vehicle Maintenance** | 9.72E-05 | 0.21 | 9.76E-05 | 0.21 |
| **Crude Oil Extraction** | 9.73E-05 | 0.10 | 9.75E-05 | 0.10 |
| **Vehicle Disposal** | 9.74E-05 | 0.001 | 9.74E-05 | 0.001 |

**Table 6.26: Summary of Sensitivity Analysis for LCA of Petrol Passenger Vehicles (PM)**

On the other hand, for **BEVs,** when the parameters electricity mix consumption and production decrease and increase by 10% from the base value, LCA PM emissions (in kg/pkm), as shown in Table 6.27, change as explained below:

1. Electricity mix consumption: LCA PM emissions decrease by 3.01% (3.54E-05) and increase by 2.74% (3.75E-05) from the reference value (3.65E-05).
2. Electricity mix production: LCA PM emissions decrease by 2.74% (3.55E-05) and increase by 2.47% (3.74E-05) from the reference value (3.65E-05).

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 3.65E-05 | 0 | 0 | |
| **Occupancy Rate** | 4.05E-05 | 11.0 | 3.32E-05 | 9.0 |
| **Kilometres Travelled** | 3.76E-05 | 3.0 | 3.55E-05 | 2.7 |
| **Electricity Mix Consumption** | 3.54E-05 | 3.01 | 3.75E-05 | 2.74 |
| **Vehicle Manufacture** | 3.54E-05 | 3.01 | 3.75E-05 | 2.74 |
| **Vehicle Maintenance** | 3.54E-05 | 3.01 | 3.75E-05 | 2.74 |
| **Electricity Mix Production** | 3.55E-05 | 2.74 | 3.74E-05 | 2.47 |
| **Vehicle Disposal** | 3.63E-05 | 0.55 | 3.66E-05 | 0.27 |

**Table 6.27: Summary of Sensitivity Analysis for LCA of BEVs (PM)**

Furthermore, the parameter of vehicle manufacture has a considerable impact on LCA results. For instance, in the case of BEVs, when this parameter's value deviates by plus or minus 10% from the reference value (3.65E-05), LCA PM emissions (kg/pkm) increase by 2.74% (3.75E-05) and decrease by 3.01% (3.54E-05), respectively, as shown in Table 6.27 above. Furthermore, the parameter of vehicle maintenance has a large effect on output results. For instance, for **BEVs,** when this parameter varies by plus or minus 10% from the base value (3.65E-05), LCA PM emissions increase by 2.74% (3.75E-05) and decrease by 3.01% (3.54E-05), respectively, as shown in Table 6.27 above. Additionally, for **LPG vehicles**, the impact of the LPG production parameter (in kg) on output results can be seen: when the value decreases and increases by 10% from the base value (2.49E-05), the total LCA PM emissions (kg/pkm) decrease by 4.42% (2.38E-05) and increase by 4.02% (2.59E-05), respectively, as shown in Table 6.28. These situations can be explained because LCA results are not just affected by the above parameters: there are other factors, including fuel production, electricity generation and advanced vehicles, which can impact on LCA results.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 2.49E-05 | 0 | 0 | |
| **Occupancy Rate** | 2.76E-05 | 10.8 | 2.26E-05 | 9.2 |
| **Kilometres Travelled** | 2.63E-05 | 5.6 | 2.37E-05 | 4.8 |
| **Fuel Consumption** | 2.36E-05 | 5.2 | 2.61E-05 | 4.8 |
| **LPG Production** | 2.38E-05 | 4.42 | 2.49E-05 | 4.02 |
| **Vehicle Manufacture** | 2.38E-05 | 4.4 | 2.59E-05 | 4.0 |
| **Vehicle Maintenance** | 2.47E-05 | 0.80 | 2.50E-05 | 0.40 |
| **Vehicle Disposal** | 2.48E-05 | 0.40 | 2.49E-05 | 0.00 |
| **LPG Processing** | 2.49E-05 | 0.001 | 2.49E-05 | 0.001 |

**Table 6.28: Summary of Sensitivity Analysis for LCA of LPG Vehicles (PM)**

Finally, other parameters including crude oil extraction and refining, LPG processing, hydrogen production and processing and vehicle disposal have much smaller impacts on LCA PM emissions so that their effect on outcome results can be ignored.

### *6.1.1.2 Public Transport Buses*

Most assumptions, parameters and factors that are input in the life cycle approach in both conventional and advanced bus technologies have significant impacts on LCA results. The first factor, passenger occupancy rate, has the largest effect on LCA particulate matter emissions results, followed by kilometres travelled factor, then fuel consumption parameters. For instance, **in conventional LSD buses** when these parameters are decreased and increased by

10% from the reference value, the LCA PM emissions will change respectively, as shown in Table 6.29 and as listed below:

1. Passenger occupancy rate decreases by 11% (5.93E-05 kg/pkm) and increases by 9.2% (4.85E-05 kg/pkm) from the reference value (5.34E-05 kg/pkm).
2. Kilometres travelled decreases by 10.1% (5.88E-05 kg/pkm) and increases by 8.2% (4.90E-05 kg/pkm) from the reference value (5.34E-05 kg/pkm).
3. Fuel consumption decreases by 9.2% (4.85E-05 kg/pkm) and increases by 9% (5.82E-05 kg/pkm) from the reference value (5.34E-05 kg/pkm).

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 5.34E-05 | 0 | 0 | |
| **Occupancy Rate** | 5.93E-05 | 11.0 | 4.85E-05 | 9.2 |
| **Kilometres Travelled** | 5.88E-05 | 10.1 | 4.90E-05 | 8.2 |
| **Fuel Consumption** | 4.85E-05 | 9.2 | 5.82E-05 | 9.0 |
| **Crude Oil Refining** | 5.31E-05 | 0.56 | 5.37E-05 | 0.56 |
| **Vehicle Manufacture** | 5.31E-05 | 0.6 | 5.37E-05 | 0.6 |
| **Vehicle Maintenance** | 5.32E-05 | 0.37 | 5.35E-05 | 0.19 |
| **Crude Oil Extraction** | 5.34E-05 | 0.001 | 5.34E-05 | 0.001 |
| **Vehicle Disposal** | 5.34E-05 | 0.001 | 5.34E-05 | 0.001 |

**Table 6.29: Summary of Sensitivity Analysis for LCA of LSD Buses (PM)**

On the other hand, in **battery electric buses**, electricity grid impact and bus manufacture parameters have much higher effects on overall LCA PM emissions. For instance, when electricity grid consumption, electricity mix production and bus manufacture are decreased and increased by 10% from the reference value, the LCA PM emissions will change respectively, as shown in Table 6.30 and as listed below:

1. Electricity grid consumption LCA PM emissions (in kg/pkm) will decrease by 5.4% (1.39E-05) and increase by 4.8% (1.54E-05) on base value (1.47E-05).
2. Electricity mix production LCA PM emissions (in kg/pkm) will decrease by 4.76% (1.40E-05) and increase by 4.76% (1.54E-05) on base value (1.47E-05).
3. Vehicle manufacture LCA PM emissions (in kg/pkm) will decrease by 2.04% (1.44E-05) and increase by 1.36% (1.49E-05) on base value (1.47E-05).

This case can be explained as follows: although LCA PM emissions are affected by the parameter's electricity impact and bus manufacture, there are also other different impacts that come from different factors such as electricity generation from non-renewable fuel or bus manufacture processing.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.47E-05 | 0 | 0 | |
| **Occupancy Rate** | 1.63E-05 | 10.9 | 1.33E-05 | 9.5 |
| **Kilometres Travelled** | 1.55E-05 | 5.4 | 1.40E-05 | 4.8 |
| **Electricity Grid Consumption** | 1.39E-05 | 5.4 | 1.54E-05 | 4.8 |
| **Electricity Mix Production** | 1.40E-05 | 4.76 | 1.54E-05 | 4.76 |
| **Vehicle Maintenance** | 1.42E-05 | 3.4 | 1.51E-05 | 2.7 |
| **Vehicle Manufacture** | 1.44E-05 | 2.04 | 1.49E-05 | 1.36 |
| **Vehicle Disposal** | 1.46E-05 | 0.68 | 1.47E-05 | 0.00 |

**Table 6.30: Summary of Sensitivity Analysis for LCA of Battery Electric Buses (PM)**

Furthermore, the impact of LPG production parameter on LCA PM emissions can be seen clearly. For instance, in **LPG buses** when this parameter is decreased and increased by 10% on base value, LCA PM emissions (in kg/pkm) will decrease by 3.41% (7.65E-06) and increase by 3.41% (8.18E-06) on base value (7.92E-06), as shown in Table 6.31. This is due to producing LPG from fossil energy (crude oil).

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 7.92E-06 | 0 | 0 | |
| **Occupancy Rate** | 8.80E-06 | 11.1 | 7.20E-06 | 9.1 |
| **Kilometres Travelled** | 8.27E-06 | 4.4 | 7.63E-06 | 3.7 |
| **Vehicle Manufacture** | 7.59E-06 | 4.2 | 8.24E-06 | 4.0 |
| **Fuel Consumption** | 7.60E-06 | 4.0 | 8.23E-06 | 3.9 |
| **LPG Production** | 7.65E-06 | 3.41 | 8.18E-06 | 3.41 |
| **Vehicle Maintenance** | 7.77E-06 | 1.89 | 8.06E-06 | 1.77 |
| **Vehicle Disposal** | 7.92E-06 | 0.001 | 7.92E-06 | 0.001 |
| **LPG Processing** | 7.92E-06 | 0.001 | 7.92E-06 | 0.001 |

**Table 6.31: Summary of Sensitivity Analysis for LCA of LPG Buses (PM)**

Finally, other parameters including crude oil extraction and refining, LPG processing, hydrogen production and processing, bus maintenance and disposal, have much smaller impacts on overall LCA PM emissions results.

### *6.1.3.3 Heavy-duty Truck Vehicles*

Generally, the parameters, assumptions and factors, such as average load, kilometres travelled, fraction load and fuel economy, have significant impacts on the overall LCA PM emissions in the cases of both rigid and articulated heavy-duty truck vehicles. For instance, for **LSD rigid**

**trucks,** when these factors decrease and increase by 10% from the reference value, the LCA PM emissions (kg/pkm) change, respectively, as shown in Table 6.32 and as outlined below:

1. Average load: LCA PM emissions (kg/pkm) increase by 11.1% (0.000285769) and decrease by 9.1% (0.000233811) from the base value (0.000257192).
2. Kilometres travelled: LCA PM emissions (kg/pkm) increase by 10.6% (0.00028457) and decrease by 8.7% (0.000234792) from the base value (0.000257192).
3. Fraction load: LCA PM emissions (kg/pkm) increase by 10.64% (0.00028457) and decrease by 8.71% (0.000234792) from the base value (0.000257192).
4. Fuel consumption: LCA PM emissions (in kg/pkm) decrease by 9.6% (0.000232552) and increase by 9.6% (0.000281832) from the base value (1.47E-05).

Although all the factors mentioned above significantly impact the LCA results, the kilometres travelled factor has a major effect on the overall LCA results.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/tkm) (kg/tkm)** | **Change (%)** | **Particulate Matter (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.000257192 | 0 | 0 | |
| **Average Load** | 0.000285769 | 11.1 | 0.000233811 | 9.1 |
| **Kilometres Travelled** | 0.00028457 | 10.6 | 0.000234792 | 8.7 |
| **Fraction Load Factor** | 0.00028457 | 10.64 | 0.000234792 | 8.71 |
| **Fuel Consumption** | 0.000232552 | 9.6 | 0.000281832 | 9.6 |
| **Crude Oil Refining** | 0.000255612 | 0.61 | 0.000258772 | 0.61 |
| **Vehicle Manufacture** | 0.000256523 | 0.3 | 0.000257861 | 0.3 |
| **Vehicle Maintenance** | 0.000256784 | 0.16 | 0.0002576 | 0.16 |
| **Crude Oil Extraction** | 0.000257068 | 0.05 | 0.000257316 | 0.05 |
| **Vehicle Disposal** | 0.00025719 | 0.001 | 0.000257194 | 0.001 |

**Table 6.32: Summary of Sensitivity Analysis for LCA of LSD Rigid Trucks (PM)**

Added to that, both the parameters electricity grid consumption and electricity mix production have significant effects on LCA PM emissions in the case of advanced trucks. For instance, for **articulated battery trucks,** when these parameters decrease and increase by 10% from their base values, LCA PM emissions (kg/pkm) change, respectively, as shown in Table 6.33 and as detailed below:

1. Electricity mix consumption: LCA PM emissions (kg/pkm) decrease by 8% (8.42E-06) and increase by 7.9% (9.87E-06) from the base value (0.000257192).
2. Electricity mix production: LCA PM emissions (kg/pkm) decrease by 7.43% (8.47E-06) and increase by 7.32% (9.82E-06) from the base value (9.15E-06).

This is because although the parameter of electricity grid consumption has a significant effect on output, factors related to electricity resources can also influence LCA results.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/tkm)** | **Change (%)** | **Particulate Matter (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 9.15E-06 | 0 | 0 | |
| **Average Load** | 1.02E-05 | 11.5 | 8.32E-06 | 9.1 |
| **Kilometres Travelled** | 9.95E-06 | 8.7 | 8.49E-06 | 7.2 |
| **Fraction Load Factor** | 9.95E-06 | 8.74 | 8.49E-06 | 7.21 |
| **Electricity Mix Consumption** | 8.42E-06 | 8.0 | 9.87E-06 | 7.9 |
| **Electricity Mix Production** | 8.47E-06 | 7.43 | 9.82E-06 | 7.32 |
| **Vehicle Manufacture** | 9.02E-06 | 1.4 | 9.28E-06 | 1.4 |
| **Vehicle Maintenance** | 9.09E-06 | 0.66 | 9.20E-06 | 0.55 |
| **Vehicle Disposal** | 9.15E-06 | 0.001 | 9.15E-06 | 0.001 |

**Table 6.33: Summary of Sensitivity Analysis for LCA of Electric Articulated Trucks (PM)**

The influence of other parameters on the LCA results for electric articulated trucks, including truck maintenance and disposal and crude oil extraction and refining, have been ignored due to their much lower impacts on life cycle modelling.

### 6.1.4 Human Toxicity-Cancer and Non-Cancer Categories (kg/pkm)

#### *6.1.4.1 Passenger Vehicles*

Most assumptions, parameters and factors that are input into the life cycle model calculations for passenger vehicles have little effect on LCA human toxicity-cancer (HTc) and human toxicity non-cancer (HTnc). However, passenger occupancy rate and the vehicle manufacture parameter have significant impacts on LCA HTc and HTnc emissions. For instance, in the case of **hybrid electric vehicles** (HEVs), when the passenger occupancy rate decreases and increases by 10% from the reference values (1.58E-09 and 7.83E-09), LCA HTc and HTnc emissions (kg/pkm) increase by 11.4% (1.76E-09) and 11.1% (8.70E-09) and decrease by 8.9% (1.44E-09) and 9.1% (7.12E-09), respectively. Also, **for HEVs,** when the vehicle manufacture value deviates by plus or minus 10% from the base value, LCA HTc and HTnc emissions (in kg/pkm) will increase by 8.9% (1.72E-09) and 6.9% (8.37E-09) from the reference values (1.58E-09 and 7.83E-09) and decrease by 8.9% (1.44E-09) and 6.8% (7.30E-09), respectively, as shown in Tables 6.34 and 6.35. The vehicle manufacture phase contributes significantly to the overall LCA HTc and HTnc, but the degree of impact depends heavily on other factors, such as fuel feedstock, advanced vehicle technology, vehicle powertrain efficiency and driving behaviour (skills). Therefore, although the parameters of vehicle manufacture and passenger occupancy rate have significant impacts on LCA HTc and HTnc, there are many other factors that directly impact the outcomes.

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Human Toxicity, Cancer (kg/pkm) | Change (%) | Human Toxicity, Cancer (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 1.58E-09 | 0 | 0 | |
| **Occupancy Rate** | 1.76E-09 | 11.4 | 1.44E-09 | 8.9 |
| **Vehicle Manufacture** | 1.44E-09 | 8.9 | 1.72E-09 | 8.9 |
| **Kilometres Travelled** | 1.59E-09 | 0.6 | 1.57E-09 | 0.6 |
| **Fuel Consumption** | 1.57E-09 | 0.6 | 1.59E-09 | 0.6 |
| **Vehicle Maintenance** | 1.57E-09 | 0.63 | 1.59E-09 | 0.63 |
| **Crude Oil Refining** | 1.58E-09 | 0.00 | 1.58E-09 | 0.00 |
| **Crude Oil Extraction** | 1.58E-09 | 0.00 | 1.58E-09 | 0.00 |
| **Vehicle Disposal** | 1.58E-09 | 0.00 | 1.58E-09 | 0.00 |

**Table 6.34: Summary of Sensitivity Analysis for LCA of HEVs (HTc)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Human Toxicity, Non-Cancer (kg/pkm) | Change (%) | Human Toxicity, Non-Cancer (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 7.83E-09 | 0 | 0 | |
| **Occupancy Rate** | 8.70E-09 | 11.1 | 7.12E-09 | 9.1 |
| **Vehicle Manufacture** | 7.30E-09 | 6.8 | 8.37E-09 | 6.9 |
| **Vehicle Maintenance** | 7.73E-09 | 1.28 | 7.94E-09 | 1.40 |
| **Kilometres Travelled** | 7.92E-09 | 1.1 | 7.76E-09 | 0.9 |
| **Fuel Consumption** | 7.76E-09 | 0.9 | 7.91E-09 | 1.0 |
| **Vehicle Disposal** | 7.76E-09 | 0.89 | 7.90E-09 | 0.89 |
| **Crude Oil Refining** | 7.82E-09 | 0.13 | 7.85E-09 | 0.26 |
| **Crude Oil Extraction** | 7.82E-09 | 0.13 | 7.84E-09 | 0.13 |

**Table 6.35: Summary of Sensitivity Analysis for LCA of HEVs (HTnc)**

In addition, although the parameter of vehicle maintenance has a small effect on the LCA HTc and HTnc results, their impact on the LCA results is more pronounced in the case of advanced vehicle technologies. For instance, for **PHEVs,** when the vehicle maintenance parameter ( in MJ) decreases and increases by 10% from the base value, LCA HTc and HTnc emissions (kg/pkm) decrease by 1.29% (2.30E-09) and 3.45% (2.52E-08) and increase by 1.7% (2.37E-09) and 3.45% (2.70E-08) from their base values (2.33E-09 and 2.61E-08), respectively, as shown in Tables 6.36 and 6.37. The reason that the maintenance phase for advanced vehicles has such an impact on LCA results compared to conventional vehicles is that advanced vehicles need more servicing and maintenance.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 2.33E-09 | 0 | 0 | |
| **Occupancy Rate** | 2.59E-09 | 11.2 | 2.12E-09 | 9.0 |
| **Vehicle Manufacture** | 2.16E-09 | 7.30 | 2.51E-09 | 7.73 |
| **Vehicle Maintenance** | 2.30E-09 | 1.29 | 2.37E-09 | 1.72 |
| **Kilometres Travelled** | 2.35E-09 | 0.9 | 2.32E-09 | 0.4 |
| **Electricity Grid Consumption** | 2.32E-09 | 0.43 | 2.35E-09 | 0.86 |
| **Fuel Consumption** | 2.33E-09 | 0.01 | 2.34E-09 | 0.4 |
| **Electricity Grid Mix Production** | 2.33E-09 | 0.001 | 2.34E-09 | 0.43 |
| **Vehicle Disposal** | 2.33E-09 | 0.001 | 2.34E-09 | 0.43 |
| **Crude Oil Refining** | 2.33E-09 | 0.001 | 2.33E-09 | 0.001 |
| **Crude Oil Extraction** | 2.33E-09 | 0.001 | 2.33E-09 | 0.001 |

**Table 6.36: Summary of Sensitivity Analysis for LCA of PHEVs (HTc)**

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 2.61E-08 | 0 | 0 | |
| **Occupancy Rate** | 2.90E-08 | 11.1 | 2.37E-08 | 9.2 |
| **Vehicle Manufacture** | 2.48E-08 | 4.98 | 2.74E-08 | 4.98 |
| **Vehicle Maintenance** | 2.52E-08 | 3.45 | 2.70E-08 | 3.45 |
| **Kilometres Travelled** | 2.64E-08 | 1.1 | 2.58E-08 | 1.1 |
| **Electricity Grid Consumption** | 2.58E-08 | 1.15 | 2.64E-08 | 1.15 |
| **Electricity Grid Mix Production** | 2.59E-08 | 0.77 | 2.63E-08 | 0.77 |
| **Vehicle Disposal** | 2.60E-08 | 0.38 | 2.62E-08 | 0.38 |
| **Fuel Consumption** | 2.61E-08 | 0.01 | 2.61E-08 | 0.01 |
| **Crude Oil Refining** | 2.61E-08 | 0.001 | 2.61E-08 | 0.001 |
| **Crude Oil Extraction** | 2.61E-08 | 0.001 | 2.61E-08 | 0.001 |

**Table 6.37: Summary of Sensitivity Analysis for LCA of PHEVs (HTnc)**

Other parameters, including crude oil extraction, LPG processing, hydrogen production and processing and vehicle disposal, have much smaller impacts on LCA results, so their effects on the overall LCA results can be ignored.

#### *6.1.4.2 Public Transport Buses*

Public transport buses' LCA HTc and HTnc are affected by many assumptions, parameters and factors. As with passenger vehicles, the passenger occupancy rate is considered the most influential factor, followed by the parameter of bus manufacture. For instance, in the case of **LSD buses,** when the passenger occupancy rate decreases and increases by 10% from the reference value, LCA HTc and HTnc emissions (in kg/pkm) increase by 11.1% (4.90E-10 kg/pkm) and 11.5% (2.52E-09 kg/pkm) and decrease by 9.1% (4.01E-10 kg/pkm) and 8.8% (2.06E-09 kg/pkm) from the reference values (4.41E-10 kg/pkm and (2.26E-09 kg/pkm), respectively. Additionally, **for LSD buses,** LCA HTc and HTnc decrease by 8.6% (4.03E-10 kg/pkm) and 5.3% (2.14E-09 kg/pkm) and increase by 8.6% (4.79E-10 kg/pkm) and 5.8% (2.39E-09 kg/pkm) from the base value when the bus manufacture value (in volumetric measurement unit) decreases and increases by 10% from the base value, as shown in Tables 6.38 and 6.39. Many emissions that can threaten human health are released during the vehicle manufacture phase, but there are other factors, including fuel production and vehicle technologies, that can also impact the LCA HTc and HTnc results.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 4.41E-10 | 0 | 0 | |
| **Occupancy Rate** | 4.90E-10 | 11.1 | 4.01E-10 | 9.1 |
| **Vehicle Manufacture** | 4.03E-10 | 8.6 | 4.79E-10 | 8.6 |
| **Kilometres Travelled** | 4.44E-10 | 0.7 | 4.38E-10 | 0.7 |
| **Fuel Consumption** | 4.38E-10 | 0.7 | 4.44E-10 | 0.7 |
| **Vehicle Maintenance** | 4.38E-10 | 0.68 | 4.44E-10 | 0.68 |
| **Crude Oil Refining** | 4.39E-10 | 0.45 | 4.43E-10 | 0.45 |
| **Crude oil Extraction** | 4.41E-10 | 0.001 | 4.41E-10 | 0.001 |
| **Vehicle Disposal** | 4.41E-10 | 0.001 | 4.41E-10 | 0.001 |

**Table 6.38: Summary of Sensitivity Analysis for LCA of LSD Buses (HTc)**

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 2.26E-09 | 0 | 0 |  |
| **Occupancy Rate** | 2.52E-09 | 11.5 | 2.06E-09 | 8.8 |
| **Vehicle Manufacture** | 2.14E-09 | 5.3 | 2.39E-09 | 5.8 |
| **Vehicle Maintenance** | 2.19E-09 | 3.10 | 2.34E-09 | 3.54 |
| **Kilometres Travelled** | 2.29E-09 | 1.3 | 2.24E-09 | 0.9 |
| **Fuel Consumption** | 2.24E-09 | 0.9 | 2.29E-09 | 1.3 |
| **Crude Oil Refining** | 2.25E-09 | 0.44 | 2.28E-09 | 0.88 |
| **Crude Oil Extraction** | 2.26E-09 | 0.001 | 2.27E-09 | 0.44 |
| **Vehicle Disposal** | 2.26E-09 | 0.001 | 2.26E-09 | 0.001 |

**Table 6.39: Summary of Sensitivity Analysis for LCA of LSD Buses (HTnc)**

In the case of advanced bus technologies, including **battery electric buses**, the assumptions, parameters and factors, such as kilometres travelled, electricity consumption and electricity production, can have noticeable impacts on the LCA results. For instance, when the kilometres travelled factor is changed from case A to case B, LCA HTc and HTnc emissions decrease by 2.4% (6.89E-10 kg/pkm) and 4.9% (6.44E-09 kg/pkm), respectively, and increase by 1.9% (6.60E-10 kg/pkm) and 4.1% (5.89E-09 kg/pkm) from the reference values (6.73E-10 kg/pkm and 6.14E-09 kg/pkm), respectively. Added to that, when the electricity mix consumption parameter (in kwh/km) decreases and increases by 10% from the base value, LCA HTc and HTnc emissions decrease by 2.1% (6.59E-10 kg/pkm) and 4.4% (5.87E-09 kg/pkm) and will increase by 2.1% (6.87E-10 kg/pkm) and 4.4% (6.41E-09 kg/pkm) from the reference values (6.73E-10 kg/pkm and 6.14E-09 kg/pkm), respectively. Moreover, when the electricity mix production parameter (in kwh/MJ) decreases and increases by 10% from the base value, LCA

HTc and HTnc decreases by 0.89% (6.67E-10 kg/pkm) and 3.58% (5.92E-09 kg/pkm), and increases by 1.04% (6.80E-10 kg/pkm) and 3.42% (6.35E-09 kg/pkm) from the base values (6.73E-10 kg/pkm and 6.14E-09 kg/pkm), respectively, as shown in Tables 6.40 and 6.41. The parameters of electricity mix consumption and production can have direct impacts on the LCA results, but there are also other impacts arising from parameters related to fuel resources and advanced vehicle technology.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 6.73E-10 | 0 | 0 | |
| **Occupancy Rate** | 7.48E-10 | 11.1 | 6.12E-10 | 9.1 |
| **Vehicle Manufacture** | 6.27E-10 | 6.8 | 7.19E-10 | 6.8 |
| **Kilometres Travelled** | 6.89E-10 | 2.4 | 6.60E-10 | 1.9 |
| **Electricity Mix Consumption** | 6.59E-10 | 2.1 | 6.87E-10 | 2.1 |
| **Vehicle Maintenance** | 6.66E-10 | 1.04 | 6.80E-10 | 1.04 |
| **Electricity Mix Production** | 6.67E-10 | 0.89 | 6.80E-10 | 1.04 |
| **Vehicle Disposal** | 6.73E-10 | 0.001 | 6.73E-10 | 0.001 |

**Table 6.40: Summary of Sensitivity Analysis for LCA of Battery Electric Buses (HTc)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 6.14E-09 | 0 | 0 | |
| **Occupancy Rate** | 6.82E-09 | 11.1 | 5.58E-09 | 9.1 |
| **Kilometres Travelled** | 6.44E-09 | 4.9 | 5.89E-09 | 4.1 |
| **Electricity Mix Consumption** | 5.87E-09 | 4.4 | 6.41E-09 | 4.4 |
| **Electricity Mix Production** | 5.92E-09 | 3.58 | 6.35E-09 | 3.42 |
| **Vehicle Manufacture** | 5.93E-09 | 3.4 | 6.35E-09 | 3.4 |
| **Vehicle Maintenance** | 6.01E-09 | 2.12 | 6.27E-09 | 2.12 |
| **Vehicle Disposal** | 6.14E-09 | 0.001 | 6.14E-09 | 0.001 |

**Table 6.41: Summary of Sensitivity Analysis for LCA of Battery Electric Buses (HTnc)**

Finally, although there are many other parameters, assumptions and factors, including fuel consumption, crude oil extraction and refining, and vehicle maintenance and disposal, which affect LCA results, they are ignored due to their low impact on HTc and HTnc emissions over a bus's lifetime.

### *6.1.4.3 Heavy-duty Truck Vehicles*

The factor of average load significantly impacts LCA HTc and HTnc. For instance, in the case of **rigid hybrid trucks,** when the average load factor (in tonnes) decreases and increases by 10% from the base value, LCA HTc and HTnc emissions (in kg/tkm) increase by 11% (1.72E-09 kg/tkm) and 11.1% (9.31E-09 kg/tkm) and decrease by 9% (1.41E-09 kg/tkm) and 9.1% (7.62E-09 kg/tkm) from their base values (1.55E-09 kg/tkm and 8.38E-09 kg/tkm), respectively. In addition, the parameter of truck manufacture also has a significant effect on

LCA results. For instance, **for hybrid rigid trucks,** when the bus manufacture value (in volumetric measurement unit) decreases or increases by 10% from the base value, LCA HTc and HTnc (in kg/tkm) decrease by 7.1% (1.44E-09 kg/tkm) and 5.4% (7.93E-09 kg/tkm) and increase by 7.1% (1.66E-09 kg/tkm) and 5.5% (8.84E-09 kg/tkm) from the base values (1.55E-09 kg/tkm and 8.38E-09 kg/tkm), respectively, as shown in Tables 6.42 and 6.43.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/tkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.55E-09 | 0 | 0 | |
| **Average Load** | 1.72E-09 | 11.0 | 1.41E-09 | 9.0 |
| **Vehicle Manufacture** | 1.44E-09 | 7.1 | 1.66E-09 | 7.1 |
| **Fuel Consumption** | 1.52E-09 | 1.9 | 1.58E-09 | 1.9 |
| **Kilometres Travelled** | 1.58E-09 | 1.9 | 1.52E-09 | 1.9 |
| **Fraction Load Factor** | 1.58E-09 | 1.94 | 1.52E-09 | 1.94 |
| **Crude Oil Refining** | 1.53E-09 | 1.29 | 1.57E-09 | 1.29 |
| **Vehicle Maintenance** | 1.54E-09 | 0.65 | 1.56E-09 | 0.65 |
| **Crude Oil Extraction** | 1.55E-09 | 0.001 | 1.55E-09 | 0.001 |
| **Vehicle Disposal** | 1.55E-09 | 0.001 | 1.55E-09 | 0.001 |

**Table 6.42: Summary of Sensitivity Analysis for LCA of Hybrid Rigid Trucks (HTc)**

| | **10% decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Non-Cancer (kg/tkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 8.38E-09 | 0 | 0 | |
| **Average Load** | 9.31E-09 | 11.1 | 7.62E-09 | 9.1 |
| **Vehicle Manufacture** | 7.93E-09 | 5.4 | 8.84E-09 | 5.5 |
| **Fuel Consumption** | 8.67E-09 | 3.5 | 8.15E-09 | 2.7 |
| **Kilometres Travelled** | 8.67E-09 | 3.46 | 8.15E-09 | 2.74 |
| **Fraction Load Factor** | 8.13E-09 | 3.0 | 8.64E-09 | 3.1 |
| **Crude Oil Refining** | 8.23E-09 | 1.79 | 8.53E-09 | 1.79 |
| **Vehicle Maintenance** | 8.29E-09 | 1.07 | 8.47E-09 | 1.07 |
| **Vehicle Disposal** | 8.35E-09 | 0.36 | 8.42E-09 | 0.48 |
| **Crude Oil Extraction** | 8.37E-09 | 0.12 | 8.40E-09 | 0.24 |

**Table 6.43: Summary of Sensitivity Analysis for LCA of Hybrid Rigid Trucks (HTnc)**

Moreover, the fraction load factor significantly affects the output results. For instance, **in the case of battery electric articulated trucks,** when the fraction load factor decreases or increases by 10% from the reference value (0.6), LCA HTc and HTnc emissions (in kg/tkm) increase by 4.64% (3.38E-10 kg/tkm) and 8.19% (3.83E-09 kg/tkm), and decrease by 4% (3.10E-10 kg/tkm) and 6.78% (3.30E-09 kg/pkm) from the base values (3.23E-10 kg/pkm and 3.54E-09 kg/tkm), respectively, as shown in Tables 6.44 and 6.45. The factors of average load and fraction load and the parameter of vehicle manufacture significantly impact the LCA HTc and HTnc results; however, there are other influential factors, namely, fuel resources, electricity generation and advanced vehicles.

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Human Toxicity, Cancer (kg/tkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 3.23E-10 | 0 | 0 |  |
| **Average Load** | 3.59E-10 | 11.1 | 2.93E-10 | 9.3 |
| **Vehicle Manufacture** | 3.06E-10 | 5.3 | 3.40E-10 | 5.3 |
| **Kilometres Travelled** | 3.38E-10 | 4.6 | 3.10E-10 | 4.0 |
| **Fraction Load Factor** | 3.38E-10 | 4.64 | 3.10E-10 | 4.02 |
| **Electricity Mix Consumption** | 3.09E-10 | 4.3 | 3.36E-10 | 4.0 |
| **Electricity Mix Production** | 3.17E-10 | 1.86 | 3.29E-10 | 1.86 |
| **Vehicle Maintenance** | 3.21E-10 | 0.62 | 3.24E-10 | 0.31 |
| **Vehicle Disposal** | 3.23E-10 | 0.001 | 3.23E-10 | 0.001 |

**Table 6.44: Summary of Sensitivity Analysis for LCA of Electric Articulated Trucks (HTc)**

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Human Toxicity, Non-Cancer (kg/tkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/tkm)** | **Change (%)** |
| **Reference Value (Base)** | 3.54E-09 | 0 | 0 |  |
| **Average Load** | 3.93E-09 | 11.0 | 3.22E-09 | 9.0 |
| **Kilometres Travelled** | 3.83E-09 | 8.2 | 3.30E-09 | 6.8 |
| **Fraction Load Factor** | 3.83E-09 | 8.19 | 3.30E-09 | 6.78 |
| **Electricity Mix Consumption** | 3.28E-09 | 7.3 | 3.80E-09 | 7.3 |
| **Electricity Mix Production** | 3.33E-09 | 5.93 | 3.74E-09 | 5.65 |
| **Vehicle Manufacture** | 3.46E-09 | 2.3 | 3.62E-09 | 2.3 |
| **Vehicle Maintenance** | 3.53E-09 | 0.28 | 3.55E-09 | 0.28 |
| **Vehicle Disposal** | 3.53E-09 | 0.28 | 3.54E-09 | 0.00 |

**Table 6.45: Summary of Sensitivity Analysis for LCA of Electric Articulated Trucks (HTnc)**

Added to that, the parameter of electricity grid mix consumption has a significant effect on the outcome. For instance, in the case of **battery electric articulated trucks,** when both electricity grid mix consumption (in kwh/tkm) and electricity grid mix production (in kwh/MJ) decrease and increased by 10% from their base values, as shown in Tables 6.44 and 6.45 above, LCA HTc and HTnc (in kg/tkm) change respectively, as listed below:

1. Electricity mix consumption decreases by 4.3% (3.09E-10 kg/pkm) and 7.3% (3.28E-09 kg/pkm) and increases by 4.3% (3.36E-10 kg/pkm) and 7.3% (3.80E-09 kg/pkm) from the reference values (3.23E-10 kg/pkm and 3.54E-09 kg/pkm).
2. Electricity mix production decreases by 1.86% (3.17E-10 kg/pkm) and 5.93% (3.33E-09 kg/pkm) and increases by 1.86% (3.29E-10 kg/pkm) and 5.93% (3.74E-09 kg/pkm) from the reference values (3.23E-10 kg/pkm and 3.54E-09 kg/pkm).

Finally, other parameters, such as crude oil extraction and refining, truck maintenance and disposal, and fuel consumption, have much smaller impacts on LCA HTn and HTnc emissions, so their effects can be ignored.

## 6.2 Discussion of Results

A sensitivity analysis determines if a small change to a parameter can considerably influence the result, or if it contributes to the variance of the output. It can also help to identify parameters that should be known accurately and reliably before drawing any conclusions or to flag non-sensitive parameters where the variance can be fixed in the region of said variance in order to simplify the model (Groen et al., 2014). This technique has been included in this study to show the impact of assumptions on the overall LCA results. Here, the sensitivity analysis revealed the importance of a vehicle's operational emissions in determining whether alternative vehicles or advanced vehicle technologies are more or less climate friendly than conventional vehicles.

Unlike earlier studies, this investigation used 15 parameters, which were applied across three case studies.

As reported by Beer et al. (Beer et al., 2001a), up to 1% of LCA GHG emission results are lower than the baseline for diesel fuel, contradicting the results in Table 6.7, which state that 8.5% of LCA GHG emission results are lower. This discrepancy can be explained by the fact that this thesis used an in-depth sensitivity analysis, which included 15 parameters that impact overall LCA results, while Beer et al. (2001b) only used a few. As a result, this thesis' output should be considered more reliable. Moreover, Matheys et al. (2006) performed a sensitivity analysis of the LCA results and used a sensitivity-analysis method on various parameters, such as energy consumption, vehicle manufacturing and vehicle recycling. The results showed that the parameters had no significant impact on the overall LCA results. This does not comply with our results (see Table 6.4) as we discovered that the vehicle-manufacture-phase parameter has a noteworthy impact on the overall LCA; like any manufactured product, the production of a motor vehicle can have environmental impacts because of the nature of the manufacturing process.

Moreover, Huang et al. (Huang et al., 2013) identified that sensitivity analyses help to establish the influence of method and boundary selection on the LCA's results. The same scholars also utilised them to check the effect of maintenance parameters on the assessment's results. This matches up with the analysis presented in Table 6.36, which suggests that the vehicle-maintenance parameter has a noticeable impact on the overall results of the LCA; hence, it's effect should not be ignored. This thesis' findings (see section 6.1) are also in agreement with a study by Groen et al. (Groen et al., 2014) who stated that the sensitivity analysis is a useful tool in the case of the non-linear LCA model. The environmental impact can be analysed by means of a global sensitivity analysis to gain more insight into output variance. Meanwhile, Henriques (Henriques, 2013) indicated that battery manufacturing has an impact on LCA GHG emissions of 3% when it increases and decreases by 50% in relation to the reference value. This disagrees with the sensitivity analysis results presented in Table 6.5, which stated that vehicle manufacture, including battery manufacturing for electric vehicles (EVs), only has an overall impact on LCA GHG emissions of 6.15% when changing the inputs by 10%. These differences are down to the fact that the earlier study assumed that the electricity produced came from renewable sources, while this thesis' values were based on electricity generated from fossil fuels.

Many other studies (Groen et al., 2014, Huang et al., 2013, Henriques, 2013, Matheys et al., 2006, Beer et al., 2001a), did not go into the same level of detail as this one has. Consequently, our investigation identified that sensitivity analyses can prove that although many parameters significantly impact life-cycle modelling, the degree of impact on the final results depends on a few key strictures, such as the occupancy rate of passengers, fuel consumption, kilometres travelled, electricity generation (whether it is from renewable or non-renewable energy sources), fuel feedstock and advanced vehicle technologies. The sensitivity analysis also assessed the effects of the assumptions, parameters and other factors on the LCA's findings; the results indicate that their impact on vehicle exhaust emissions can be seen in almost all types of transportation. Indeed, some of the parameters significantly affect the LCA results just as others trigger much more inconsequential effects. Also, some parameters, factors and assumptions only affect conventional vehicle LCA results, while others only affect the LCA results of advanced vehicle technologies or alternative fuel-powered vehicles.

Similarly, the variation can be dramatic, highlighting the sensitivity of global warming potential (GWP), energy resource depletion and PM emissions, and how they are all affected by many different features, assumptions and parameters. The sensitivity analysis revealed that the passenger occupancy rate has a significant effect on the environmental impact and energy demands of both passenger vehicles and public transport buses during these vehicles' lifetimes (see sections 6.1.1 and 6.1.2). Furthermore, fuel economy and kilometres travelled also noticeably affect the LCA GHG emissions, energy use and PM results (see sections 6.1.1, 6.1.2 and 6.1.3); the impact of the vehicle-manufacturing parameter on LCA HTc and HTnc is also observable (see section 6.1.4).

Meanwhile, the crude-oil-refinement stricture is the key factor in influencing the LCA energy consumption results (see Table 6.16), and the effect of electricity mix consumption and production is both noticeable and considerable in relation to advanced vehicle technologies/battery electric vehicles (see section 6.1.1). For heavy-duty truck vehicles, two central issues are the average load and the fraction load. Both significantly impact the LCA's GWP, cumulative energy demand and the level of impact on human health (see sections 6.1.1.3, 6.1.2.3, 6.1.3.3 and 6.1.4.3). Conversely, the sensitivity analysis showed that some parameters, including crude oil extraction, LPG production and processing, hydrogen production and processing and vehicle maintenance and disposal, have negligible influences on LCA outcomes, so they can be excluded from life-cycle modelling (see Tables 6.3, 6.6 and 6.8).

# CHAPTER 7: BIOFUEL VEHICLES' LCA

## 7.1 Results and Findings

The International Energy Agency (IEA) identifies biofuel as a major player in the decarbonisation of the transport sector. Biofuels are an attractive option due to their high energy density, convenient handling and storage properties. They can also 'drop in' to the existing fuel supply and end-use infrastructure with minimal modification and expense required (Australian Goverment, 2021). Much of the literature states that biofuel-powered transportation has significantly reduced GHG emissions, particulate matter (PM) and human toxicity (cancer and non-cancer) (HTc and HTnc), hence the low impact on both human health and the environment. This chapter looks at biofuel LCA for both bioethanol passenger vehicles and biodiesel buses.

### 7.1.1 Comparison Between LCA of Bioethanol and Petrol Passenger Vehicles

Bioethanol can be directly used in vehicles and behaves in a similar fashion to conventional fuels. Bioethanol has a high-octane rating that enables high engine compression ratios, which increases engine efficiency and performance. Pure ethanol is available (E100), plus it is also available at low/high levels, such as E5, E10, E25, E40 and E85. It is designed to operate in any blend of petrol and ethanol up to 83%. The LCA results indicate that both pure and blended bioethanol (high/low levels of ethanol) significantly reduce LCA GHG emissions, energy use and PM compared to conventional baseline petrol vehicles. In Table and Figure 7.1, the results indicate that high levels of ethanol-fuelled vehicles produce fewer GHG emissions than vehicles fuelled by low levels of ethanol and petrol.

| Vehicle Model | Fuel Cycle (kg/pkm) | Tailpipe Emissions (kg/pkm) | Vehicle Manufacture (kg/pkm) | Vehicle Maintenance (kg/pkm) | Vehicle Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|---|---|---|
| **E85** | −0.09112 | 0.046 | 0.029 | 0.00602 | 0.00212 | −0.00736 |
| **E40** | −0.0181 | 0.1138 | 0.029 | 0.00602 | 0.00212 | 0.133 |
| **E25** | 0.005 | 0.14 | 0.029 | 0.00602 | 0.00212 | 0.183 |
| **E10** | 0.028 | 0.169 | 0.029 | 0.00602 | 0.00212 | 0.234 |
| **Petrol Baseline** | 0.0412 | 0.1808 | 0.029 | 0.00602 | 0.00212 | 0.259 |

**Table 7.1: Comparison between LCA GHG Emissions (kg/pkm) of Bioethanol Vehicles**

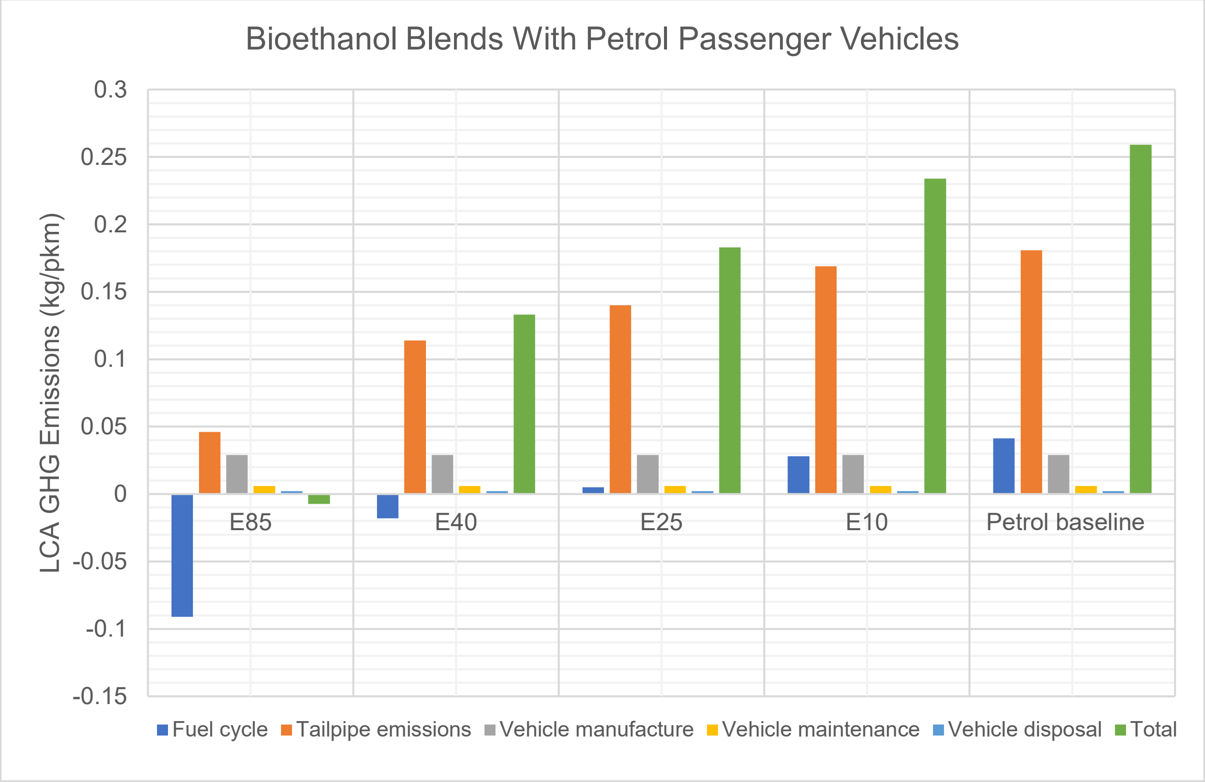


**Figure 7.1: Comparison between LCA GHG Emissions (kg/pkm) of Bioethanol Vehicles**

Similarly, bioethanol vehicles also use less energy relative to petrol vehicle, as is demonstrated by the results in Table 7.2 and Figure 7.2.

| **Vehicle model** | **Fuel Cycle and Tailpipe Emissions (MJ/pkm)** | **Vehicle Manufacture (MJ/pkm)** | **Vehicle Maintenance (MJ/pkm)** | **Vehicle Disposal (MJ/pkm)** | **Total (MJ/pkm)** |
|---|---|---|---|---|---|
| **E85** | 1.17 | 0.404 | 0.113 | 0.0117 | 1.7 |
| **E40** | 2.17 | 0.404 | 0.113 | 0.0117 | 2.69 |
| **E25** | 2.46 | 0.404 | 0.113 | 0.0117 | 2.99 |
| **E10** | 2.77 | 0.404 | 0.113 | 0.0117 | 3.3 |
| **Petrol Baseline** | 2.84 | 0.404 | 0.113 | 0.017 | 3.37 |

**Table 7.2: Comparison between LCA Energy Use (MJ/pkm) of Bioethanol Vehicles**

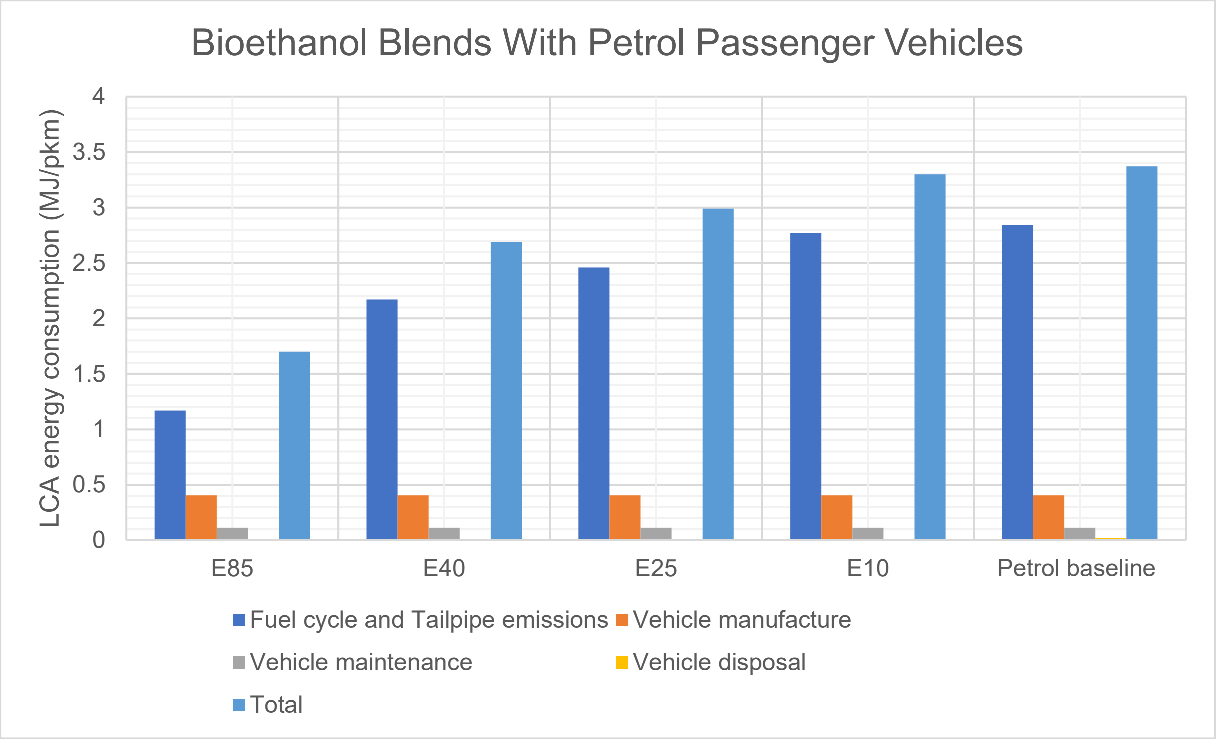


**Figure 7.2: Comparison between LCA Energy Use (MJ/pkm) of Bioethanol Vehicles**

Moreover, in Table 7.3 and Figure 7.3, the results show that vehicles powered by low levels of bioethanol emit less PM than petrol vehicles.

| **Vehicle Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **E10** | 4.47E-05 | 1.22E-05 | 5.70E-05 |
| **E25** | 4.57E-05 | 1.22E-05 | 5.80E-05 |
| **E40** | 4.69E-05 | 1.22E-05 | 5.91E-05 |
| **E85** | 5.00E-05 | 1.22E-05 | 6.22E-05 |
| **Petrol Baseline** | 8.52E-05 | 1.22E-05 | 9.74E-05 |

**Table 7.3: Comparison between LCA PM (kg/pkm) of Bioethanol Vehicles**

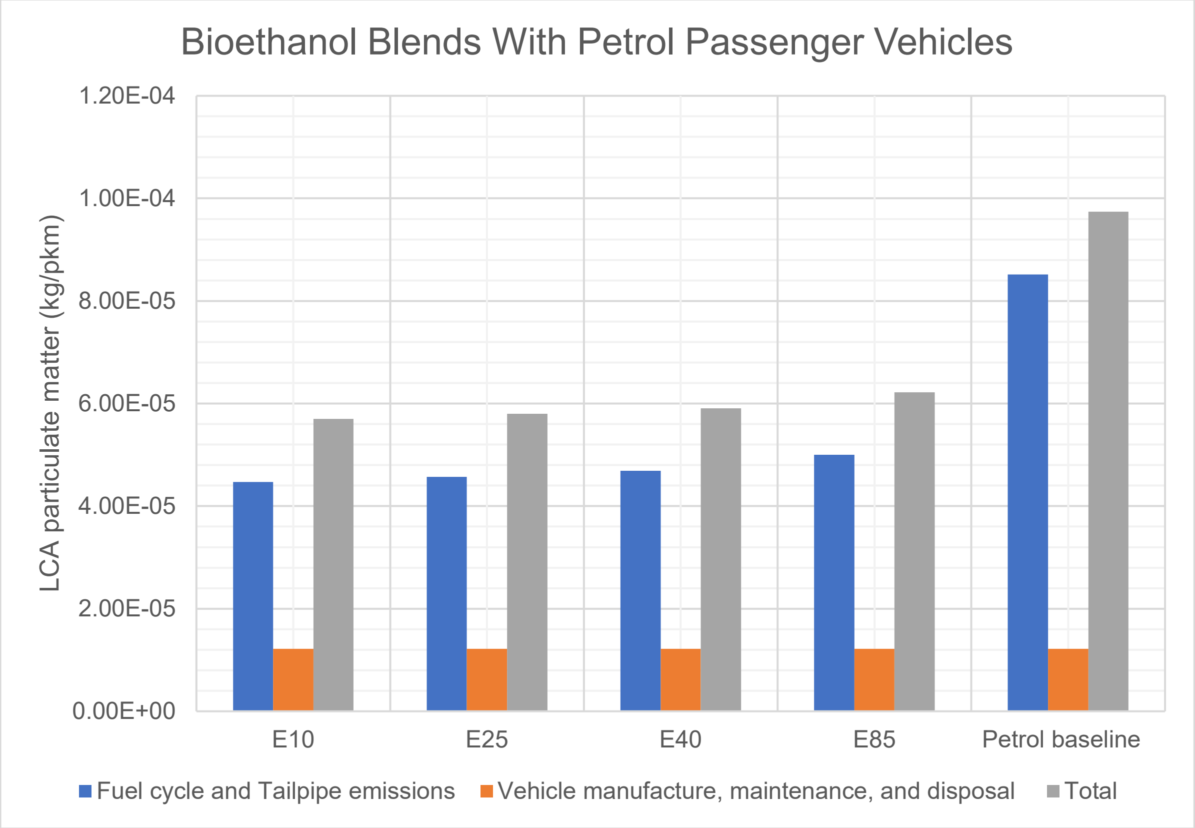


**Figure 7.3: Comparison between LCA PM (kg/pkm) of Bioethanol Vehicles**

The results in the tables and figures above can be explained in that bioethanol has a high-octane number, which helps reduce vehicle exhaust emissions, while the octane number is lower for conventional internal combustion engine vehicles running on petrol.

Regarding human health, the results show that both high and low levels of ethanol have significant effects on human life. In other words, LCA HTc and HTnc of conventional internal combustion engine petrol cars are much lower than those of both pure and blended bioethanol cars, as can be seen in Tables 7.4 and 7.5 and Figures 7.4 and 7.5, respectively.

| **Vehicle Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **Petrol Baseline** | 1.60E-10 | 1.41E-09 | 1.57E-09 |
| **E10** | 1.69E-10 | 1.41E-09 | 1.58E-09 |
| **E25** | 1.7E-10 | 1.41E-09 | 1.58E-09 |
| **E40** | 1.73E-10 | 1.41E-09 | 1.59E-09 |
| **E85** | 1.76E-10 | 1.41E-09 | 1.59E-09 |

**Table 7.4: Comparison between LCA HTc (kg/pkm) of Bioethanol Vehicles**

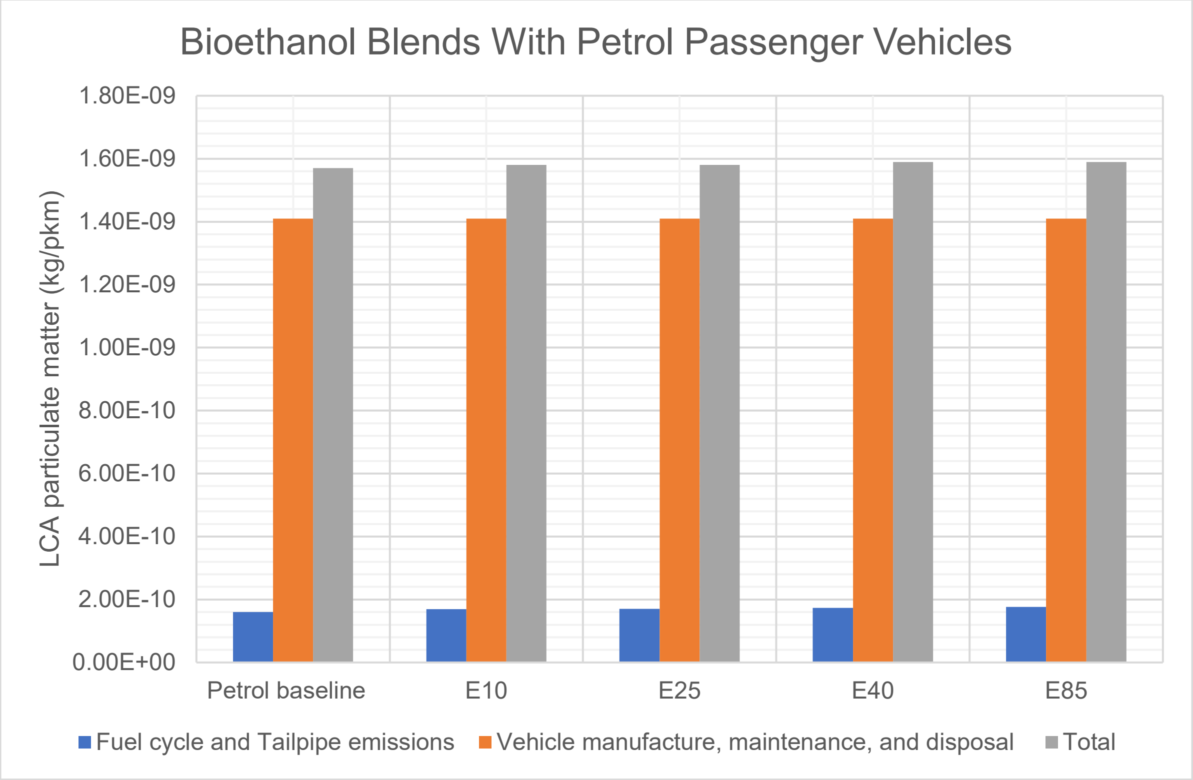


**Figure 7.4: Comparison between LCA HTc (kg/pkm) of Bioethanol Vehicles**

| **Vehicle Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **Petrol Baseline** | 1.47E-09 | 5.45E-09 | 6.92E-09 |
| **E10** | 2.75E-09 | 5.45E-09 | 8.21E-09 |
| **E25** | 4.6E-09 | 5.45E-09 | 1.01E-08 |
| **E40** | 6.47E-09 | 5.45E-09 | 1.19E-08 |
| **E85** | 1.23E-08 | 5.45E-09 | 1.78E-08 |

**Table 7.5: Comparison between LCA HTnc (kg/pkm) of Bioethanol Vehicles**

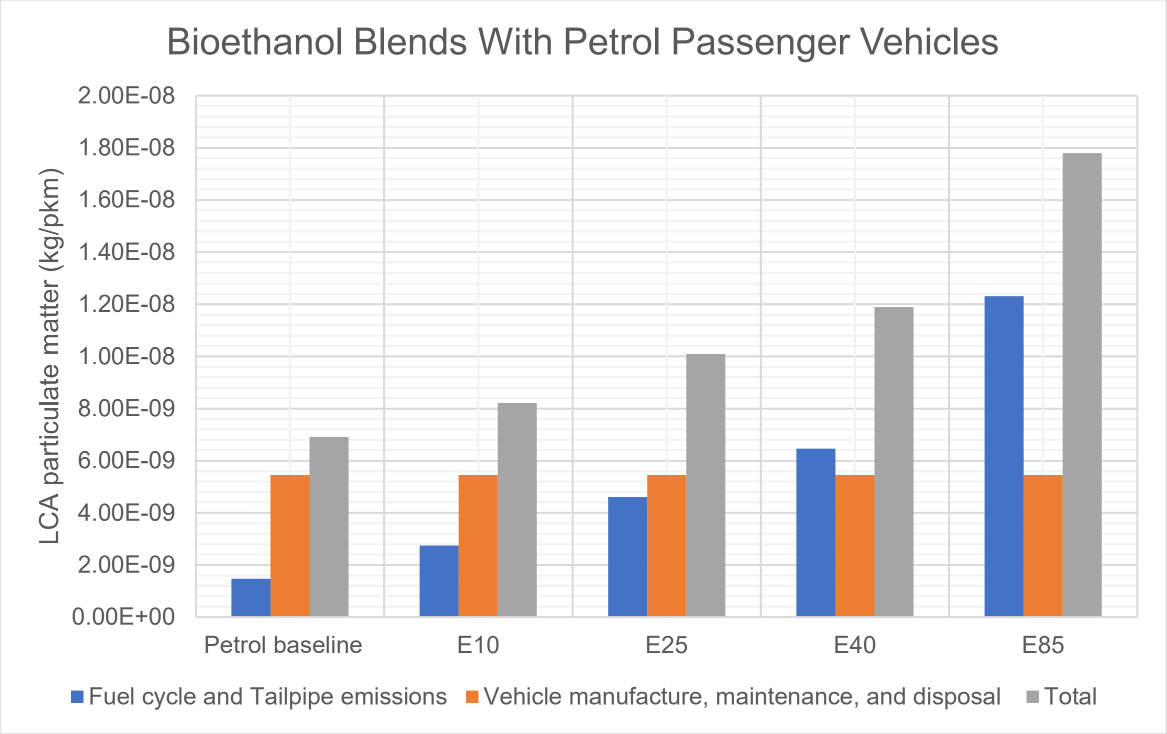


**Figure 7.5: Comparison between LCA HTnc (kg/pkm) of Bioethanol Vehicles**

The overall impact on health from passenger vehicles depends on exposure to bioethanol feedstock, which varies from region to region. The blend of bioethanol affects overall LCA results so that if the percentage increases (high level of bioethanol), the energy use and emissions reduce. Vice versa, the car exhaust emissions and energy depletion resources increase when a low level of blended bioethanol is used.

### 7.1.2 Comparison Between LCA of Biodiesel and Low Sulphur Diesel Buses

Biodiesel is a form of diesel fuel, derived from plants or animals, consisting of long-chain fatty acid esters. The three primary ways to transport biodiesel are truck, rail and barge. This study examines the use of biodiesel in public transport buses. Pure biodiesel can necessitate changing the engine design, and it is recommended that low level blends (B5 and B20) are used in many low sulphur diesel (LSD) buses to negate the need for any engine modification. Biodiesel raises the cetane number of the fuel and improves fuel lubricity. A higher cetane number means that the engine is easier to start and reduces ignition delay. The results presented in the tables and figures show that buses fuelled by pure biodiesel (BD100) release fewer GHG emissions, use less energy and are less of a risk to human health (HTnc) relative to conventional baseline LSD buses. The results in Table 7.6 and Figure 7.6 show that pure biodiesel buses produce fewer GHG emissions than other types of bus.

| **Bus Model** | **Fuel Cycle (kg/pkm)** | **Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture (kg/pkm)** | **Vehicle Maintenance (kg/pkm)** | **Vehicle Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|---|---|---|
| **BD100** | −0.0355 | 0.0106 | 0.00885 | 0.0133 | 0.000233 | −0.00255 |
| **BD20** | 0.00016 | 0.04064 | 0.00885 | 0.0133 | 0.000233 | 0.0631 |
| **LSD Bus Baseline** | 0.00686 | 0.03904 | 0.00885 | 0.0133 | 0.000233 | 0.0682 |
| **BD5** | 0.00645 | 0.04675 | 0.00885 | 0.0133 | 0.000233 | 0.0756 |

**Table 7.6: Comparison of LCA GHG Emissions (kg/pkm) of Biodiesel Buses**

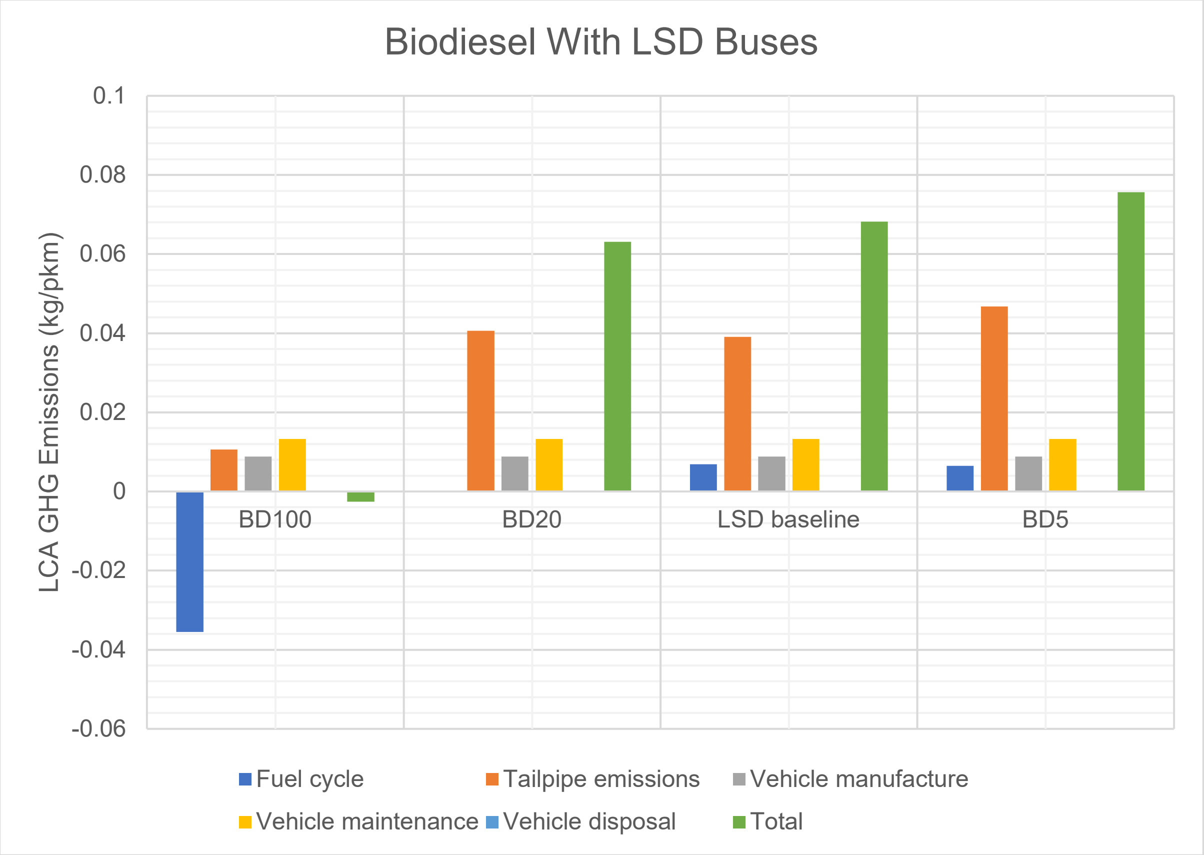


Figure 7.6: Comparison of LCA GHG Emissions (kg/pkm) of Biodiesel Buses

Furthermore, pure biodiesel-fuelled buses consume less energy than conventional buses, as shown in Table 7.7 and Figure 7.7.

| **Bus Model** | **Fuel Cycle and Tailpipe Emissions (MJ/pkm)** | **Vehicle Manufacture (MJ/pkm)** | **Vehicle Maintenance (MJ/pkm)** | **Vehicle Disposal (MJ/pkm)** | **Total (MJ/pkm)** |
|---|---|---|---|---|---|
| **BD100** | 0.138 | 0.112 | 0.16 | 8.61E-05 | 0.41 |
| **LSD Bus Baseline** | 0.541 | 0.112 | 0.16 | 8.61E-05 | 0.812 |
| **BD20** | 0.577 | 0.112 | 0.16 | 8.61E-05 | 0.849 |
| **BD5** | 0.65 | 0.112 | 0.16 | 8.61E-05 | 0.922 |

Table 7.7: Comparison of LCA Energy Use (MJ/pkm) of Biodiesel Buses

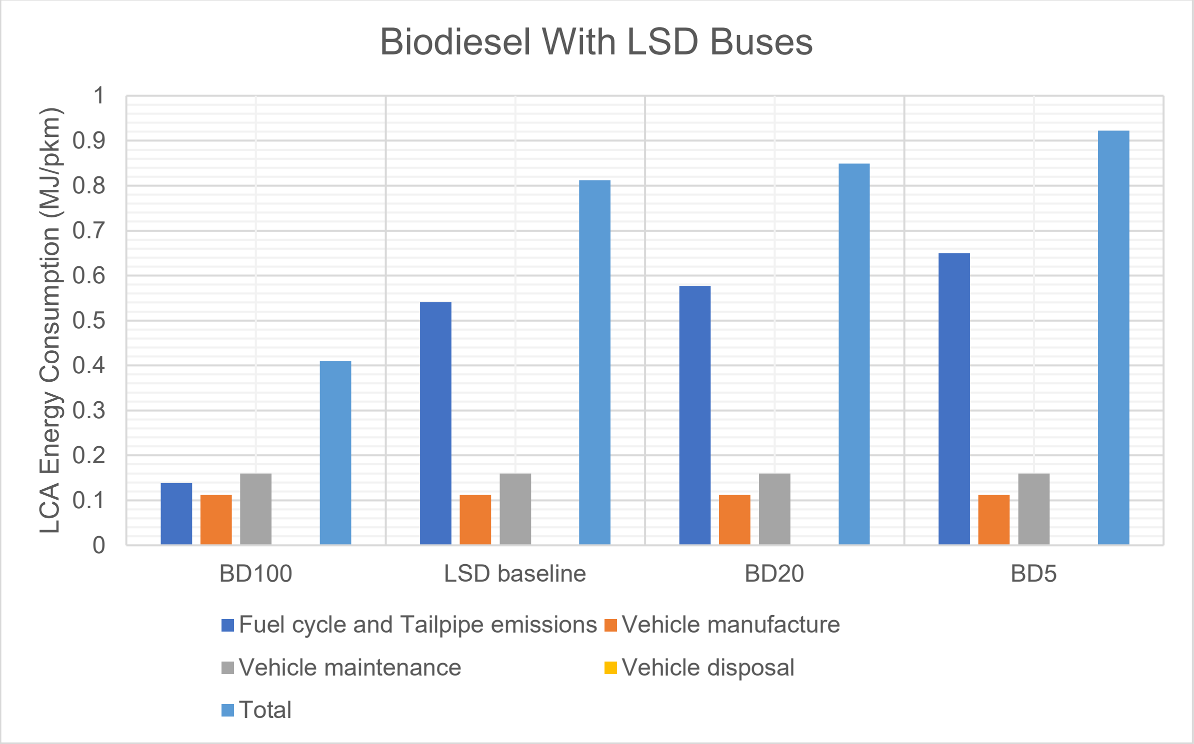


**Figure 7.7: Comparison of LCA Energy Use (MJ/pkm) of Biodiesel Buses**

The results in Table 7.8 and Figure 7.8 show that pure biodiesel poses less of a risk of human health (HTnc) compared to other types of bus.

| Bus model | Fuel Cycle and Tailpipe Emissions (kg/pkm) | Vehicle Manufacture, Maintenance and Disposal (kg/pkm) | Total(kg/pkm) |
|---|---|---|---|
| **BD100** | 1.89E-10 | 2.00E-09 | 2.19E-09 |
| **LSD Bus baseline** | 2.64E-10 | 2.00E-09 | 2.26E-09 |
| **BD20** | 3.05E-10 | 2.00E-09 | 2.31E-09 |
| **BD5** | 3.23E-10 | 2.00E-09 | 2.32E-09 |

**Table 7.8: Comparison of LCA HTnc (g/pkm) of Biodiesel Buses**

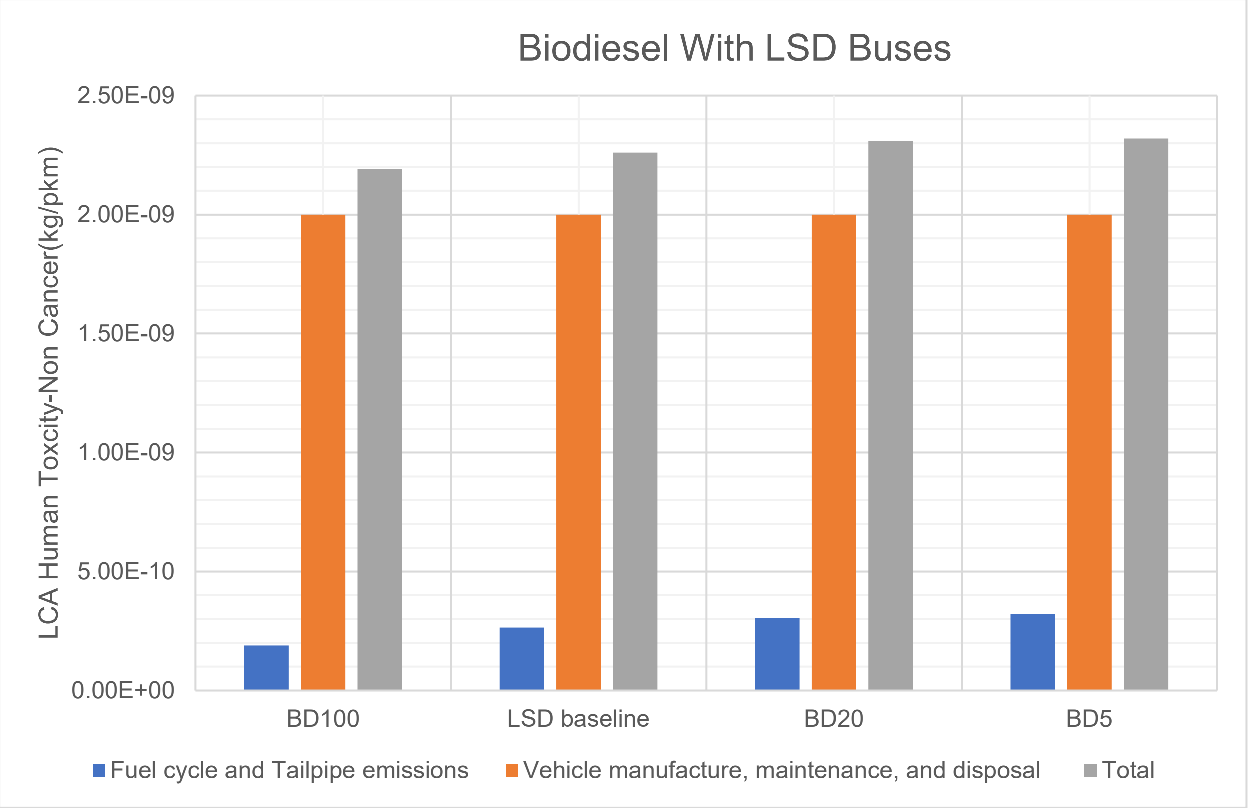


**Figure 7.8: Comparison of LCA HTnc (g/pkm) of Biodiesel Buses**

On the other hand, LCA PM and HTc for BD100, BD20 and BD5 are higher than for conventional LSD buses. The results in Table 7.9 and Figure 7.9 indicate that LSD buses emit less PM than biodiesel buses.

| **Bus Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Vehicle Manufacture, Maintenance and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **LSD Bus Baseline** | 4.86E-05 | 4.84E-06 | 5.34E-05 |
| **BD100** | 5.19E-05 | 4.84E-06 | 5.67E-05 |
| **BD20** | 5.87E-05 | 4.84E-06 | 6.35E-05 |
| **BD5** | 6.01E-05 | 4.84E-06 | 6.50E-05 |

**Table 7.9: Comparison of LCA PM (kg/pkm) of Biodiesel Buses**

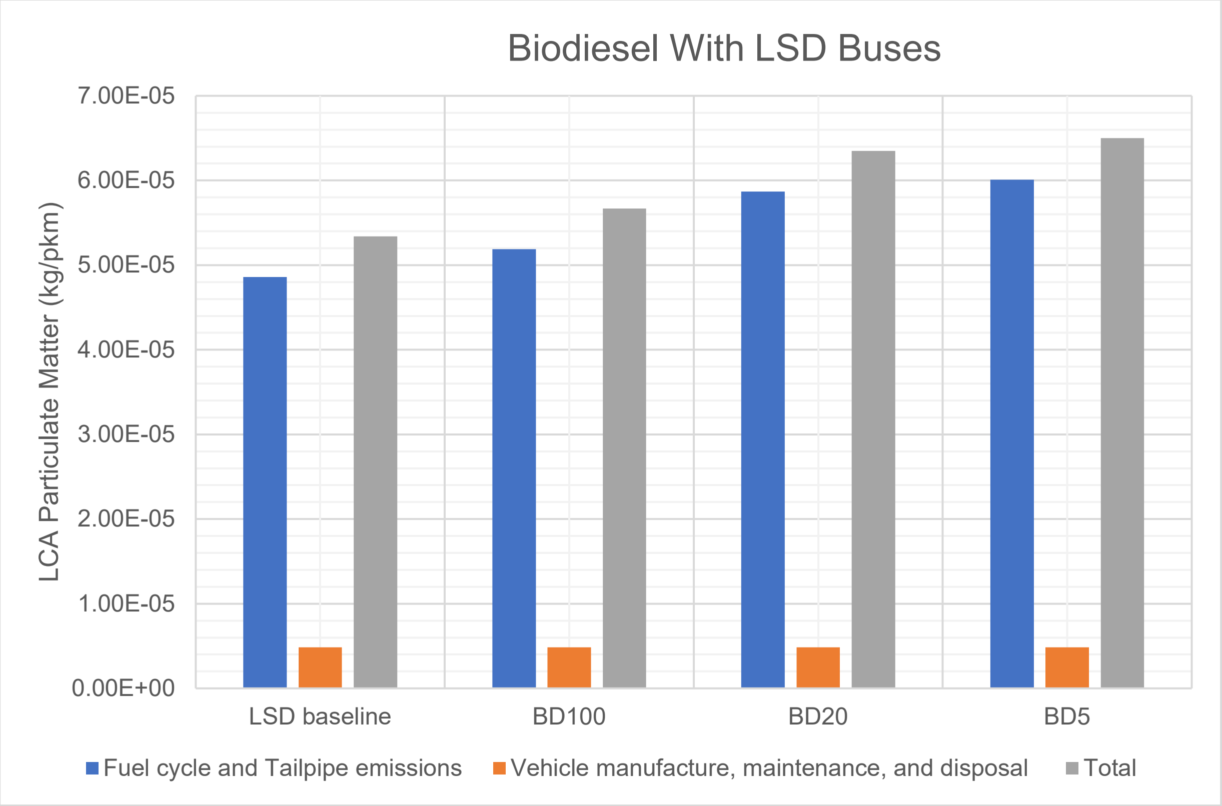


**Figure 7.9: Comparison of LCA PM (kg/pkm) of Biodiesel Buses**

In addition, pure biodiesel buses have a greater effect on LCA HTc than other types of bus. This can be seen clearly in Table 7.10 and Figure 7.10.

| Bus model | Fuel Cycle and Tailpipe Emissions (kg/pkm) | Vehicle Manufacture, Maintenance and Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|
| **LSD Bus baseline** | 3.12E-11 | 4.09E-10 | 4.41E-10 |
| **BD5** | 3.93E-11 | 4.09E-10 | 4.49E-10 |
| **BD20** | 4.01E-11 | 4.09E-10 | 4.50E-10 |
| **BD100** | 4.35E-11 | 4.09E-10 | 4.53E-10 |

**Table 7.10: Comparison of LCA HTc (kg/pkm) of Biodiesel Buses**

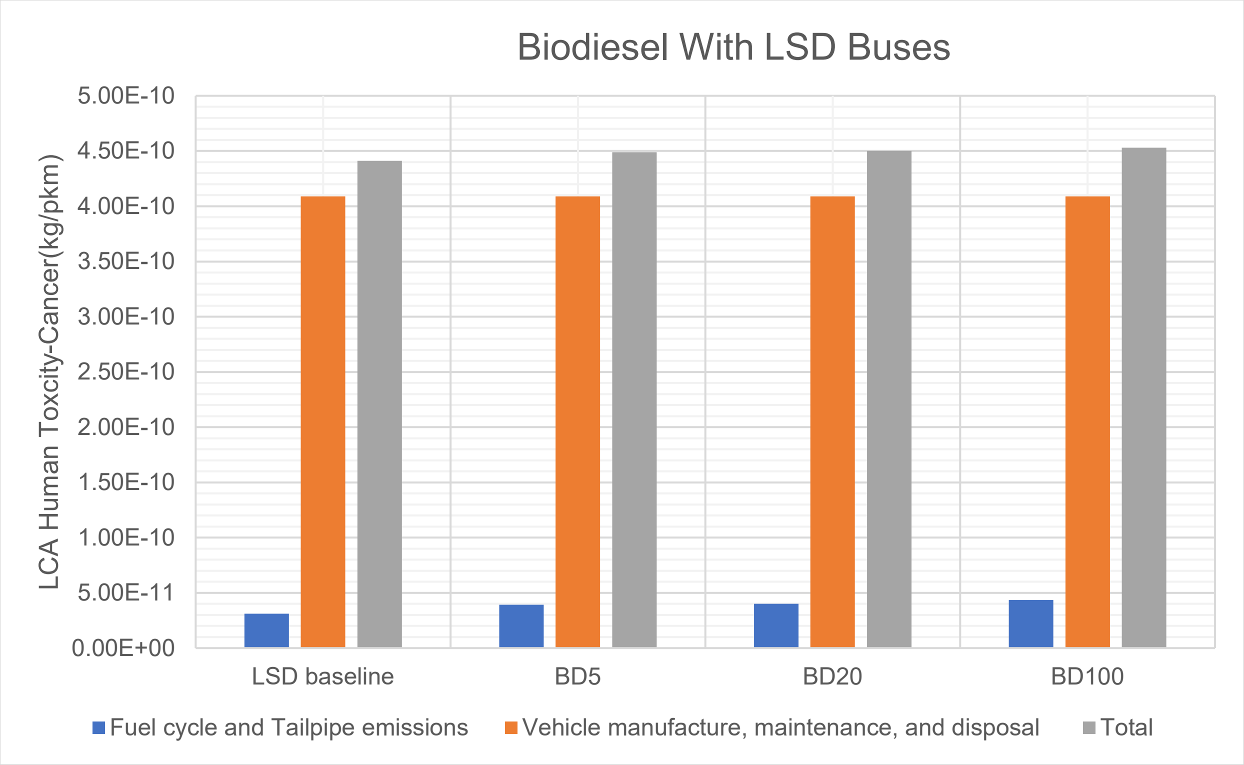


**Figure 7.10: Comparison of LCA HTc (kg/pkm) of Biodiesel Buses**

Observably, biodiesel buses pose less of a risk to human health and the environment than other types of bus. This is because of biodiesel buses' injection, spray and engine characteristics, which aim to reduce harmful exhaust emissions. However, the use of pure biodiesel can have an impact on bus powertrain efficiency because biodiesel is highly viscous, so more power is needed to operate the engine system. Therefore, it is preferable to use a low level of biodiesel blended with LSD, such as BD5 and BD20, to avoid high fuel viscosity issues.

## 7.2 Uncertainty Analysis of LCA for Biofuel Vehicles: Results and Findings

Uncertainty analysis is used to show the range of possible values wherein the true measurement value lies. So, in order to check the data used to calculate the LCA biofuel results, uncertainty analysis is performed to determine which data are close to or far from the mean (average). In addition, uncertainty analysis is considered an important technique that increases the transparency of LCA data and results. The results show that the coefficient of variation (CV) is close to the mean value where energy demand, global warming potential (GWP) and PM are concerned. For instance, for E10, as shown in Table 7.11 and Figure 7.11, the CV for energy use, GHG emissions and PM are 4%, 2% and 16%, respectively. However, the data for HTc and HTnc deviate further from the mean, with CVs of 31% and 32%, respectively.

| Impact Category | Mean | SD | CV % |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2826631 | 0.13691196 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.23198795 | 0.004529233 | 2 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.54E-09 | 4.80E-10 | 31 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 7.96E-09 | 2.57E-09 | 32 |
| **Particulate Matter(kg/pkm)** | 5.76E-05 | 9.15E-06 | 16 |

**Table 7.11: Uncertainty Analysis of E10 Passenger Vehicles' LCA**

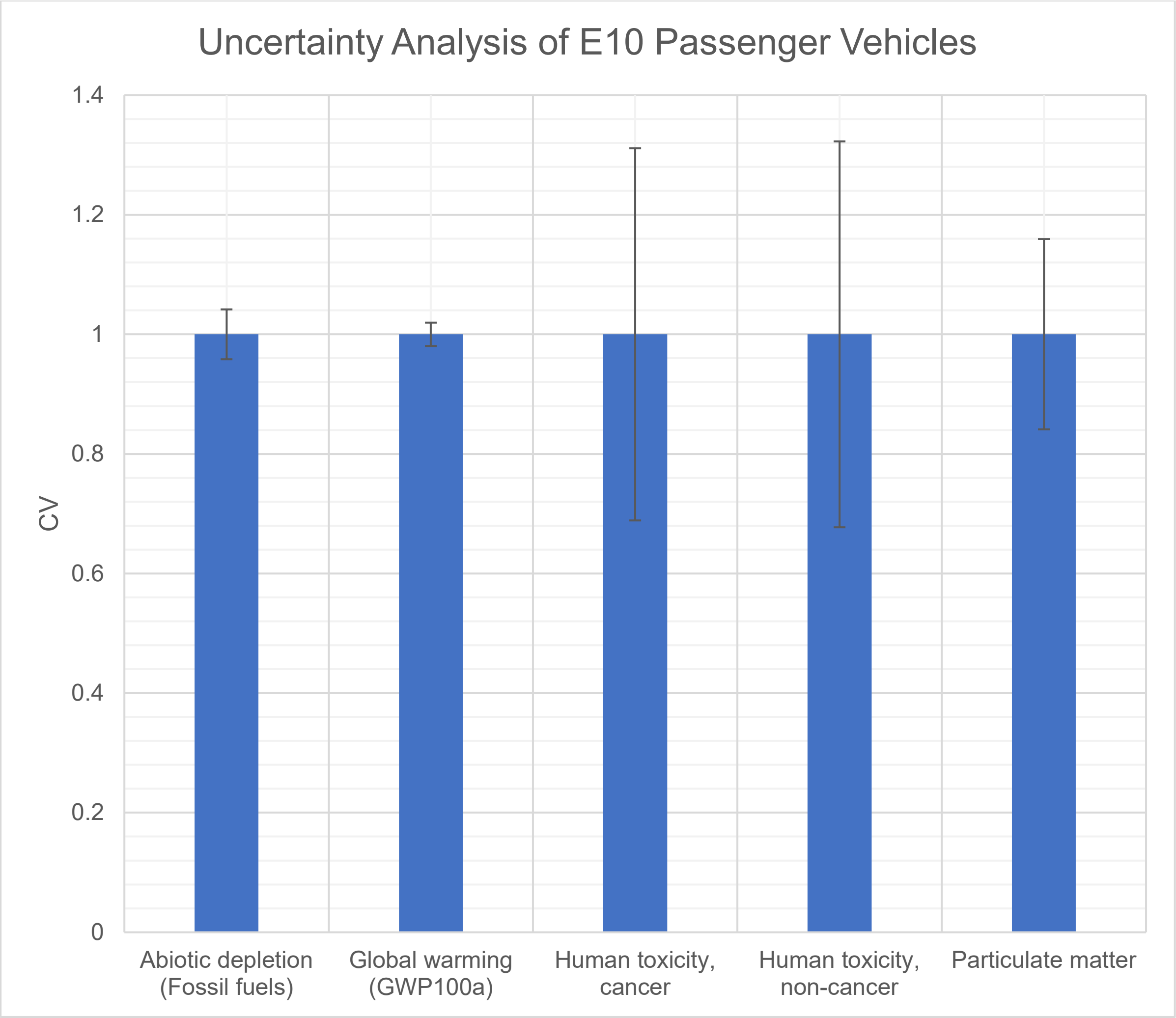


**Figure 7.11: Uncertainty Analysis of E10 Passenger Vehicles' LCA**

Unfortunately, the CV of high biofuel blends, such as E85 (used in passenger vehicles) and pure biodiesel (used in buses), is much further from the mean value, as can be seen in Table 7.12 and Figure 7.12 for buses fuelled by pure biodiesel. The results show that the CV is 10% for energy use, −150% for GHG emissions, 34% for HTc, 305% for HTnc and 1% for PM. This situation arose because the data used to model the fuel pathway (the production of biofuel) has not been validated or it is not adapted or linked to the global database within the LCA SimaPro software.

| Impact Category | Mean | SD | CV % |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.38711147 | 0.040092441 | 10 |
| **Global Warming (GWP100a) (kg/pkm)** | −0.004815615 | 0.007233712 | −150 |
| **Human Toxicity, Cancer(kg/pkm)** | 4.56E-10 | 1.55E-10 | 34 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 2.07E-09 | 6.14E-10 | 30 |
| **Particulate Matter(kg/pkm)** | 5.67E-05 | 7.75E-07 | 1 |

**Table 7.12: Uncertainty Analysis of BD100 Buses' LCA**

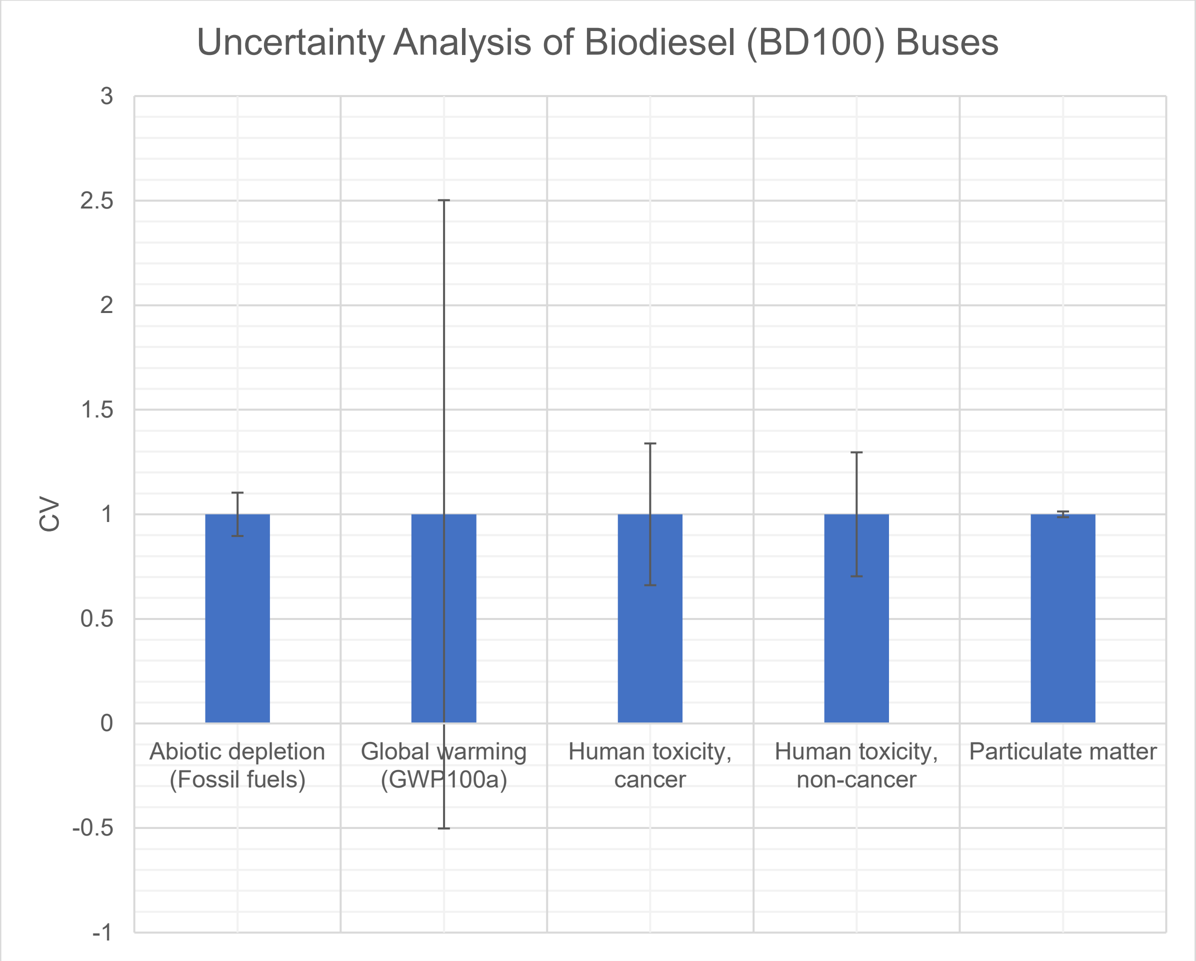


**Figure 7.12: Uncertainty Analysis of BD100 Buses' LCA**

This uncertainty analysis has been repeated for all types of biofuel vehicles, and the results can be found in Appendix F.

## 7.3 Sensitivity Analysis of Biofuel Vehicles' LCA: Results and Findings

Sensitivity analysis highlights the most important set of parameters in the model to determine whether the data needs to be improved. It also enhances the interpretation of the results.

Many parameters play a significant role in the overall biofuel LCA results, though others have a negligible effect. The analysis indicates that the most influential factors that directly impact the LCA results concerning GWP, energy use and PM are, in descending order, passenger occupancy rate, kilometres travelled and fuel consumption. For instance, for **E10 passenger vehicles,** when the passenger occupancy rate deviates from the base value (0.23434551) by plus or minus 10%, LCA GWP (kg/pkm) increases by 11.1% (0.2603839) and decreases by 9.1% (0.21304137), as shown in Table 7.13, Figure 7.13 and Table 7.14. There are also other factors, including fuel resources and alternative vehicles, which can impact LCA results.

| **Impact Category** | **Reference Value (Base)** | **Case A (−10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.2603839 | 0.21304137 | 11.1 | −9.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.6640523 | 2.997861 | 11 | −9 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 6.33E-05 | 5.18E-05 | 11 | −9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.76E-09 | 1.44E-09 | 11 | −9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 9.12E-09 | 7.46E-09 | 11 | −9 |

**Table 7.13: Sensitivity Analysis for LCA of E10 (occupancy rate parameter)**

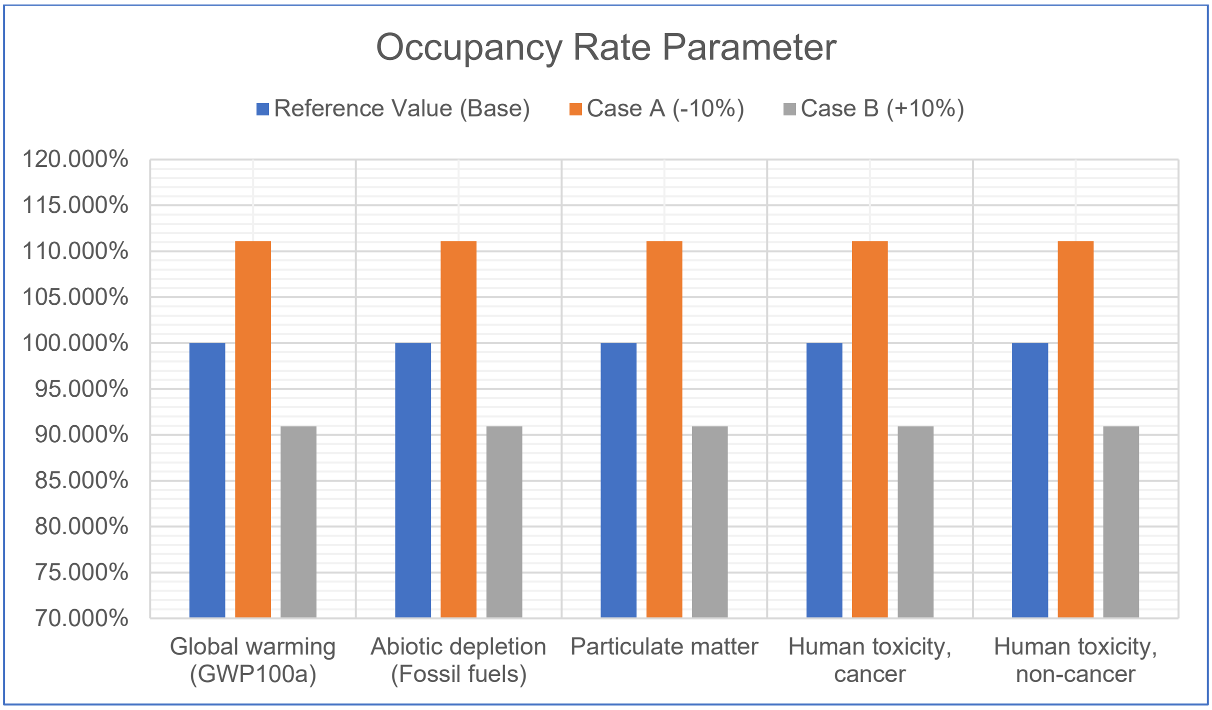


**Figure 7.13: Sensitivity Analysis for LCA of E10 (occupancy rate parameter)**

This analysis was repeated for other vehicle and fuel types, and the results can be found in Appendix H. Below is a summary of the sensitivity analysis for vehicles' LCA.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.23434551 | 0 | 0 | |
| **Occupancy Rate** | 0.2603839 | 11.1 | 0.21304137 | 9.1 |
| **Kilometres Travelled** | 0.25625534 | 9.3 | 0.21641928 | 7.6 |
| **Fuel Consumption** | 0.21462666 | 8.4 | 0.25406436 | 8.4 |
| **Vehicle Manufacture** | 0.23144458 | 1.2 | 0.23724644 | 1.2 |
| **Vehicle Maintenance** | 0.23374308 | 0.26 | 0.23494794 | 0.26 |
| **Crude Oil Refining** | 0.23402653 | 0.14 | 0.23466449 | 0.14 |
| **Vehicle Disposal** | 0.23413317 | 0.09 | 0.23455785 | 0.09 |
| **Crude Oil Extraction** | 0.23418743 | 0.07 | 0.23450358 | 0.07 |
| **Ethanol Production** | 0.23447925 | 0.06 | 0.23421177 | 0.06 |
| **Ethanol Processing** | 0.23444486 | 0.04 | 0.23424616 | 0.04 |

**Table 7.14: Summary of Sensitivity Analysis for LCA of E10 Passenger Vehicles (GWP)**

LCA energy use (in MJ/pkm) increases by 9.3% (3.6052408) and decreases by 7.6% (3.04597960) from the base value (3.2976471) when the kilometres travelled value is increased and decreased by 10%, respectively, as shown in Table 7.15.

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Abiotic Depletion (Fossil Fuels) (MJ/pkm) | Change (%) | Abiotic Depletion (Fossil Fuels) (MJ/pkm) | Change (%) |
| **Reference Value (Base)** | 3.2976471 | 0 | 0 | |
| **Occupancy Rate** | 3.6640523 | 11.1 | 2.997861 | 9.1 |
| **Kilometres Travelled** | 3.6052408 | 9.3 | 3.0459796 | 7.6 |
| **Fuel Consumption** | 3.0208128 | 8.4 | 3.5744814 | 8.4 |
| **Crude Oil Refining** | 3.2430352 | 1.66 | 3.352259 | 1.66 |
| **Crude Oil Extraction** | 3.2451732 | 1.59 | 3.350121 | 1.59 |
| **Vehicle Manufacture** | 3.2572116 | 1.2 | 3.3380826 | 1.2 |
| **Vehicle Maintenance** | 3.2863231 | 0.34 | 3.3089711 | 0.34 |
| **Ethanol Production** | 3.2916887 | 0.18 | 3.3036055 | 0.18 |
| **Ethanol Processing** | 3.2916887 | 0.18 | 3.3036055 | 0.18 |
| **Vehicle Disposal** | 3.2964762 | 0.04 | 3.298818 | 0.04 |

**Table 7.15: Summary of Sensitivity Analysis for LCA of E10 (energy use)**

LCA PM emissions (in kg/pkm) decrease by 7.9% (5.25E-05) and increase by 7.7% (6.14E-05) from the base value (5.70E-05) when the fuel economy (fuel consumption) values varies from the base value by plus or minus 10%, as shown in Table 7.16.

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Particulate Matter (kg/pkm) | Change (%) | Particulate Matter (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 5.70E-05 | 0 | 0 | |
| **Occupancy Rate** | 6.33E-05 | 11.1 | 5.18E-05 | 9.1 |
| **Kilometres Travelled** | 6.19E-05 | 8.6 | 5.29E-05 | 7.2 |
| **Fuel Consumption** | 5.25E-05 | 7.9 | 6.14E-05 | 7.7 |
| **Vehicle Manufacture** | 5.60E-05 | 1.8 | 5.80E-05 | 1.8 |
| **Ethanol Production** | 5.67E-05 | 0.53 | 5.73E-05 | 0.53 |
| **Ethanol Processing** | 5.67E-05 | 0.53 | 5.73E-05 | 0.53 |
| **Crude Oil Refining** | 5.68E-05 | 0.35 | 5.72E-05 | 0.35 |
| **Vehicle Maintenance** | 5.68E-05 | 0.35 | 5.72E-05 | 0.35 |
| **Crude Oil Extraction** | 5.69E-05 | 0.18 | 5.71E-05 | 0.18 |
| **Vehicle Disposal** | 5.70E-05 | 0.001 | 5.70E-05 | 0.001 |

**Table 7.16: Summary of Sensitivity Analysis for LCA of E10 (PM)**

The vehicle manufacture parameter plays a significant role in the overall LCA HTc and HTnc results. For instance, for **E40 passenger vehicles,** when the vehicle manufacture value (in volumetric measurement unit) fluctuates by 10% from the base value, as shown in Tables 7.17 and 7.18, the LCA HTc values change as outlined below:

1. LCA HTc decreases by 8.8% (1.45E-09) and increases by 8.2% (1.72E-09) from the base value (1.59E-09).
2. LCA HTnc decreases by 3.4% (1.15E-08) and increases by 8.25 (1.24E-08) from the base value (1.19E-08).

Although the vehicle manufacture parameter has a significant impact on LCA HTc and HTnc, there are other parameters, namely, fuel feedstock and alternative vehicles (fuel generation), that similarly affect the results.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm** | **Change (%)** |
| **Reference Value (Base)** | 1.59E-09 | 0 | 0 | |
| **Occupancy Rate** | 1.76E-09 | 10.7 | 1.44E-09 | 9.4 |
| **Vehicle Manufacture** | 1.45E-09 | 8.8 | 1.72E-09 | 8.2 |
| **Fuel Consumption** | 1.57E-09 | 1.3 | 1.60E-09 | 0.6 |
| **Ethanol Production** | 1.58E-09 | 0.63 | 1.59E-09 | 0.00 |
| **Ethanol Processing** | 1.58E-09 | 0.63 | 1.59E-09 | 0.00 |
| **Vehicle Maintenance** | 1.58E-09 | 0.63 | 1.59E-09 | 0.00 |
| **Crude Oil Refining** | 1.58E-09 | 0.63 | 1.59E-09 | 0.00 |
| **Vehicle Disposal** | 1.58E-09 | 0.63 | 1.59E-09 | 0.00 |
| **Kilometres Travelled** | 1.60E-09 | 0.6 | 1.57E-09 | 1.3 |
| **Crude Oil Extraction** | 1.59E-09 | 0.001 | 1.59E-09 | 0.001 |

**Table 7.17: Summary of Sensitivity Analysis for LCA of E40 (HTc)**

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.19E-08 | 0 | 0 | |
| **Occupancy Rate** | 1.33E-08 | 11.8 | 1.08E-08 | 9.2 |
| **Kilometres Travelled** | 1.26E-08 | 5.9 | 1.13E-08 | 5.0 |
| **Fuel Consumption** | 1.13E-08 | 5.0 | 1.26E-08 | 5.9 |
| **Vehicle Manufacture** | 1.15E-08 | 3.4 | 1.24E-08 | 4.2 |
| **Ethanol Production** | 1.15E-08 | 3.36 | 1.24E-08 | 4.20 |
| **Ethanol Processing** | 1.15E-08 | 3.36 | 1.24E-08 | 4.20 |
| **Vehicle Maintenance** | 1.19E-08 | 0.001 | 1.20E-08 | 0.84 |
| **Crude Oil Refining** | 1.19E-08 | 0.001 | 1.19E-08 | 0.001 |
| **Vehicle Disposal** | 1.19E-08 | 0.001 | 1.20E-08 | 0.84 |
| **Crude Oil Extraction** | 1.19E-08 | 0.001 | 1.19E-08 | 0.001 |

**Table 7.18: Summary of Sensitivity Analysis for LCA of E40 (HTnc)**

The parameter of crude oil refining has a considerable effect on LCA energy use results. For instance, for **BD20 buses,** when the value deviates by plus or minus 10% from the base value (0.84865396), LCA energy use (in MJ/pkm) decreases by 5.62% (0.80096721) and increases by 5.62% (0.89634071), as shown in Table 7.19. The processes of crude oil refining consume significant amounts of energy, which is why this parameter significantly influences outcomes.

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.84865396 | 0 | 0 |  |
| **Occupancy Rate** | 0.94294885 | 11.1 | 0.7715036 | 9.1 |
| **Kilometres Travelled** | 0.91275399 | 7.6 | 0.79620849 | 6.2 |
| **Fuel Consumption** | 0.79096394 | 6.8 | 0.90634398 | 6.8 |
| **Crude Oil Refining** | 0.80096721 | 5.62 | 0.89634071 | 5.62 |
| **Vehicle Maintenance** | 0.83265135 | 1.89 | 0.86465658 | 1.89 |
| **Crude Oil Extraction** | 0.83479426 | 1.63 | 0.86251367 | 1.63 |
| **Vehicle Manufacture** | 0.83748981 | 1.3 | 0.85981812 | 1.3 |
| **Biodiesel Production** | 0.84630689 | 0.28 | 0.85100104 | 0.28 |
| **Vehicle Disposal** | 0.84864535 | 0.001 | 0.84866257 | 0.001 |
| **Biodiesel Processing** | 0.84864571 | 0.001 | 0.84866222 | 0.001 |

**Table 7.19: Summary of Sensitivity Analysis for LCA of BD20 (energy use)**

The parameters of ethanol production and processing have much smaller effects on LCA GHG emissions, energy use and PM emissions, while LCA HTnc has a considerable effect on the outcome. For instance, for **E25 passenger vehicles,** when the ethanol production and processing parameters vary by plus or minus 10% from the base value (1.01E-08), LCA HTnc (in kg/pkm) increases by 1.98% (1.03E-08) and 1.98% (1.03E-08), and decreases by 3.17% (9.78E-09) and 3.17% (9.78E-09), respectively, as shown in Table 7.20. The impacts of these parameters depend on the sources of ethanol, whether it is derived from fossil fuels or from renewable energy sources.

|  | **10% Decrease** |  | **10% Increase** |  |
|---|---|---|---|---|
|  | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.01E-08 | 0 | 0 |  |
| **Occupancy Rate** | 1.12E-08 | 10.9 | 9.14E-09 | 9.5 |
| **Fuel Consumption** | 9.59E-09 | 5.0 | 1.05E-08 | 4.0 |
| **Kilometres Travelled** | 1.06E-08 | 5.0 | 9.63E-09 | 4.7 |
| **Vehicle Manufacture** | 9.61E-09 | 4.9 | 1.05E-08 | 4.0 |
| **Ethanol Production** | 9.78E-09 | 3.17 | 1.03E-08 | 1.98 |
| **Ethanol Processing** | 9.78E-09 | 3.17 | 1.03E-08 | 1.98 |
| **Vehicle Disposal** | 9.98E-09 | 1.19 | 1.01E-08 | 0.001 |
| **Crude Oil Refining** | 1.00E-08 | 0.99 | 1.01E-08 | 0.001 |
| **Vehicle Maintenance** | 1.00E-08 | 0.99 | 1.01E-08 | 0.001 |
| **Crude Oil Extraction** | 1.00E-08 | 0.99 | 1.01E-08 | 0.001 |

**Table 7.20: Summary of Sensitivity Analysis for LCA of E25 (HTnc)**

The biodiesel production parameter has a noticeable but smaller impact on LCA results. For instance, for **BD20 buses,** when biodiesel production deviates by plus or minus 10% from the base value (0.063130348), LCA GHG emissions (in kg/pkm) decrease by 1.12% (0.063834978) and increase by 1.12% (0.062425718), as shown in Table 7.21.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.063130348 | 0 | 0 | |
| **Occupancy Rate** | 0.070144831 | 11.1 | 0.057391225 | 9.1 |
| **Kilometres Travelled** | 0.067660517 | 7.2 | 0.059423846 | 5.9 |
| **Fuel Consumption** | 0.059053195 | 6.5 | 0.0672075 | 6.5 |
| **Vehicle Maintenance** | 0.061802707 | 2.10 | 0.064457988 | 2.10 |
| **Vehicle Manufacture** | 0.062245445 | 1.4 | 0.06401525 | 1.4 |
| **Biodiesel Production** | 0.063834978 | 1.12 | 0.062425718 | 1.12 |
| **Crude Oil Refining** | 0.062796696 | 0.53 | 0.063463999 | 0.53 |
| **Crude Oil Extraction** | 0.063088596 | 0.07 | 0.063172099 | 0.07 |
| **Vehicle Disposal** | 0.063107008 | 0.04 | 0.063153687 | 0.04 |
| **Biodiesel Processing** | 0.063129622 | 0.001 | 0.063131073 | 0.001 |

**Table 7.21: Summary of Sensitivity Analysis for LCA of BD20 (GWP)**

Other parameters, such as crude oil extraction, biodiesel processing, vehicle maintenance and disposal, have much smaller impacts on life cycle modelling, so their effects on overall LCA results can be ignored.

## 7.4 Discussion of Results

### 7.4.1 Biofuel Vehicles

An LCA has been performed on four different types of bioethanol passenger vehicles (E10, E25, E40 and E85) and three different types of biodiesel automobiles (BD5, BD20 and BD100) during this study using the AusLCI, and other Australian vehicle emission data where it was appropriate. In relation to this, Ashnani et al. (Ashnani et al., 2015) demonstrated that when pure biofuel is used, modifications of the powertrain system need to be made and vehicles can emit more toxic gases, including PM10 and PM2.5, which can impact human health directly.

These findings are in agreement with our own results (see Tables 7.3 and 7.9 and Figures 7.3 and 7.9). This thesis also concurs with a study by Xue et al. (Xue et al., 2011) who showed that biodiesel buses produce significantly less CO2, PM, CO and HC but significantly more NOx than conventional LSD buses (see section 7.1.2). It is important to use a low level of biodiesel in order to control air pollution. Moreover, Tessum et al. (Tessum et al., 2010) showed that the E85 has the lowest impact on the environment, followed by the BD20 and then the E10, which is consistent with the results in sections 7.1.1 and 7.1.2. Biofuel has a high-octane number, which helps to reduce vehicle exhaust emissions, but the octane number is lower for petrol and LSD fuels.

Wang et al. (Wang et al., 1999) highlighted various LCA results for both E10 and E85 vehicles when compared to baseline petrol vehicle, which are listed below:

1. E10 vehicles exhibit 6% lower fuel consumption, 1% lower GHG emissions and 3% less energy consumption.
2. E85 vehicles enjoy a 75% reduction in fuel consumption, a 19% reduction in GHG emissions and a 35% reduction in energy consumption.

These findings are not consistent with the results presented in Tables 3.4, 7.1 and 7.2 and Figures 3.4, 7.1 and 7.2. The study results underlined that E10 vehicles offer 1.25% lower fuel consumption, 9.6% lower GHG emissions and 2% less energy consumption when compared to petrol vehicles; E85 vehicles were shown to provide a reduction of 8.8% in terms of fuel consumption, a 75% reduction in GHG emissions and a 49% reduction in energy use when compared to a petrol vehicle. This can be explained by the fact that this thesis utilised Australian fuel consumption, emissions factor and driving cycle figures to calculate these figures, yet earlier studies were based on different sources of data; hence, the overall LCA results differ between studies.

Meanwhile, by Özçelik et al. (Özçelik et al., 2015) and Durbin and Norbeck (Durbin and Norbeck, 2002) highlighted that the use of 2%–5% ethanol blended with 95% petrol can significantly reduce a vehicle's exhaust emissions, including $CO_2$, CO, HC and NOx. They stated that when vehicles switched to BD20, there was a significant reduction in HC, CO and PM, but NOx emissions increased. This backs up the emissions levels found in Tables 7.3, 7.9 and Figures 7.3, 7.9. The use of biofuel (pure or mixed with conventional fuels) can facilitate significant reductions in vehicle exhaust emissions. In addition, Beer et al. (Beer et al., 2001a) indicated that the LCA's PM is 4.89E-4kg/pkm for a biodiesel bus during the tailpipe emission phase. This is inconsistent with our LCA PM value in Table 7.9, which highlighted it as 5.19E-5kg/pkm for the same type of vehicle. This is because Beer et al. (2001b) only reported on the tailpipe emission and fuel cycle phases, while our research considered all of them.

Finally, pure biofuel or a high-level blend seems to release significantly fewer GHG emissions and air pollutants. However, powertrain modifications are required (a change to the engine's design) (Guarieiro and Guarieiro, 2013). Also, pure biofuel or a high ratio within a fuel mix has a low engine-heating value, resulting in more toxic gas emissions; therefore, it is preferable to use a small amount of biofuel, which has the benefit of lower emissions without having to alter the design of the engine.

### 7.4.2 Uncertainty Analysis of Biofuel Vehicle

An important consideration in the examination of biofuel data is that most of the emissions data is highly variable; thus, when comparing different fuels, it is difficult to know whether observed variations reflect a genuine difference between the two fuels or if they merely reflect the statistical variability. The biofuel data used in this thesis has been somewhat problematic in terms of its availability – few examples exist in the previous literature and those that do often do not have the required level of detail that makes them suitable for analysis. Moreover, Beer et al. (Beer et al., 2001a) asserted that comparisons between biofuels needs to be made on a statistical basis wherever possible, which complies with our findings in section 7.2. Although their study used a simplified approach, which meant comparisons with the models in thesis were not possible, the areas that were identified as lacking sufficient data are still in agreement. Another example of this is the CV of the LCA's PM, which was estimated by Beer et al. (2001b) to be 61% for a biodiesel bus. This does not echo the results presented in Table 7.12, which showed that the CV for the LCA's PM is 1%. This disparity is due to our research methodology employing the entire LCA, while the earlier study only used the uncertainty-analysis theory during the fuel pathway and tailpipe emissions phases.

The uncertainty analysis is considered one of the most important set of parameters when determining which data needs to be improved; it is a valuable tool for ensuring the quality of the information in LCA modelling ((Noshadravan et al., 2015, Wei et al., 2015, Cellura et al., 2011). This also agrees with what is presented in section 7.2. Finally, the findings of the uncertainty analysis seem to prove that the largest source of uncertainty in the biofuel vehicle's LCA results are the GWP values of both E85 passenger cars and pure biodiesel buses – this is because most of the data used to estimate the LCA measurements of biofuel vehicles was adapted from global rather than Australian databases (an Australian database was not available at the time). On the other hand, the data used to model the LCA of cumulative energy use and the effect on human health is close to the mean, indicating that it is reliable.

### 7.4.3 Sensitivity Analysis of Biofuel Vehicles

Sensitivity analyses are considered valuable tools for ensuring trustworthy results with regard to LCAs. The independent global sensitivity analysis aims to analyse the variability of results because of the variations in input parameters.

Here, the sensitivity analysis of biofuel vehicle LCA findings is not consistent with the results obtained by Beer et al. (Beer et al., 2001a) who stated that if fugitive emissions exceed approximately 4 % of supply, embodied emissions of greenhouse gases will exceed those of LSDs. This can again be explained due to the fact that their study only focused on fuel pathway and vehicle tailpipe emissions while we included the entire LCA. We also identified that the sensitivity analysis provides useful insights about the significance of different input parameters on the overall variation within the LCA's findings regarding the GWP, cumulative energy use and human health effects of biofuel vehicles. The passenger occupancy rate is considered the most crucial factor in noticeably impacting LCA energy use and emissions, followed by the parameters of kilometres travelled and fuel economy. The sensitivity analysis also clearly reveals the effect of the vehicle-manufacturing parameter on LCA HTc and HTnc levels. On the other hand, other strictures, including biofuel production and processing, crude oil extraction and refinement and vehicle maintenance and disposal, had much smaller effects on the results, so their impact on life-cycle modelling can be ignored.

# CHAPTER 8: LCA CASE STUDY: PUBLIC TRANSPORT BUSES

## 8.1 Introduction

In 2018, the South Australian Department of Transport, Energy and Infrastructure (DPTI) proposed to evaluate and compare the performance of several trial buses (public transport buses) in the city of Adelaide. The objectives of the project were to:

1. assess the performance of the DPTI Trial Buses regarding GHG emissions, energy use, fuel economy, air pollutants and electrical economy
2. provide a recommendation to DPTI for the optimal bus.

The full LCA is considered an important tool that compares alternative and conventional buses. The whole LCA comprises the fuel pathway (fuel production and electricity generation), bus operation phase (tailpipe emissions and maintenance) and the bus cradle-to-grave (C2G) phase (manufacture and disposal). The case study involved using the LCA SimaPro software and Australian literature to develop an approach that estimates the energy use, GHG emissions and air pollutants – particulate matter (PM); human toxicity, cancer (HTc) and human toxicity, non-cancer (HTnc) – of DPTI Trial Buses (public transport buses in South Australia) over the buses' lifetimes. Also, the study focused on the buses' potential to reduce fuel or electricity consumption.

## 8.2 Method and Database

The data used in this chapter comes from the South Australian DPTI, including the on-board fuel consumption and the DPTI Trial Buses' conditions/powertrain model. Additionally, this study used the Australian National Life Cycle Inventory Database (AusLCI) from the LCA SimaPro software to estimate energy use and emissions during fuel production, bus manufacturing, maintenance and disposal.

### 8.2.1 Bus Conditions

Tables 8.1 and 8.2 present the DPTI Trial Buses' conditions and powertrain model, respectively. They include the DPTI Trial Buses' specifications, including bus load, number of passengers, bus lifetime, annual kilometres travelled, engine model and power.

| **Bus Fleet Number/Bus Model** | **Bus Type** | **Bus (weight) kg[1]** | **Seating[1]** | **Annual Kilometres Travelled[1]** | **Bus Lifetime (year)[1]** | **Passenger Occupancy Rate[2]** |
|---|---|---|---|---|---|---|
| **1902/Scania** | EuroVI | 19100 | 45 | 65000 | 25 | 20 |
| **1905/Micro Hybrid** | Micro Hybrid | 13128 | 35 | 65000 | 25 | 20 |
| **2450/Scania** | EuroVI | 9100 | 45 | 65000 | 25 | 20 |
| **2451/Volvo** | EuroVI | 19500 | 44 | 65000 | 25 | 20 |
| **2452/Mercedes** | EuroVI | 18000 | 46 | 65000 | 25 | 20 |

**Table 8.1: DPTI Trial Buses conditions**

1 Australian Government, Department of Planning and Transport Infrastructure(South Australian Government, 2019)

2 Australian Transport Assessment and Planning(Australian Transport, 2020)

| **Bus Fleet Number/Bus Model** | **Engine Type and Capacity (Engine Model)[1]** | **Max Engine Power (kw)and Max Engine Revolution (rpm)[1]** | **Max Engine Torque (Nm @ rpm)[1]** |
|---|---|---|---|
| **1902/Scania** | Scania DC09 108 K01 Euro VI 320 hp | 239 @ Not given | Not given |
| **1905/Micro Hybrid** | Mercedes-Benz OM 934 5.1 L | 155 @ 2300 | 850 @ 1200–1600 |
| **2450/Scania** | Scania DC09 108 K01 Euro VI 320 hp | 239 @ Not given | Not given |
| **2451/Volvo** | D8K320 7.7 L 6Cyl Euro VI | 235 @ Not given | 1200 @ 1050–1600 |
| **2452/Mercedes** | Mercedes-Benz OM 936LA (Euro 6) | 220@2200 | 1250 @ 1200 |

**Table 8.2: Engine Model/Power of DPTI Trial Buses**

1 Australian Government, Department of Planning and Transport Infrastructure(South Australian Government, 2019)

### 8.2.2 DPTI Trial Buses Database

The LCA modelling database of public transport buses in South Australia is shown in Table 8.3.

| LCA Stage | Database Used |
|---|---|
| Fuel pathway, including fuel production and electricity generation | • AusLCI<br>• Australian National Greenhouse Account Factor (NGAF)<br>• Australian National Pollution Inventory (NPI) |
| Real world bus operation phase (tailpipe emissions) | • The Australian Government's Department of Planning and Transport Infrastructure's on-board fuel consumption database<br>• Emissions factor (EURO 6) from the Australian National Greenhouse Account Factor (see Table **E**.1 in Appendix E) |
| Bus operation phase (bus maintenance) | • Ecoinvent<br>• AusLCI |
| Bus non-operational phase (bus manufacture and disposal) | • Ecoinvent<br>• AusLCI |

**Table 8.3: Databases Used to Develop the LCA of DPTI Trial Buses**

### 8.2.3 Modelling the Life Cycle Assessment of DPTI Trial Buses

Calculating the life cycle energy use, GHG emissions and air pollutants of DPTI Trial Buses in the city of Adelaide was done by using the LCA SimaPro software. The following procedures were undertaken to build an approach that calculated the whole life cycle assessment (LCA) of buses:

1. The environmental impact assessment of the fuel pathway (fuel production) was achieved using the AusLCI database.

2. Based on the Australian on-board driving cycle database, the energy demand, GHG emissions, PM, HTc and HTnc during the bus operation phase (tailpipe emissions) were calculated by using the average (mean) fuel consumption, as shown in Table 8.4.
3. The environmental impact and energy depletion incurred during bus manufacture were evaluated using the AusLCI database.
4. Bus maintenance depends on the kilometres travelled and the average bus payload. The replacement of batteries, tyres and oil changes were also included, based on the AusLCI database.
5. The processes of vehicle end of life (disposal) comprise vehicle dismantling, shredding and disposal, which involve energy use and emissions. Again, the calculations were based on the AusLCI database.

The project involved the evaluation of energy use, GHG emissions and air pollutants, such as PM, HTc and HTnc in relation to various typesof bus, including conventional and hybrid. Each bus makes many trips and passes through different locations in Adelaide, including urban, coastal and hilly regions.

| **DPTI Bus Trial Model** | **Average (Mean) Fuel Consumption (L/100 km) On-road Data** |
|---|---|
| **1902/Scania** | 37.44 |
| **1905/Micro Hybrid** | 36.42 |
| **2450/Scania** | 37.36 |
| **2451/Volvo** | 36.84 |
| **2452/Mercedes** | 40.88 |

**Table 8.4: The Average (mean) Fuel Consumption of DPTI Trial Buses**

## 8.3 DPTI Trial Buses LCA: Results and Findings

Public transport buses are an important transportation facet in South Australia. The current bus network extends through all parts of Adelaide, including the city centre, beach and hilly areas. Based on the DPTI and the Australian Transport Assessment and Planning, the average kilometres travelled, lifetime and passenger occupancy rate are listed below:

1. The annual bus kilometres travelled are 65000.
2. DPTI Trial Buses lifetime is 25 years.
3. The passenger occupancy rate is 20.

The results shown in Tables 8.5, 8.6, 8.7, 8.8 and Figures 8.1, 8.2, 8.3, 8.4 indicate that the 1905/micro hybrid bus significantly reduces LCA GHG emissions, energy demand, particulate matter and human toxicity non cancer compared to other types of buses, including conventional LSD Scania, Volvo and Mercedes. In other words, the results stated that advanced bus technologies, including the micro hybrid (1905), offer significant energy savings and release fewer emissions than buses with conventional internal combustion engines. Furthermore, it is noted that most of the LCA GHG emissions, particulate matter released, and energy consumed occurs from tailpipe emissions (the operation phase), followed by upstream emissions (the fuel pathway).

| DPTI Trial Buses Model | Fuel Cycle (kg/pkm) | Tailpipe Emissions (kg/pkm) | Vehicle Manufacture (kg/pkm) | Vehicle Maintenance (kg/pkm) | Vehicle Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|---|---|---|
| **1905/Micro Hybrid** | 0.00892 | 0.04958 | 0.00166 | 0.00236 | 4.79E-05 | 0.0625 |
| **2451/LSD Volvo** | 0.00902 | 0.05078 | 0.00163 | 0.00245 | 4.31E-05 | 0.0639 |
| **2450/LSD Scania** | 0.00915 | 0.05145 | 0.00163 | 0.00245 | 4.31E-05 | 0.0648 |
| **1902/ LSD Scania** | 0.00917 | 0.05163 | 0.00163 | 0.00245 | 4.31E-05 | 0.0649 |
| **2452/LSD Mercedes** | 0.01 | 0.0563 | 0.00163 | 0.00245 | 4.31E-05 | 0.0704 |

**Table 8.5: LCA GHG Emissions (kg/pkm) of DPTI Trial Buses**

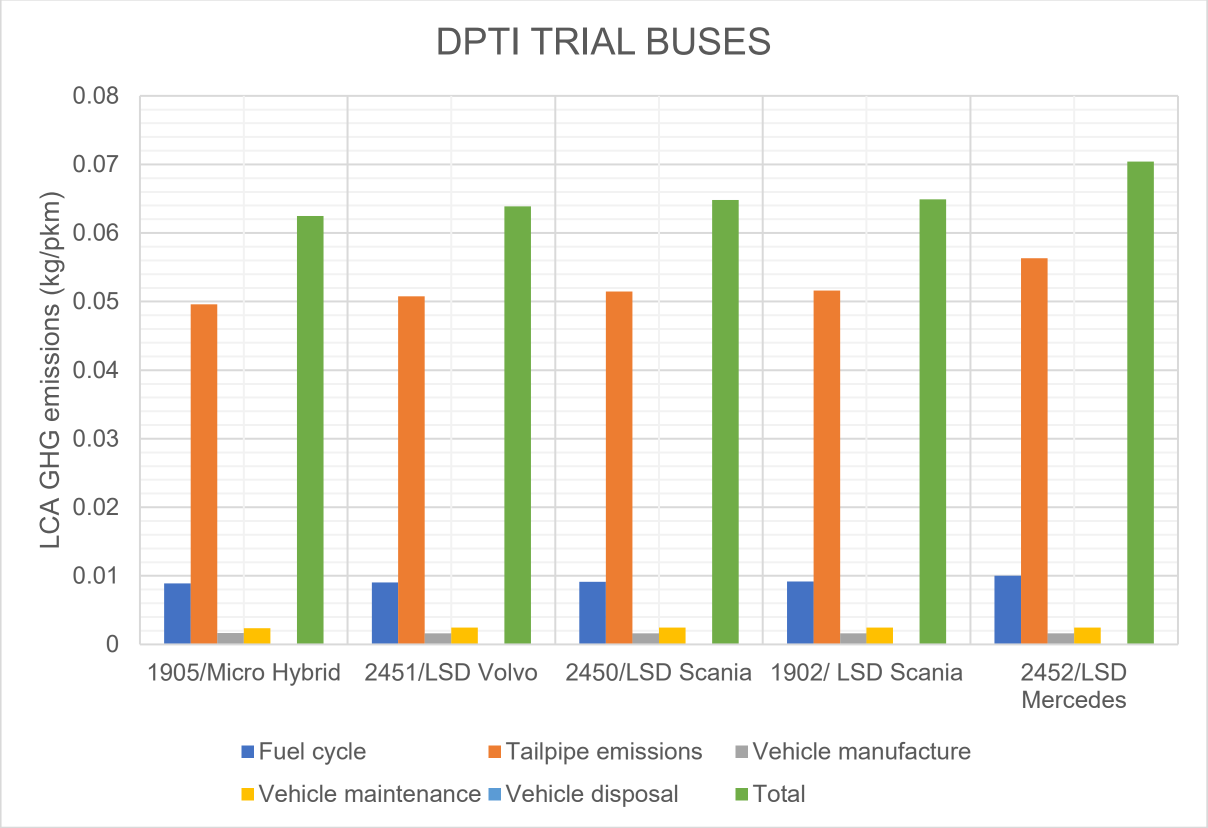


**Figure 8.1: LCA GHG Emissions (kg/pkm) of DPTI Trial Buses**

| DPTI Trial Buses Model | Fuel Cycle and Tailpipe Emissions (MJ/pkm) | Vehicle Manufacture (MJ/pkm) | Vehicle Maintenance (MJ/pkm) | Vehicle Disposal (MJ/pkm) | Total (MJ/pkm) |
|---|---|---|---|---|---|
| **1905/Micro Hybrid** | 0.703 | 0.0209 | 0.0294 | 2.32E-05 | 0.754 |
| **2451/LSD Volvo** | 0.711 | 0.0206 | 0.0295 | 1.59E-05 | 0.761 |
| **2450/LSD Scania** | 0.721 | 0.0206 | 0.0295 | 1.59E-05 | 0.771 |
| **1902/ LSD Scania** | 0.723 | 0.0206 | 0.0295 | 1.59E-05 | 0.773 |
| **2452/LSD Mercedes** | 0.791 | 0.0206 | 0.0295 | 1.59E-05 | 0.841 |

**Table 8.6: LCA Energy Use (MJ/pkm) of DPTI Trial Buses**

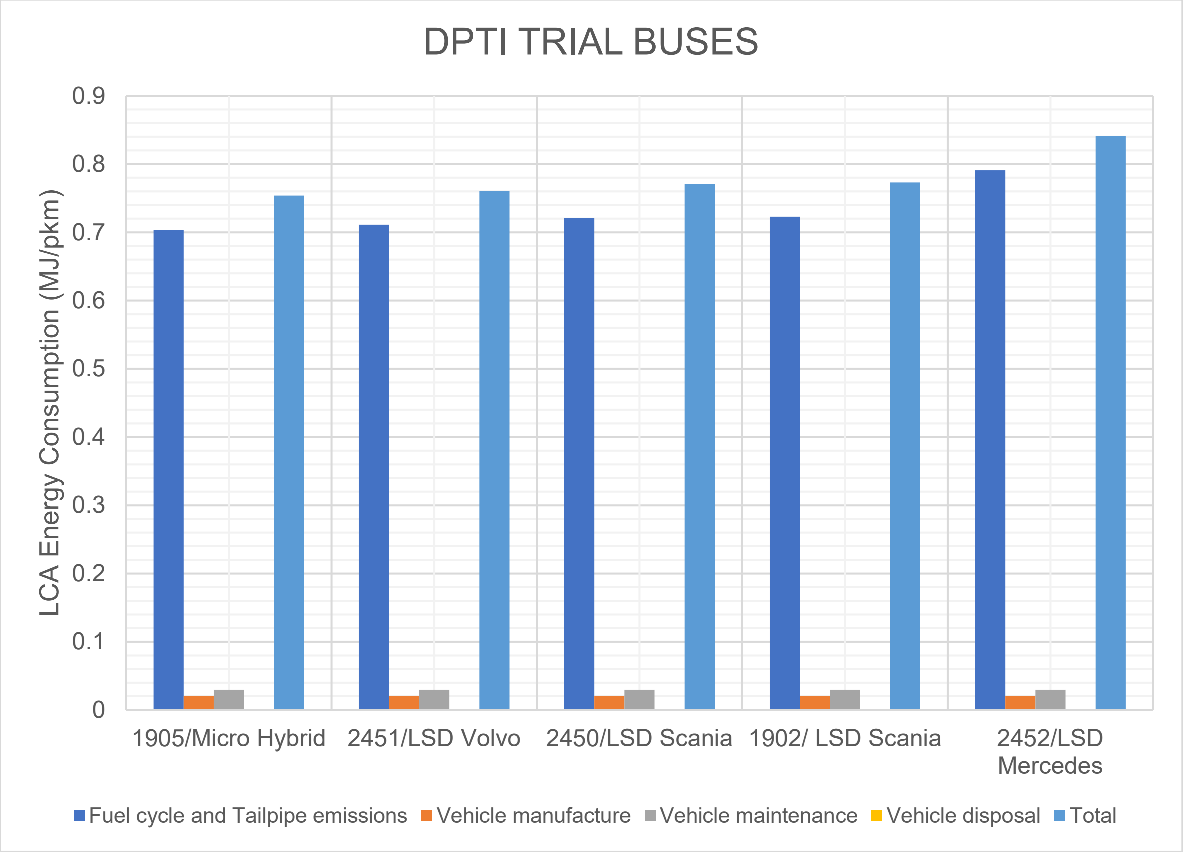


**Figure 8.2: LCA Energy Use (MJ/pkm) of DPTI Trial Buses**

| DPTI Trial Buses Model | Fuel Cycle and Tailpipe Emissions (kg/pkm) | Bus Manufacture, Maintenance, and Disposal (kg/pkm) | Total (kg/pkm) |
|---|---|---|---|
| **1905/Micro Hybrid** | 7.18E-06 | 9.30E-07 | 8.11E-06 |
| **2451/LSD Volvo** | 7.26E-06 | 8.93E-07 | 8.15E-06 |
| **2450/LSD Scania** | 7.36E-06 | 8.93E-07 | 8.26E-06 |
| **1902/ LSD Scania** | 7.38E-06 | 8.93E-07 | 8.27E-06 |
| **2452/LSD Mercedes** | 8.07E-06 | 8.93E-07 | 8.96E-06 |

**Table 8.7: LCA PM (kg/pkm) of DPTI Trial Buses**

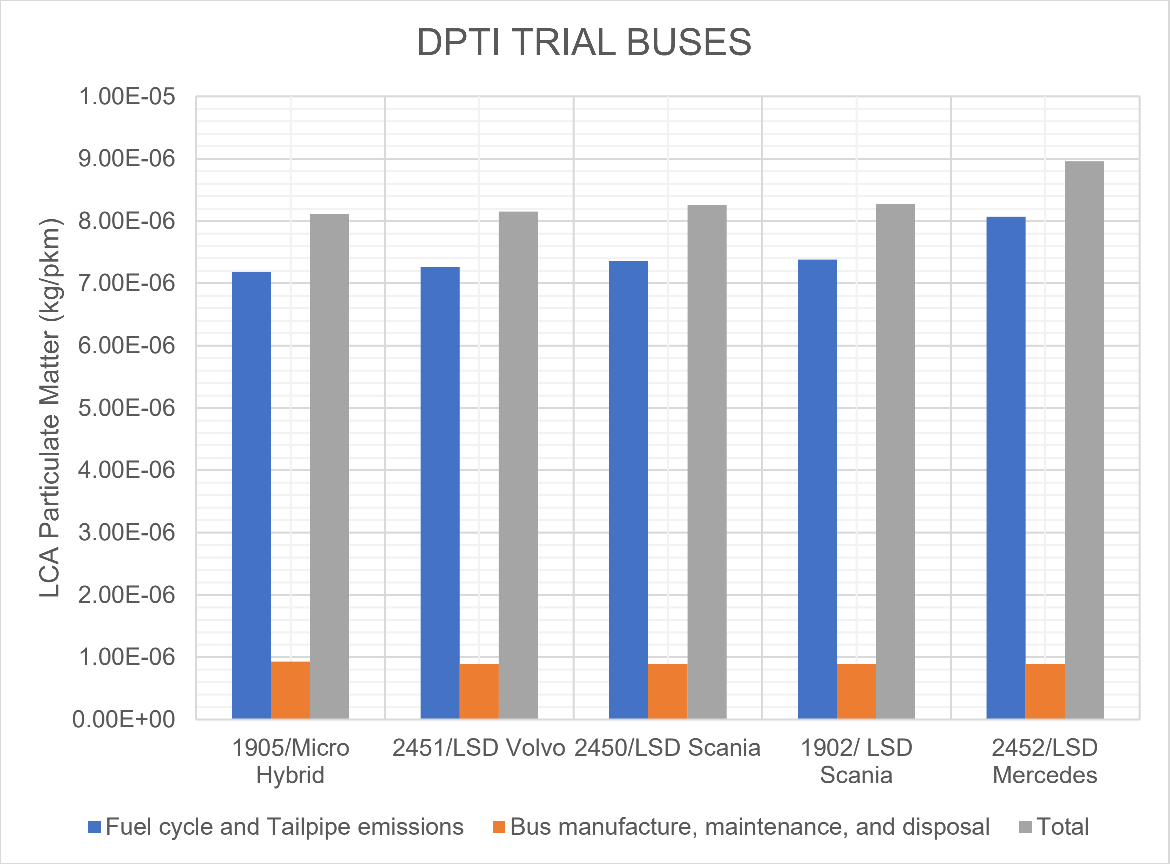


**Figure 8.3: LCA PM (kg/pkm) of DPTI Trial Buses**

| **DPTI Trial Buses Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Bus Manufacture, Maintenance, and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| **1905/Micro Hybrid** | 3.43E-10 | 3.46E-10 | 6.89E-10 |
| **2451/LSD Volvo** | 3.47E-10 | 3.69E-10 | 7.17E-10 |
| **1902/ LSD Scania** | 3.53E-10 | 3.69E-10 | 7.22E-10 |
| **2450/LSD Scania** | 3.52E-10 | 3.69E-10 | 7.22E-10 |
| **2452/LSD Mercedes** | 3.86E-10 | 3.69E-10 | 7.55E-10 |

**Table 8.8: LCA HTnc (kg/pkm) of DPTI Trial Buses**

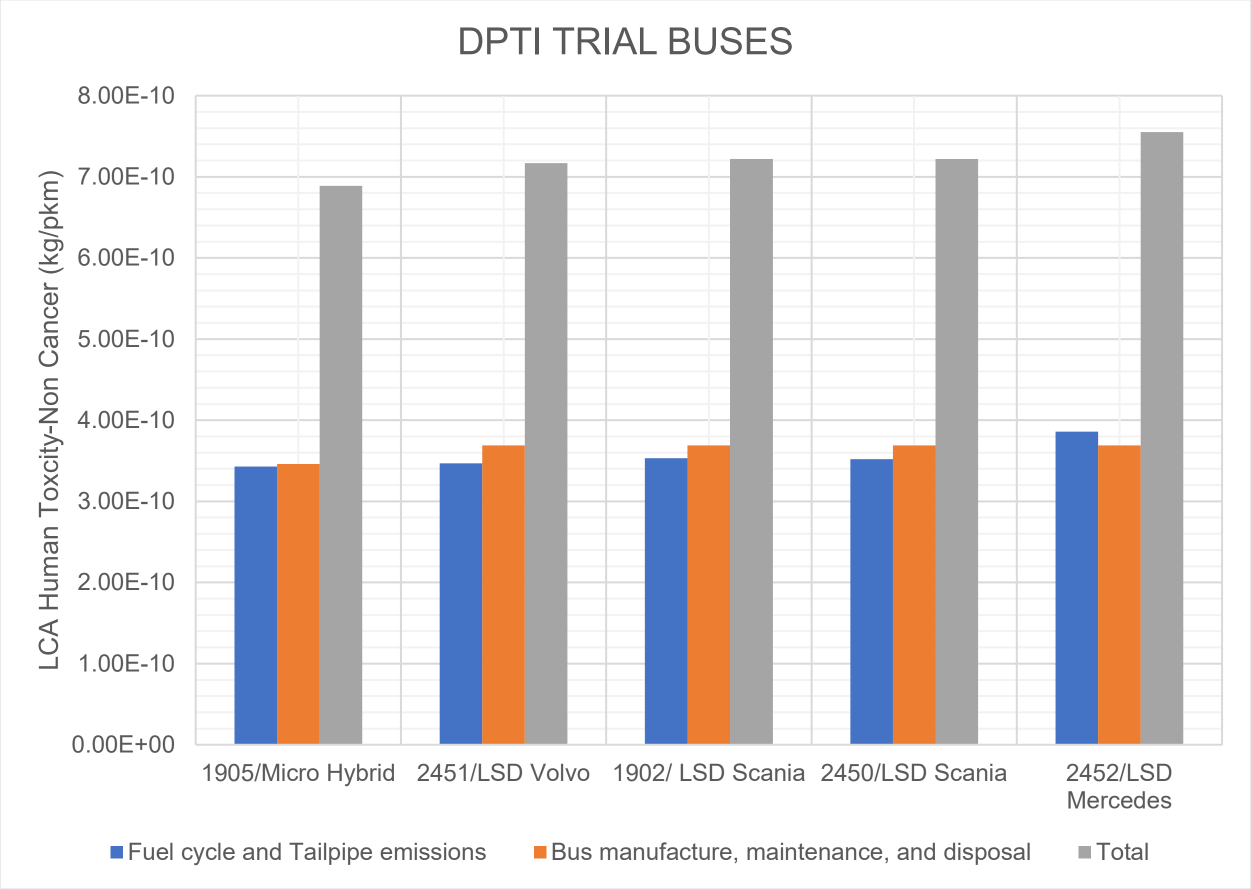


**Figure 8.4: LCA HTnc (kg/pkm) of DPTI Trial Buses**

On the other hand, Table 8.9 and Figure 8.5 shows that LCA human toxicity cancer value for the 1902/Scania LSD bus is much smaller than that of other buses. This is due to a number of reasons, the first of which is that bus fuel economy plays a significant role in relation to energy demand and emissions. For instance, if the bus powertrain consumes a high amount of fuel, the environmental impact on both human health and the environment increases. Other factors that directly affect the LCA results include bus powertrain efficiency, bus driving behaviour (the driving cycle) and driver skill. In addition, most of the LCA human toxicity cancer and non-cancer is released during the vehicle manufacture phase. The amount depends on bus fuel consumption (fuel economy) and the vehicle manufacturing material, which determines the energy use and emissions.

| **DPTI Trial Buses Model** | **Fuel Cycle and Tailpipe Emissions (kg/pkm)** | **Bus Manufacture, Maintenance, and Disposal (kg/pkm)** | **Total (kg/pkm)** |
|---|---|---|---|
| 1902/ LSD Scania | 4.11E-11 | 7.56E-11 | 1.17E-10 |
| 2450/LSD Scania | 4.17E-11 | 7.56E-11 | 1.17E-10 |
| 2451/LSD Volvo | 4.11E-11 | 7.56E-11 | 1.17E-10 |
| 1905/Micro Hybrid | 4.06E-11 | 7.81E-11 | 1.19E-10 |
| 2452/LSD Mercedes | 4.57E-11 | 7.56E-11 | 1.21E-10 |

**Table 8.9: LCA HTc (kg/pkm) of DPTI Trial Buses**

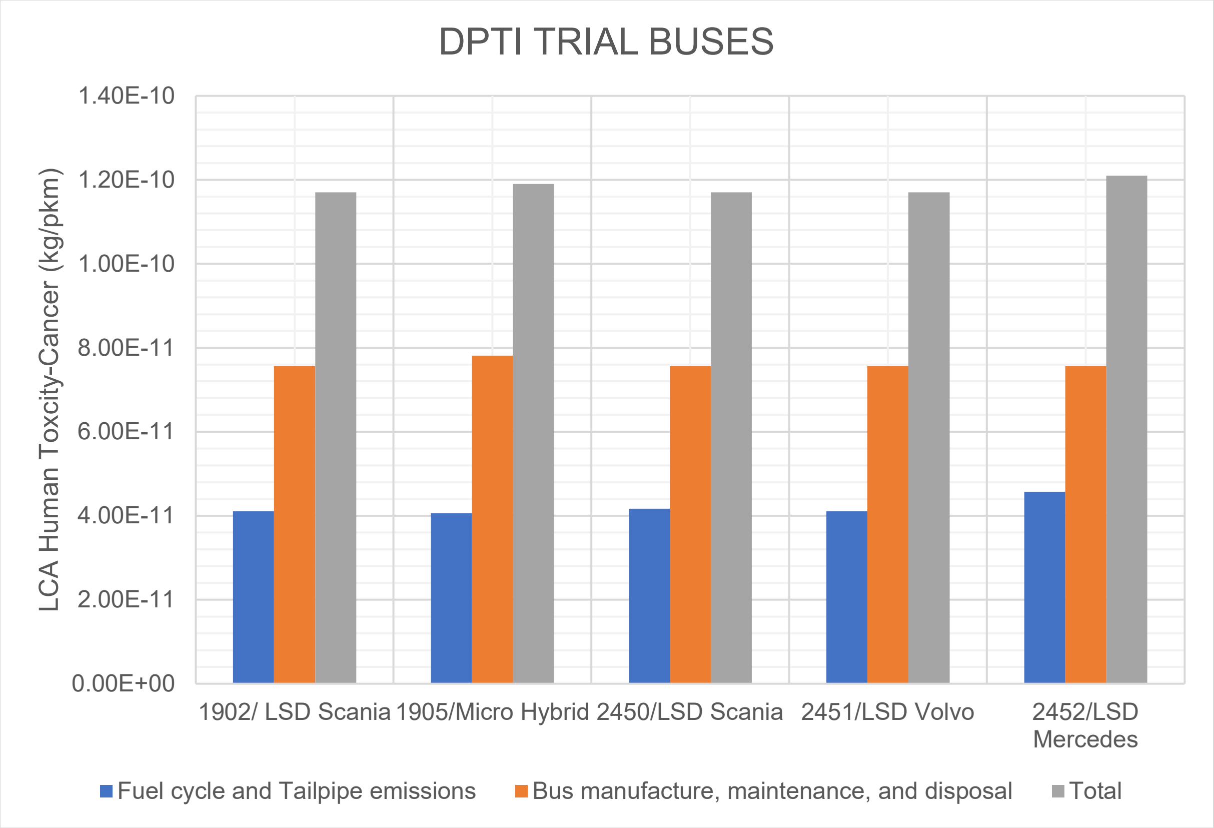


**Figure 8.5: LCA HTc (kg/pkm) of DPTI Trial Buses**

## 8.4 Uncertainty Analysis of LCA for DPTI Trial Buses: Results and Findings

Evaluating uncertainty is relatively new in environmental LCA, but it provides useful information to assess the reliability of LCA-based decisions and can guide future research towards reducing uncertainty. The uncertainty due to input data is identified in this chapter.

The results show that the most influential factors for the LCA results are the LCA PM, HTc and HTnc. For instance, in Table 8.10 and Figure 8.6, the 1902/Scania bus results indicate that the coefficient of variation (CV) is close to the mean value for both the energy demand and global warming potential (GWP) categories. The CV is 6% for energy use and 3% for GHG emissions. This means that the database used to build the LCA GHG emissions and energy use of public transport buses in South Australia is reliable.

| **Impact Category** | **Mean** | **SD** | **CV%** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76939747 | 0.042403057 | 6 |
| **Global warming (GWP100a) (kg/pkm)** | 0.063622779 | 0.002211738 | 3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.20E-10 | 5.76E-11 | 48 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.14E-10 | 1.68E-10 | 24 |
| **Particulate Matter (kg/pkm)** | 8.27E-06 | 1.92E-06 | 23 |

**Table 8.10: Uncertainty Analysis of 1902/Scania Buses' LCA**

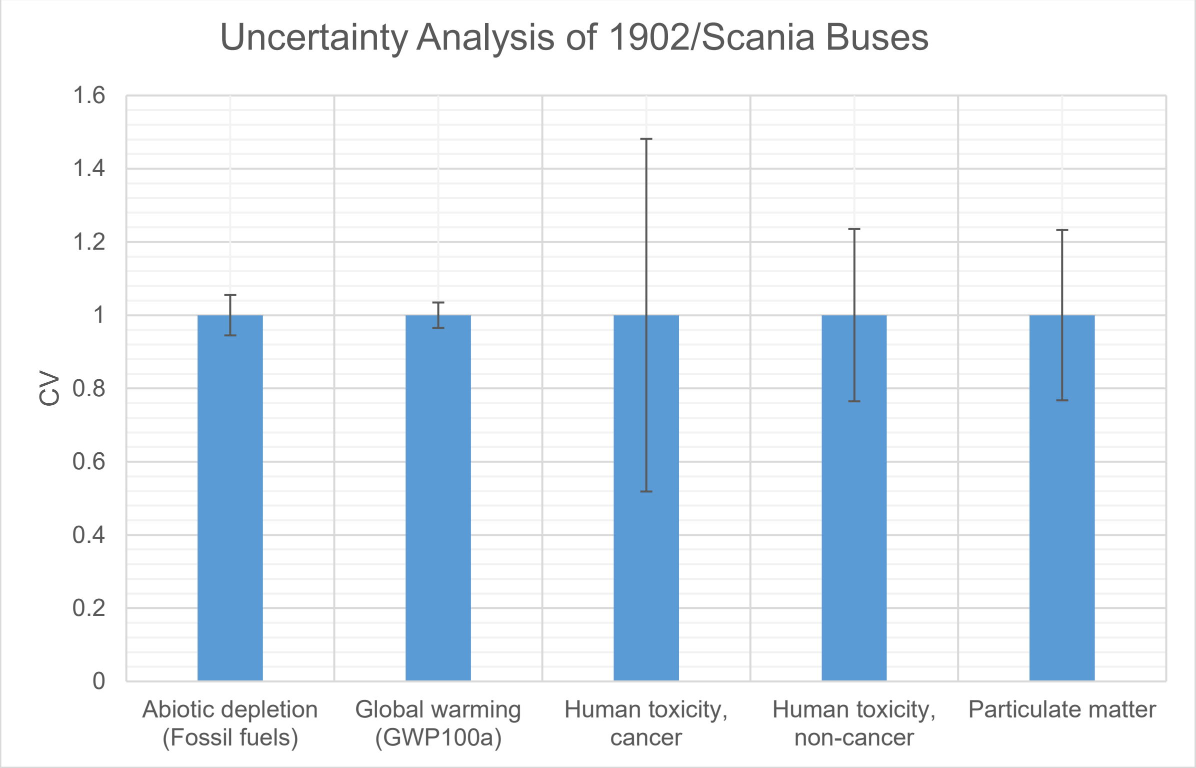


**Figure 8.6: Uncertainty Analysis of 1902/Scania Buses' LCA**

The data related to human health is far from the mean value. The uncertainty ranges can be seen clearly in LCA PM, HTc and HTnc. For instance, in Table 8.11 and Figure 8.7, for the 1905/ micro hybrid bus, the CV is 24% for PM, 36% for HTc and 37% for HTnc. This situation has arisen because most of the data related to human health has been adapted to the Australian database from global databases (namely, from the USA and the EU).

| Impact Category | Mean | SD | CV% |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.74863301 | 0.037380738 | 5 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.062059954 | 0.001984212 | 3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.18E-10 | 4.21E-11 | 36 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.83E-10 | 2.52E-10 | 37 |
| **Particulate Matter (kg/pkm)** | 8.13E-06 | 1.96E-06 | 24 |

**Table 8.11: Uncertainty Analysis of 1905/Micro Hybrid Buses' LCA**

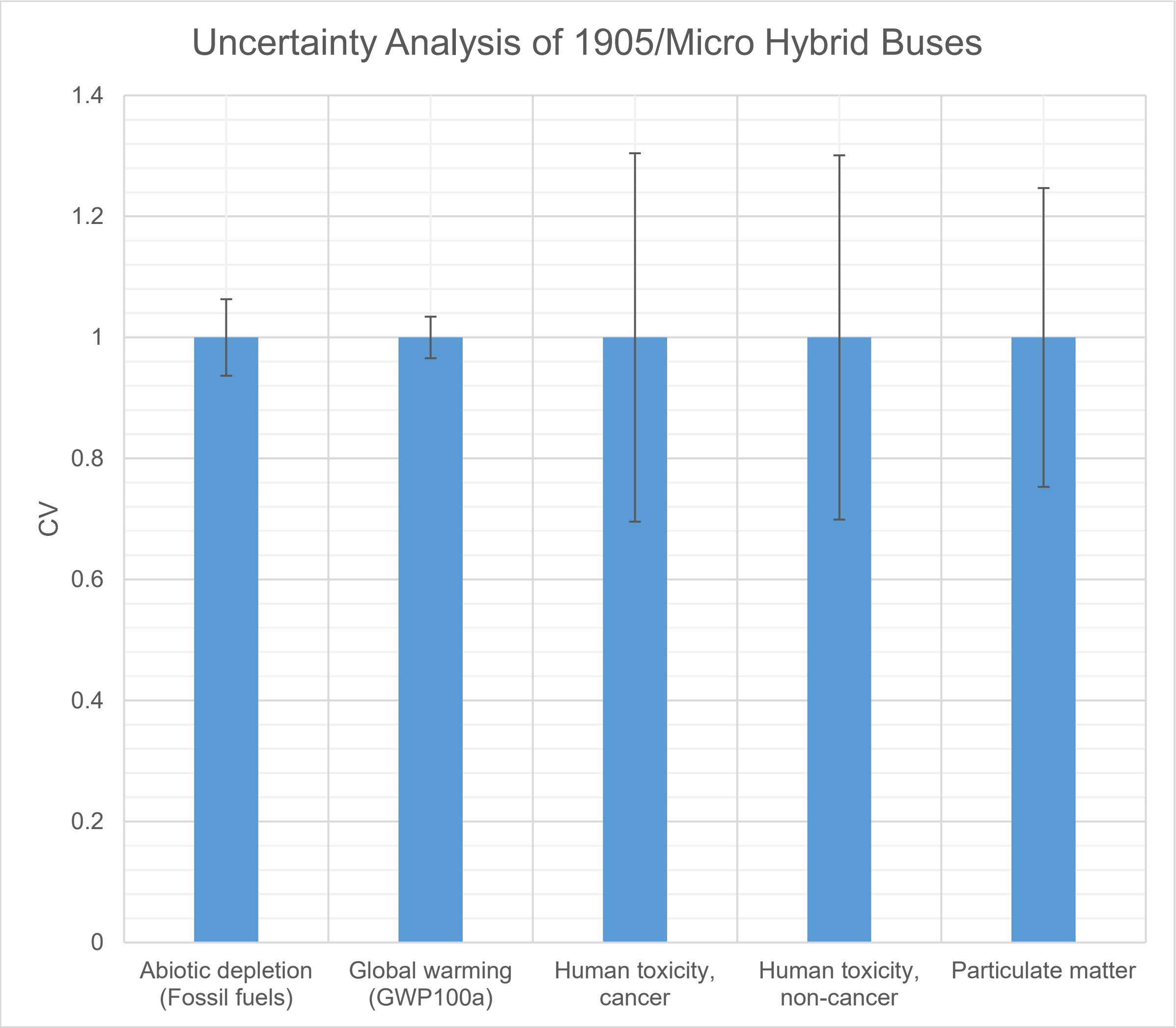


**Figure 8.7: Uncertainty Analysis of 1905/Micro Hybrid Buses' LCA**

Sensitivity analyses were performed for all other types of bus, and the results can be found in Appendix F.

## 8.5 The Sensitivity Analysis of DPTI Trial Buses LCA: Results and Findings

The LCA results for public transport buses (DPTI Trial Buses) in South Australia are necessary in order to identify the parameters that considerably change the output, and which might warrant further investigation. Therefore, in order to enhance confidence in the results, sensitivity analyses were performed with variations assumptions. The parameters that significantly influence the overall LCA results are outlined below.

### 8.5.1 Kilometres Travelled

The effect of this factor can be considerable, especially for impact categories GWP, energy used and PM. For instance, for the **1902/ LSD Scania bus,** when the kilometres travelled value deviates by plus or minus 10% from the reference value (1625000 km), the LCA changes as detailed below:

1. LCA GHG emissions increase by 10.4% (0.071634896) and decrease by 8.5% (0.0593608).
2. LCA energy use increases by 10.4% (0.85340259) and decreases by 8.5% (0.70735938).
3. LCA PM increases by 9.9% (9.09E-06) and decreases by 8.1% (7.60E-06).

The effect of the kilometres travelled value is the lowest on both LCA HTc and HTnc. For instance, for **1902/ LSD Scania buses,** when this factor varies from the base value by plus or minus 10%, the following changes occur:

1. LCA HTc (in kg/pkm) increases by 4.3% (1.22E-10) and decreases by 2.6% (1.14E-10) from the base value (1.17E-10).

2. LCA HTnc increases by 5.5% (7.62E-10) and decreases by 4.4% (6.90E-10) from the base value (7.22E-10), as shown in Tables 8.12, 8.13, 8.14, 8.15, 8.16 and 8.17 and Figure 8.8.

   Notably, the LCA results also depend on fuel resources and advanced vehicle technologies.

| Impact Category | Reference Value (Base) | Case A (−10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.071634896 | 0.0593608 | 10.4 | −8.5 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77307882 | 0.85340259 | 0.70735938 | 10.4 | −8.5 |
| **Particulate Matter (kg/pkm)** | 8.27E-06 | 9.09E-06 | 7.60E-06 | 9.9 | −8.1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.22E-10 | 1.14E-10 | 4.3 | −2.6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.62E-10 | 6.90E-10 | 5.5 | −4.4 |

**Table 8.12: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (kilometres travelled parameter)**

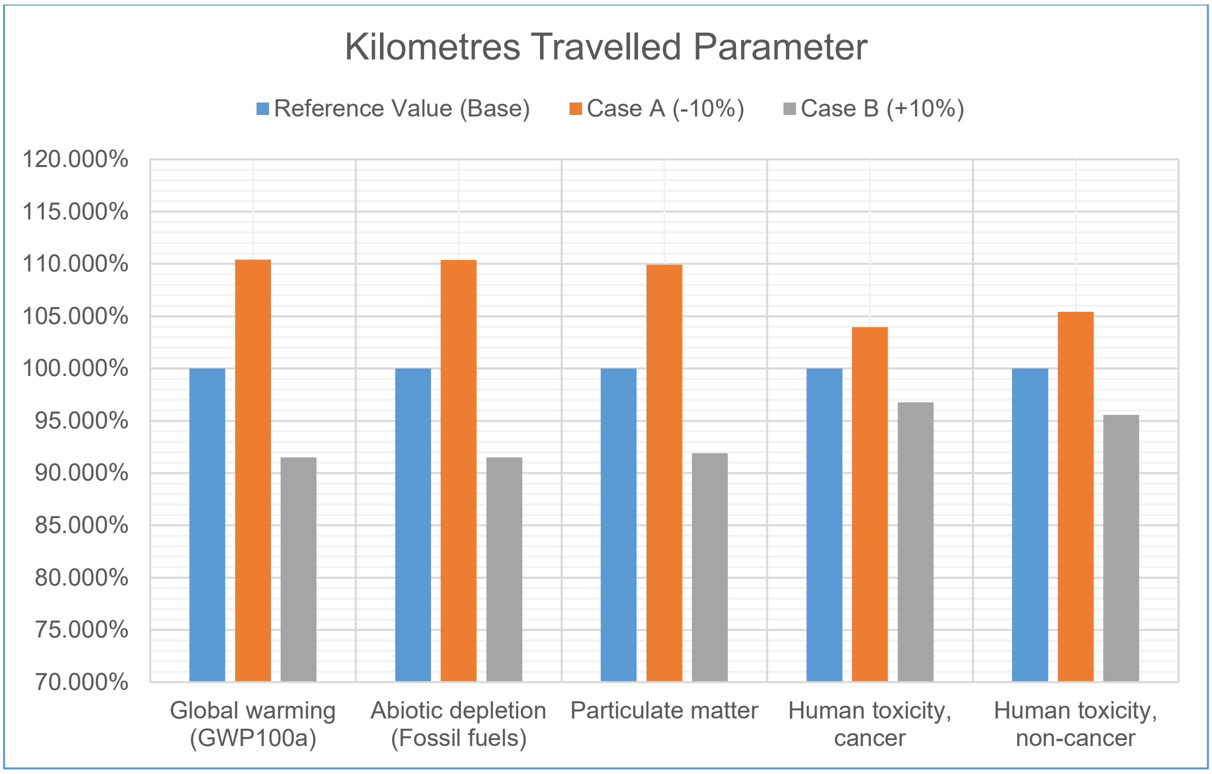


**Figure 8.8: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (kilometres travelled parameter)**

This analysis has been performed for other vehicle and fuel types, and the full results can be found in Appendix I. Below is a summary of the sensitivity analyses for vehicles' LCA.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.064884143 | 0 | 0 | |
| **Kilometres Travelled** | 0.071634896 | 10.4 | 0.0593608 | 8.5 |
| **Occupancy Rate** | 0.071222159 | 9.8 | 0.059773538 | 7.9 |
| **Fuel Consumption** | 0.063967354 | 1.4 | 0.065800933 | 1.4 |
| **Crude Oil Refining** | 0.06444583 | 0.68 | 0.065322456 | 0.68 |
| **Vehicle Maintenance** | 0.064639065 | 0.38 | 0.065129222 | 0.38 |
| **Vehicle Manufacture** | 0.064720793 | 0.3 | 0.065047494 | 0.3 |
| **Crude Oil Extraction** | 0.064829295 | 0.08 | 0.064938992 | 0.08 |
| **Vehicle Disposal** | 0.064879835 | 0.01 | 0.064888452 | 0.01 |

**Table 8.13: Summary of Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (GWP)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Abiotic Depletion (Fossil Fuels) (MJ/pkm) | Change (%) | Abiotic Depletion (Fossil Fuels) (MJ/pkm) | Change (%) |
| **Reference Value (Base)** | 0.77307882 | 0 | 0 | |
| **Kilometres Travelled** | 0.85340259 | 10.4 | 0.70735938 | 8.5 |
| **Occupancy Rate** | 0.8483861 | 9.7 | 0.71237587 | 7.9 |
| **Fuel Consumption** | 0.70078743 | 9.4 | 0.84537022 | 9.4 |
| **Crude Oil Refining** | 0.71043349 | 8.10 | 0.83572415 | 8.10 |
| **Crude Oil Extraction** | 0.75487155 | 2.36 | 0.7912861 | 2.36 |
| **Vehicle Maintenance** | 0.77012479 | 0.38 | 0.77603286 | 0.38 |
| **Vehicle Manufacture** | 0.77101796 | 0.3 | 0.77513969 | 0.3 |
| **Vehicle Disposal** | 0.77307723 | 0.001 | 0.77308041 | 0.001 |

**Table 8.14: Summary of Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (energy use)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Particulate Matter (kg/pkm) | Change (%) | Particulate Matter (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 8.27E-06 | 0 | 0 | |
| **Kilometres Travelled** | 9.09E-06 | 9.9 | 7.60E-06 | 8.1 |
| **Occupancy Rate** | 9.00E-06 | 8.8 | 7.69E-06 | 7.0 |
| **Fuel Consumption** | 7.53E-06 | 8.9 | 9.01E-06 | 8.9 |
| **Crude Oil Refining** | 7.93E-06 | 4.11 | 8.62E-06 | 4.23 |
| **Vehicle Manufacture** | 8.21E-06 | 0.7 | 8.33E-06 | 0.7 |
| **Vehicle Maintenance** | 8.24E-06 | 0.36 | 8.30E-06 | 0.36 |
| **Crude Oil Extraction** | 8.25E-06 | 0.24 | 8.30E-06 | 0.36 |
| **Vehicle Disposal** | 8.27E-06 | 0.001 | 8.27E-06 | 0.001 |

**Table 8.15: Summary of Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (PM)**

|  | 10% Decrease |  | 10% Increase |  |
|---|---|---|---|---|
|  | Human Toxicity, Cancer (kg/pkm) | Change (%) | Human Toxicity, Cancer (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 1.17E-10 | 0 | 0 |  |
| **Vehicle Manufacture** | 1.10E-10 | 6.0 | 1.24E-10 | 6.0 |
| **Kilometres Travelled** | 1.22E-10 | 4.3 | 1.14E-10 | 2.6 |
| **Fuel Consumption** | 1.13E-10 | 3.4 | 1.22E-10 | 4.3 |
| **Occupancy Rate** | 1.14E-10 | 2.6 | 1.21E-10 | 3.4 |
| **Crude Oil Refining** | 1.14E-10 | 2.56 | 1.20E-10 | 2.56 |
| **Vehicle Maintenance** | 1.17E-10 | 0.001 | 1.18E-10 | 0.85 |
| **Crude Oil extraction** | 1.17E-10 | 0.001 | 1.17E-10 | 0.001 |
| **Vehicle Disposal** | 1.17E-10 | 0.001 | 1.17E-10 | 0.001 |

**Table 8.16: Summary of Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (HTc)**

|  | 10% Decrease |  | 10% Increase |  |
|---|---|---|---|---|
|  | Human Toxicity, Non-Cancer (kg/pkm) | Change (%) | Human Toxicity, Non-Cancer (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 7.22E-10 | 0 | 0 |  |
| **Kilometres Travelled** | 7.62E-10 | 5.5 | 6.90E-10 | 4.4 |
| **Fuel Consumption** | 6.87E-10 | 4.8 | 7.58E-10 | 5.0 |
| **Vehicle Manufacture** | 6.99E-10 | 3.2 | 7.46E-10 | 3.3 |
| **Crude Oil Refining** | 7.02E-10 | 2.77 | 7.43E-10 | 2.91 |
| **Vehicle Maintenance** | 7.09E-10 | 1.80 | 7.36E-10 | 1.94 |
| **Occupancy Rate** | 7.25E-10 | 0.4 | 7.27E-10 | 0.7 |
| **Crude Oil Extraction** | 7.20E-10 | 0.28 | 7.24E-10 | 0.28 |
| **Vehicle Disposal** | 7.22E-10 | 0.001 | 7.22E-10 | 0.001 |

**Table 8.17: Summary of Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (HTnc)**

### 8.5.2 Passenger Occupancy Rate

The effect of the passenger occupancy rate parameter can be observed on LCA GWP, energy use and PM emissions, while it has very little impact on either LCA HTc or HTnc. For instance, for the **2452/LSD Mercedes bus**, when the passenger occupancy rate increases and decreases by 10% from the reference value (20), LCA GWP, energy use, PM, HTc and HTnc change as detailed below and as shown in Tables 8.18, 8.19, 8.20, 8.21 and 8.22, respectively:

1. increase by 9.9% (0.071634896), 9.9% (0.85340259), 9% (9.09E-06), 1.7% (1.19E-10) and 0.8% (7.61E-10), respectively
2. decrease by 8% (0.0593608), 8% (0.70735938), 7.1% (7.60E-06), 3.3% (1.25E-10) and 0.3% (7.57E-10), respectively.

Passenger occupancy rate does not alter the LCA human health impact much, but its impact can be seen clearly on LCA GWP, energy use and PM.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.070436485 | 0 | 0 | |
| **Kilometres Travelled** | 0.077804164 | 10.5 | 0.064408384 | 8.6 |
| **Occupancy Rate** | 0.077391427 | 9.9 | 0.064821121 | 8.0 |
| **Fuel Consumption** | 0.069433921 | 1.4 | 0.071439049 | 1.4 |
| **Crude Oil Refining** | 0.069957164 | 0.68 | 0.070915806 | 0.68 |
| **Vehicle Maintenance** | 0.070191406 | 0.35 | 0.070681563 | 0.35 |
| **Vehicle Manufacture** | 0.070273135 | 0.2 | 0.070599835 | 0.2 |
| **Crude Oil Extraction** | 0.070376505 | 0.09 | 0.070496465 | 0.09 |
| **Vehicle Disposal** | 0.070432176 | 0.01 | 0.070440793 | 0.01 |

**Table 8.18: Summary of Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (GWP)**

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.84071409 | 0 | 0 | |
| **Kilometres Travelled** | 0.92855288 | 10.4 | 0.76884598 | 8.5 |
| **Occupancy Rate** | 0.92353639 | 9.9 | 0.77386247 | 8.0 |
| **Fuel Consumption** | 0.76165917 | 9.4 | 0.919769 | 9.4 |
| **Crude Oil Refining** | 0.77220771 | 8.15 | 0.90922046 | 8.15 |
| **Crude Oil Extraction** | 0.82080335 | 2.37 | 0.86062482 | 2.37 |
| **Vehicle Maintenance** | 0.83776005 | 0.35 | 0.84366812 | 0.35 |
| **Vehicle Manufacture** | 0.83865322 | 0.2 | 0.84277495 | 0.2 |
| **Vehicle Disposal** | 0.8407125 | 0.001 | 0.84071567 | 0.001 |

**Table 8.19: Summary of Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (energy use)**

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Particulate Matter (kg/pkm)** | **Change (%)** | **Particulate Matter (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 8.96E-06 | 0 | 0 | |
| **Kilometres Travelled** | 9.86E-06 | 10.0 | 8.23E-06 | 8.1 |
| **Occupancy Rate** | 9.77E-06 | 9.0 | 8.32E-06 | 7.1 |
| **Fuel Consumption** | 8.16E-06 | 8.9 | 9.77E-06 | 9.0 |
| **Crude Oil Refining** | 8.58E-06 | 4.24 | 9.34E-06 | 4.24 |
| **Vehicle Manufacture** | 8.90E-06 | 0.7 | 9.02E-06 | 0.7 |
| **Vehicle Maintenance** | 8.93E-06 | 0.33 | 8.99E-06 | 0.33 |
| **Crude Oil Extraction** | 8.93E-06 | 0.33 | 8.99E-06 | 0.33 |
| **Vehicle Disposal** | 8.96E-06 | 0.001 | 8.96E-06 | 0.001 |

**Table 8.20: Summary of Sensitivity Analysis of LCA for 2452/LSD Mercedes Buses (PM)**

|  | 10% Decrease |  | 10% Increase |  |
|---|---|---|---|---|
|  | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.21E-10 | 0 | 0 |  |
| **Vehicle Manufacture** | 1.14E-10 | 5.8 | 1.28E-10 | 5.8 |
| **Kilometres Travelled** | 1.26E-10 | 4.1 | 1.17E-10 | 3.3 |
| **Fuel Consumption** | 1.17E-10 | 3.3 | 1.26E-10 | 4.1 |
| **Crude Oil Refining** | 1.18E-10 | 2.48 | 1.24E-10 | 2.48 |
| **Occupancy Rate** | 1.19E-10 | 1.7 | 1.25E-10 | 3.3 |
| **Vehicle Maintenance** | 1.21E-10 | 0.001 | 1.22E-10 | 0.83 |
| **Crude Oil Extraction** | 1.21E-10 | 0.001 | 1.21E-10 | 0.001 |
| **Vehicle Disposal** | 1.21E-10 | 0.001 | 1.21E-10 | 0.001 |

**Table 8.21: Summary of Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (HTc)**

|  | 10% Decrease |  | 10% Increase |  |
|---|---|---|---|---|
|  | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 7.55E-10 | 0 | 0 |  |
| **Kilometres Travelled** | 7.98E-10 | 5.7 | 7.20E-10 | 4.6 |
| **Fuel Consumption** | 7.17E-10 | 5.0 | 7.94E-10 | 5.2 |
| **Vehicle Manufacture** | 7.32E-10 | 3.0 | 7.79E-10 | 3.2 |
| **Crude Oil Refining** | 7.33E-10 | 2.91 | 7.78E-10 | 3.05 |
| **Vehicle Maintenance** | 7.42E-10 | 1.72 | 7.69E-10 | 1.85 |
| **Occupancy Rate** | 7.61E-10 | 0.8 | 7.57E-10 | 0.3 |
| **Crude Oil Extraction** | 7.53E-10 | 0.26 | 7.57E-10 | 0.26 |
| **Vehicle Disposal** | 7.55E-10 | 0.001 | 7.55E-10 | 0.001 |

**Table 8.22: Summary of Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (HTnc)**

### 8.5.3 Fuel Consumption

The fuel consumption parameter (in L/100 km) has a direct impact on LCA energy use and emissions. For instance, when the fuel consumption value for the **2451/ LSD Volvo bus** decreases or increases from the reference value (36.84 L/100 km) by 10%, the LCA GWP, energy use, PM, HTc and HTnc change, respectively, as listed below and as shown in Tables 8.23, 8.24, 8.25, 8.26 and 8.27:

1. decreases by 1.4% (0.063967354), 9.3% (0.70078743), 8.8% (7.53E-06), 3.4% (1.13E-10) and 4.9% (6.87E-10)
2. increases by 1.4% (0.065800933), 9.3% (0.84537022), 9% (9.01E-06), 3.4% (1.22E-10) and 4.7% (7.58E-10).

This parameter has a noticeable impact on life cycle energy use and emissions for most types of bus. Also, the impact of this parameter is much greater for conventional buses than for advanced buses.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** | **Global Warming (GWP100a) (kg/pkm)** | **Change (%)** |
| Reference Value (Base) | 0.063909597 | 0 | 0 | |
| Kilometres Travelled | 0.070552067 | 10.4 | 0.058474849 | 8.5 |
| Occupancy Rate | 0.07013933 | 9.7 | 0.058887586 | 7.9 |
| Fuel Consumption | 0.063007499 | 1.4 | 0.064811695 | 1.4 |
| Crude Oil Refining | 0.063478308 | 0.67 | 0.064340886 | 0.67 |
| Vehicle Maintenance | 0.063664519 | 0.38 | 0.064154675 | 0.38 |
| Vehicle Manufacture | 0.063746247 | 0.3 | 0.064072947 | 0.3 |
| Crude Oil Extraction | 0.063855627 | 0.08 | 0.063963567 | 0.08 |
| Vehicle Disposal | 0.063905289 | 0.01 | 0.063913905 | 0.01 |

**Table 8.23: Summary of Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (GWP)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Abiotic Depletion (Fossil Fuels) (MJ/pkm) | Change (%) | Abiotic Depletion (Fossil Fuels) (MJ/pkm) | Change (%) |
| **Reference Value (Base)** | 0.76149366 | 0 | 0 | |
| **Kilometres Travelled** | 0.84053019 | 10.4 | 0.69682741 | 8.5 |
| **Occupancy Rate** | 0.8355137 | 9.7 | 0.7018439 | 7.8 |
| **Fuel Consumption** | 0.69036079 | 9.3 | 0.83262654 | 9.3 |
| **Crude Oil Refining** | 0.69985227 | 8.09 | 0.82313506 | 8.09 |
| **Crude Oil Extraction** | 0.74357817 | 2.35 | 0.77940915 | 2.35 |
| **Vehicle Maintenance** | 0.75853963 | 0.39 | 0.7644477 | 0.39 |
| **Vehicle Manufacture** | 0.7594328 | 0.3 | 0.76355453 | 0.3 |
| **Vehicle Disposal** | 0.76149208 | 0.001 | 0.76149525 | 0.001 |

**Table 8.24: Summary of Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (energy use)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | Particulate Matter (kg/pkm) | Change (%) | Particulate Matter (kg/pkm) | Change (%) |
| **Reference Value (Base)** | 8.15E-06 | 0 | 0 | |
| **Kilometres Travelled** | 8.96E-06 | 9.9 | 7.49E-06 | 8.1 |
| **Fuel Consumption** | 7.43E-06 | 8.8 | 8.88E-06 | 9.0 |
| **Occupancy Rate** | 8.87E-06 | 8.8 | 7.58E-06 | 7.0 |
| **Crude Oil Refining** | 7.81E-06 | 4.17 | 8.50E-06 | 4.29 |
| **Vehicle Manufacture** | 8.09E-06 | 0.7 | 8.22E-06 | 0.9 |
| **Crude Oil extraction** | 8.13E-06 | 0.25 | 8.18E-06 | 0.37 |
| **Vehicle Maintenance** | 8.13E-06 | 0.25 | 8.18E-06 | 0.37 |
| **Vehicle Disposal** | 8.15E-06 | 0.001 | 8.15E-06 | 0.001 |

**Table 8.25: Summary of Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (PM)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.17E-10 | 0 | 0 | |
| **Vehicle Manufacture** | 1.10E-10 | 6.0 | 1.24E-10 | 6.0 |
| **Fuel Consumption** | 1.13E-10 | 3.4 | 1.21E-10 | 3.4 |
| **Kilometres Travelled** | 1.21E-10 | 3.4 | 1.13E-10 | 3.4 |
| **Occupancy Rate** | 1.14E-10 | 2.6 | 1.20E-10 | 2.6 |
| **Crude Oil Refining** | 1.14E-10 | 2.56 | 1.20E-10 | 2.56 |
| **Vehicle Maintenance** | 1.16E-10 | 0.85 | 1.17E-10 | 0.001 |
| **Crude Oil Extraction** | 1.17E-10 | 0.001 | 1.17E-10 | 0.001 |
| **Vehicle Disposal** | 1.17E-10 | 0.001 | 1.17E-10 | 0.001 |

**Table 8.26: Summary of Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (HTc)**

| | 10% Decrease | | 10% Increase | |
|---|---|---|---|---|
| | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 7.17E-10 | 0 | 0 | |
| **Kilometres Travelled** | 7.55E-10 | 5.3 | 6.85E-10 | 4.5 |
| **Fuel Consumption** | 6.82E-10 | 4.9 | 7.51E-10 | 4.7 |
| **Vehicle Manufacture** | 6.93E-10 | 3.3 | 7.40E-10 | 3.2 |
| **Crude Oil Refining** | 6.96E-10 | 2.93 | 7.37E-10 | 2.79 |
| **Vehicle Maintenance** | 7.03E-10 | 1.95 | 7.30E-10 | 1.81 |
| **Crude Oil Extraction** | 7.15E-10 | 0.28 | 7.19E-10 | 0.28 |
| **Occupancy Rate** | 7.18E-10 | 0.1 | 7.22E-10 | 0.7 |
| **Vehicle Disposal** | 7.17E-10 | 0.001 | 7.17E-10 | 0.001 |

**Table 8.27: Summary of Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (HTnc)**

### 8.5.4 Bus Manufacture, Maintenance and Disposal

The effect of the bus manufacture parameter on LCA HTc and HTnc is obvious, while its impact on LCA GWP, energy use and PM are much smaller. For instance, when the bus manufacture parameter values for the **2450/LSD Scania Bus** increase and decrease by 10% from the base value, LCA HTc and HTnc change, respectively, as listed below and as shown in Tables 8.28 and 8.29:

1. decrease by 6% (1.10E-10) and 3.3% (6.99E-10) from the base values (1.17E-10 and 7.22E-10)
2. increase by 6% (1.24E-10) and 3.2% (7.46E-10) from the base values.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 1.17E-10 | 0 | 0 | |
| **Vehicle Manufacture** | 1.10E-10 | 6.0 | 1.24E-10 | 6.0 |
| **Kilometres Travelled** | 1.22E-10 | 4.3 | 1.13E-10 | 3.4 |
| **Fuel Consumption** | 1.13E-10 | 3.4 | 1.21E-10 | 3.4 |
| **Occupancy Rate** | 1.14E-10 | 2.6 | 1.21E-10 | 3.4 |
| **Crude Oil Refining** | 1.14E-10 | 2.56 | 1.20E-10 | 2.56 |
| **Crude Oil Extraction** | 1.17E-10 | 0.001 | 1.17E-10 | 0.001 |
| **Vehicle Maintenance** | 1.17E-10 | 0.001 | 1.18E-10 | 0.85 |
| **Vehicle Disposal** | 1.17E-10 | 0.001 | 1.17E-10 | 0.001 |

**Table 8.28: Summary of Sensitivity Analysis for LCA of 2450/LSD Scania Buses (HTc)**

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** | **Human Toxicity, Non-Cancer (kg/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 7.22E-10 | 0 | 0 | |
| **Kilometres Travelled** | 7.61E-10 | 5.4 | 6.90E-10 | 4.4 |
| **Fuel Consumption** | 6.86E-10 | 5.0 | 7.57E-10 | 4.8 |
| **Vehicle Manufacture** | 6.98E-10 | 3.3 | 7.45E-10 | 3.2 |
| **Crude Oil Refining** | 7.01E-10 | 2.91 | 7.42E-10 | 2.77 |
| **Vehicle Maintenance** | 7.08E-10 | 1.94 | 7.35E-10 | 1.80 |
| **Occupancy Rate** | 7.24E-10 | 0.3 | 7.26E-10 | 0.6 |
| **Crude Oil Extraction** | 7.20E-10 | 0.28 | 7.23E-10 | 0.14 |
| **Vehicle Disposal** | 7.21E-10 | 0.14 | 7.22E-10 | 0.001 |

**Table 8.29: Summary of Sensitivity Analysis for LCA of 2450/LSD Scania LPG Buses (HTnc)**

Although the effect of bus maintenance on the LCA results is small, the effect on LCA HTnc is much greater. For instance, for **2450/LSD Scania buses,** when the bus maintenance parameter (in MJ) deviates from the base value (7.22E-10) by plus or minus 10%, LCA HTnc increases by 1.94% (7.08E-10) and decreases by 1.8% (7.35E-10), respectively, as shown in Table 8.24 above. Finally, the bus disposal parameter has a much smaller effect on the LCA results as a whole, so its impact can be ignored.

### 8.5.5 Crude Oil Extraction and Refining

The impact categories GWP, cumulative energy depletion and influence on human health are not much affected by the crude oil extraction and refining parameters. However, the crude oil refining parameter has a significant effect on LCA energy resource depletion. For instance, for the **1905/Micro Hybrid bus,** when the crude oil refining value deviates by plus or minus 10% from the base value (0.75359602), LCA energy use decreases by 8.09% (0.69265737) or increases by 8.09% (0.81453467), as shown in Table 8.30.

| | **10% Decrease** | | **10% Increase** | |
|---|---|---|---|---|
| | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** | **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | **Change (%)** |
| **Reference Value (Base)** | 0.75359602 | 0 | 0 | |
| **Kilometres Travelled** | 0.83173148 | 10.4 | 0.68966701 | 8.5 |
| **Occupancy Rate** | 0.068636322 | 9.7 | 0.057638611 | 7.8 |
| **Fuel Consumption** | 0.68327411 | 9.3 | 0.82391794 | 9.3 |
| **Crude Oil Refining** | 0.69265737 | 8.09 | 0.81453467 | 8.09 |
| **Crude Oil Extraction** | 0.73588478 | 2.35 | 0.77130726 | 2.35 |
| **Vehicle Maintenance** | 0.75065149 | 0.39 | 0.75654055 | 0.39 |
| **Vehicle Manufacture** | 0.75150518 | 0.3 | 0.75568686 | 0.3 |
| **Vehicle Disposal** | 0.75359371 | 0.001 | 0.75359834 | 0.001 |

**Table 8.30: Summary of Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (energy use)**

## 8.6 Discussion of Results

### 8.6.1 Department of Transport, Energy and Infrastructure (DPTI) Trial Buses

Adelaide metro buses (DPTI trial buses) are considered an essential public transport service in South Australia. In terms of emissions, this thesis' findings concur with studies by (Ercan and Tatari, 2015, Cooper et al., 2012, Kytö et al., 2012, Victorian department of transport, 2010, Williamson, 2012). In relation to this agreement, two important points are listed below:

1. Hybrid buses produce more HC and $NO_x$ emissions than LSD buses.
2. Battery-powered electric buses enact significant reductions to GHG emissions relative to conventional and alternative fuel-powered buses. Driving behaviour and average driving cycle speed also affect bus exhaust emissions and fuel consumption.

A report for the Australian Greenhouse Office (AGO) by Beer et al. (Beer et al., 2001a) highlighted that LCA GHG emissions and PM are 1.291kg/km and 6.8E-4kg/km, respectively, for LSD buses during the tailpipe emission phase. This does not match the LCA GHG emissions and PM in Tables 8.5 and 8.7 and Figures 8.1 and 8.3, which present them as 0.07 kg/pkm and 8.07E-6 kg/km, respectively, for LSD Mercedes buses. This is because Beer et al. (2001b) estimated the emissions during the use phase only, yet this study included the entire LCA. The environmental impact of the Adelaide metro buses project underlined that the 1905/micro hybrid bus saves a significant amount of energy and emissions in comparison with a conventional bus. Indeed, the study's findings proved that there are many options to make South Australia's public transport bus fleet more sustainable. One is the use of alternative fuel (fuel derived from renewable energy sources); another is to use advanced vehicle technologies instead of conventional vehicles. Furthermore, improving the buses' fuel economy, their vehicle powertrain efficiency and the high-compression engine ratio could help to reduce the impact of vehicles on both human health and the environment.

### 8.6.2 Uncertainty Analysis of DPTI trial buses

It is important to address and minimise the uncertainty in data used to model LCAs. The data's quality assessment should be performed to determine the critical level of parameter impact on the overall results of the assessment in relation to DPTI trial buses. Noshadravan et al. (2015) identified that the data utilised during the use phase can be improved, yet they did not examine information from the fuel pathway and the vehicle operation phases, which would have led to uncertainty in the analysis. This is not consistent with the results presented in section 8.6, which modelled the LCA on the operational, fuel cycle and vehicle non-operational phases.

Meanwhile, Cellura et al. (Cellura et al., 2011) examined the sources uncertainty and found significant differences between the energy and environment indices, concurring with what we uncovered (see section 8.4). The uncertainty-analysis method needs to develop a sensitivity analysis to strengthen the reliability of the results. Furthermore, the uncertainty identified in relation to the required assumptions, factors and parameters could be significant due to the lack of data. This can be seen in life-cycle modelling relating to human health. The data points are further from the mean and there is even more deviation within the dataset (see section 8.4); therefore, it is important to address and minimise the uncertainty in the data used by conducting further investigations.

### 8.6.3 Sensitivity Analysis of DPTI trial buses

Sensitivity analyses that consistently analyse the sensitivity of each parameter in the model are usually performed with sampling-based approaches, such as the Monte Carlo simulation, with an added procedure for variance decomposition. In relation to this, Beer et al. (Beer et al., 2001b) indicated that the sensitivity-analysis method can be used to determine the effect of different levels of emissions, showing that up to 0.25% of emissions and greenhouse gas emissions are still lower than the baseline. This contradicts our own findings (see section 8.5) because we employed various key assumptions that have significant impacts on the overall LCA results found in this thesis.

Sensitivity analyses can also be used to identify the contributions of different parameters, factors and assumptions during life-cycle modelling. The most significant factors influencing the DPTI's trial's buses' environmental impact and energy consumption over their lifetimes were, in descending order, the passenger occupancy rate, the kilometres travelled and the fuel economy (see sections 8.5.1, 8.5.2 and 8.5.3). Moreover, the bus's manufacturing parameter was found to have a significant impact on LCA HTc and HTnc, while the crude oil refinement parameter dominates the LCA energy use results (see section 8.5.4). Other parameters, including crude oil extraction, bus maintenance and disposal, can be ignored because they have little effect on life cycle modelling (see section 8.5.5). Finally, the sensitivity-analysis findings identified the critical environmental characteristics of several major strictures and the influence they have on overall performance. While many parameters have some effect, a few have a major influence on the overall LCA results. This is in line with studies by Groen et al. (Groen et al., 2014) and Huang et al. (Huang et al., 2013).

# CHAPTER 9: THE ENVIRONMENTAL RATING SCORES OF VEHICLES

An environmental rating scoring system is a good way to ensure that the LCA provide users with an appropriate evaluation of the vehicle and fuel under consideration. Each car is given a green score based on an environmental damage index, which reflects the cost to human health from air pollution associated with vehicle manufacturing, the production and distribution of fuel, vehicle tailpipe and GHG emissions. The vehicle rating score can give consumers important information about a vehicle over the course of its plausible lifetime.

## 9.1 Results and Findings

The Green Vehicle Guide (GVG) uses vehicle emissions scores (zero to ten) and fuel economy data to compare environmental performance across vehicle classes. The vehicles with higher exhaust emissions or fuel economy scores are considered more environmentally friendly than those with lower scores. The environmental rating score of vehicles are necessary in order to provide consumers with more information to help them decide whether a particular vehicle meets their specific requirements or not. Many factors, such as fuel consumption, electricity consumption, life cycle cost, vehicle exhaust emissions, annual vehicle kilometres travelled and fuel cycle cost, are used to calculate the vehicle rating score for Australian transportation, including for both light- and heavy-duty truck vehicles. Unlike previous studies, the rating developed in this thesis is based on both the whole life cycle assessment, including the fuel pathway phase, vehicle operation phase (tailpipe emissions) and the vehicle manufacture phase, as well as the GVG (An Australian Government Initiative, 2020). Vehicles are ranked as listed below:

1. The highest vehicle rating score of five stars is awarded if the LCA GHG emissions range between 0–75 g/pkm or g/tkm.

2. A high average vehicle rating score of four stars is awarded if the LCA GHG emissions range between 76–182 g/pkm or g/tkm.
3. A low average vehicle rating score of three stars is awarded if the LCA GHG emissions range between 183–370 g/pkm or g/tkm.
4. A low score of one or two stars is awarded if the LCA GHG emissions exceed 371 g/pkm or g/tkm.

Tables and Figures 9.1–9.3 summarise the overall rating scores of different types of transportation, including passenger vehicles, public transport buses and heavy-duty truck vehicles. The results indicate that in regard to passenger vehicles, advanced vehicle technologies have higher rating scores than conventional vehicles. The results presented in Table 9.1 and Figure 9.1 illustrate that conventional internal combustion engine vehicles running on petrol and LSD produce significantly higher vehicle exhaust emissions. So, their rating scores are lower than those of advanced-technology and alternative vehicles. In other words, vehicles powered by alternative fuels have higher rating scores than vehicles powered by fossil fuels.

| **Passenger Vehicle Model** | **HEV** | **BEV** | **PHEV** | **LSD** | **Petrol** |
|---|---|---|---|---|---|
| **LCA GHG emissions (g/pkm)** | 130 | 158 | 162 | 242 | 259 |
| **Overall rating stars** | 4 | 4 | 4 | 3 | 3 |

**Table 9.1: Overall Rating Scores of Passenger Vehicles**

**Figure 9.1: Overall Rating Scores of Passenger Vehicles**

The results revealed that public transport buses powered by alternative fuels have higher rating scores than other types of bus. The results in Table 9.2 and Figure 9.2 show that CNG buses have a lower impact on the environment and produce fewer GHG emissions than other types of bus, which is why their rating score is higher.

| Public Transport Buses Model | CNG | LPG | LSD | Hybrid | Battery Electric |
|---|---|---|---|---|---|
| **LCA GHG emissions (g/pkm)** | 22.2 | 63.4 | 68.2 | 79.5 | 97.4 |
| **Overall rating stars** | 5 | 5 | 5 | 4 | 4 |

**Table 9.2: Overall Rating Scores of Public Transport Buses**

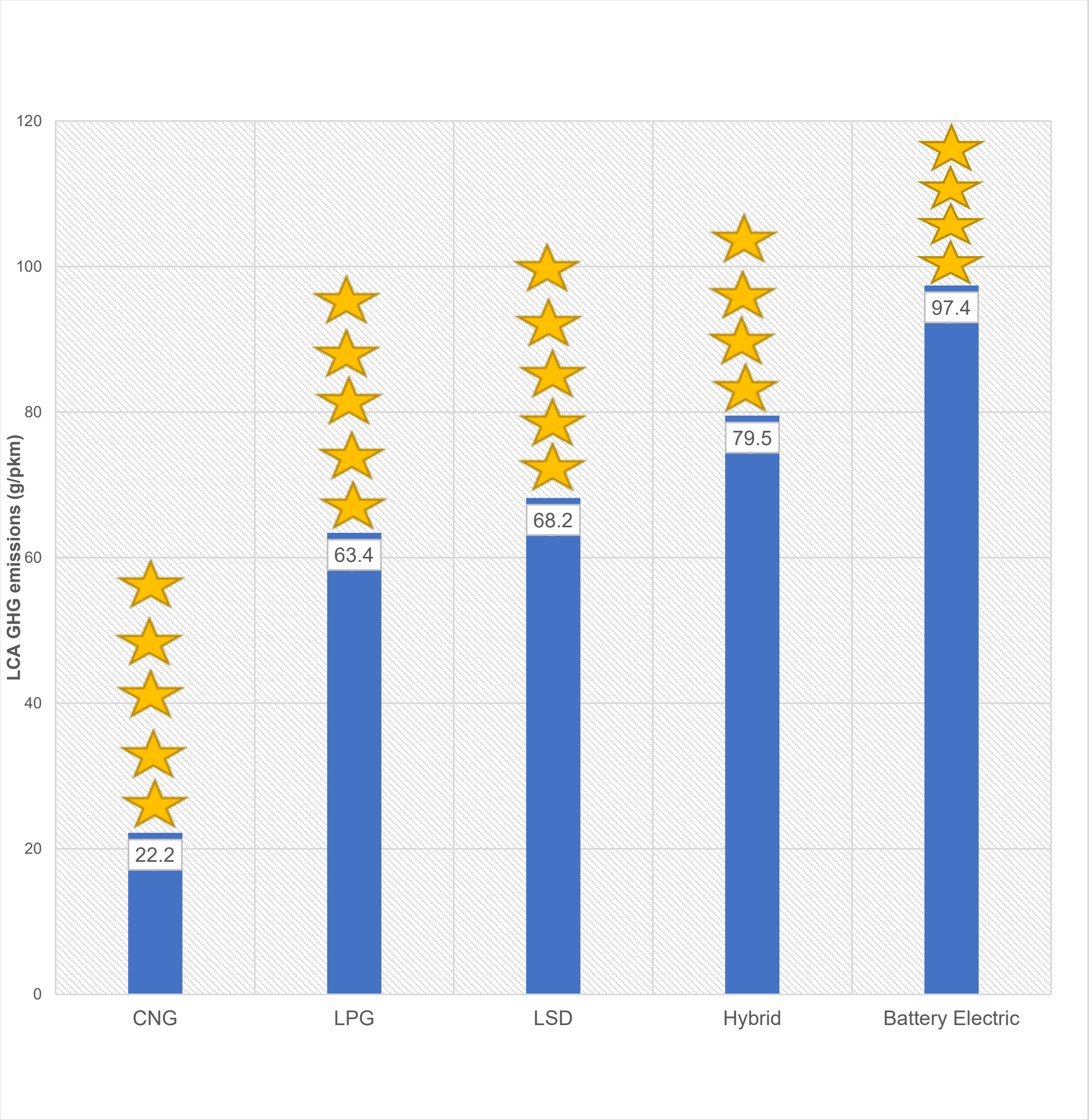


**Figure 9.2: Overall Rating Scores of Public Transport Buses**

Advanced heavy-duty truck vehicles, including battery electric articulated trucks, have higher rating scores than other types of trucks. In Table 9.3 and Figure 9.3, the results show that advanced vehicles or battery electric trucks have lower impacts on the environment, which equates to higher rating scores. This means that both drivers and passengers are at less risk of injury.

| **Heavy-duty Truck Vehicles Model** | **Articulated Electric** | **Articulated LSD** | **Articulated Electric** | **Rigid Hybrid** | **Rigid LSD** | **Rigid Hybrid** |
|---|---|---|---|---|---|---|
| **LCA GHG Emissions (g/tkm)** | 73.2 | 124 | 140 | 283 | 316 | 480 |
| **Overall Rating Stars** | 5 | 4 | 4 | 3 | 3 | 2 |

**Table 9.3: Overall Rating Scores of Heavy-Duty Truck Vehicles**

**Figure 9.3: Overall Rating Scores of Heavy-Duty Truck Vehicles**

## 9.2 Discussion of Results

The environmental rating scores of vehicles were ascertained for different types of Australian road vehicles, including passenger vehicles, public transport buses and heavy-duty truck vehicles. In order to determine a vehicle's rating score, it is necessary to define and include all of the relevant parameters, such as different types of pollution (including air pollution) and vehicle noise emissions. Alternative vehicles like electric and hybrid examples are sustainable because they are shown to cause the least amount of environmental damage. In addition, the environmental impact of vehicles associated with different fuels are evaluated over the vehicles' lifetimes by using all of the stages of the LCA, including the fuel pathway, the vehicle’s operational usage and its manufacture (Van Mierlo et al., 2003). This is consistent with the results presented in section 9.1.

Nevertheless, it is difficult to rank the environmental rating scores of vehicles that use different types of fuels (e.g. petroleum and electric) and those linked to different types of road vehicles (e.g. heavy road vehicles and light passenger vehicles). This is due to the extreme variations in their technologies and their utilisation of different sources of fuels. This thesis’ results are consistent with findings by Timmermans et al. (2006); they stated that battery-based electric and CNG vehicles have lower environmental impacts (and therefore high rating scores), and LPG vehicles have the best environmental score of all conventional vehicles. Battery electric buses have great potential to reduce emissions into the environment, so they are considered high-rated vehicles relative to other types of heavy-duty vehicles studied during our research. Lastly, the aforementioned scores of vehicles obtained in relation to our methodology showed that in order to attain a high score, it is necessary to consider fuel economy, fuel feedstock, fuel standards, vehicle exhaust emissions, engine efficiency (engine heating value), vehicle lifetime (kilometres travelled) and the vehicle mode factor due to their marked influence on vehicle ranking.

# CHAPTER 10: CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

## 10.1 Conclusions

This thesis assessed and determined the environmental sensitivities and uncertainties linked to alternative fuel, advanced technology and conventional road vehicles using LCAs. The negative potential impacts of transportation on the environment include the degradation of air quality and increases in GHG emissions, which can lead to a greater threat of global climate change. The study included LCAs of passenger vehicles, public transit buses and rigid and articulated heavy-duty truck vehicles. LCAs of biofuel vehicles were also calculated. Additionally, a case study using public transport buses (DPTI trial buses, see Chapter 8) was examined, and the environmental rating scores of vehicles were determined. The vehicle operation phase (tailpipe emissions), upstream emissions (fuel pathway stage) and the vehicle's non-operational phase (vehicle manufacture phase) significantly impact the overall LCA results. Listed below are the key findings of this study, based on an extensive analysis of many vehicles, fuels and technologies in the context of LCAs:

1) Passenger Vehicles

    - Alternative vehicles or vehicles powered by alternative fuels produce fewer GHG emissions and air pollutants compared to conventional internal combustion engine vehicles and advanced-technology vehicles (see Chapter 4). Moreover, for most types of automobiles, especially conventional and alternative-fuel-powered vehicles, the life-cycle phase that produces the most GHG emissions/criteria air pollutants and consumes the most energy is the vehicle operation phase (70–80%), followed by the fuel pathway (10–15%) and then the vehicle manufacturing, maintenance and disposal phases (10–15%).

However, the fuel pathway, including electricity generation for advanced vehicle technologies, contributes the majority of emissions because the electricity is derived from non-renewable energy sources (fossil fuels).

- The LCA results obtained for passenger vehicles from this thesis differ from those provided in the reviewed literature (Nealer and Hendrickson, 2015, Messagie et al., 2014, Castro et al., 2003) by around 10-20%. This can be explained in relation to the use of different datasets, changes to vehicle technologies and/or the variations of the scope of the LCA.

2) Public Transport Buses

- Chapter 4 showed that significant savings of GHG emissions and air pollutants can be made by public transport buses that are powered by alternative fuels, namely CNG and fuel-cell buses. Furthermore, the study concluded that although the battery-powered electric bus releases zero tailpipe emissions into the environment, the power supply is responsible for most of the emissions, especially if the electricity used is generated from fossil fuels. The analysis showed that if electricity is generated from renewable sources, then emissions are significantly reduced. Furthermore, our study concluded that due to population growth, public and private transport policies might bring about divergent impacts and consequences depending on the order of growth. The effectiveness of public/private transport varies depending on current and future urban transport situations. Public transport can move more people in much less space than private cars, reducing traffic congestion and air pollution from idling vehicles; passengers also avoid the stress of driving on a daily basis in highly congested areas (Linda, STEG, 2003).

- The LCA results obtained for public transport buses from this thesis differ from those provided in the reviewed literature (Ally and Pryor, 2007, Beer et al., 2001b) by 1%–14%. This is due to various sources of data being employed and changes to vehicle technologies.

3) Heavy-duty Truck Vehicles

   - The study concluded that the environmental effects of freight transport in terms of both rigid and articulated heavy-duty truck vehicles relate to air pollution, global climate concerns, noise, water pollution, accidents, land use and habitat fragmentation. Unlike passenger vehicles and public transit buses, battery-powered electric trucks have significantly reduced GHG emissions and air pollutants when compared to conventional and hybrid electric trucks; however, whether they are fit for purpose over long distances is questionable (see Chapter 4).
   - The LCA results obtained for heavy-duty truck vehicles in this thesis match up well with earlier studies (Hao et al., 2012, Fulton et al., 2009, Facanha and Horvath, 2007).

4) Biofuel Vehicles

   - Chapter 7 showed that biofuel vehicles have a lower impact on both human health and the environment than vehicles powered by LSD and petrol. Although biofuel vehicles produce few GHG emissions/little PM and are therefore less of a risk to human health, they are still not common worldwide as high levels of biofuel necessitate modifications being made to the engine design; nevertheless, if a low level of biofuel is used, vehicle exhaust emissions can be reduced without changing the powertrain's design. In addition, biofuel is expensive and not easily available. The study concluded that although biofuel vehicles are classified as a sustainable means of transportation because they use renewable fuel instead of fossil fuel, they have a low energy output and a negative impact on the vehicle powertrain (low heating value). A low level of biofuel, including a low level of ethanol (E10 for passenger vehicles), and a low level of biodiesel (BD5 for public transport buses) could be a good option to avoid low heating values in engines and to reduce vehicle exhaust emissions.

- Here, the LCA results obtained with regard to biofuel vehicles from differ from those provided in previous studies (Beer et al., 2001a, Wang et al., 1999) by 8%–25%. This is because different data sets were utilised, changes to vehicle technologies were made and various fuel sources were scrutinised, including renewable and fossil examples.

5) Public Transport Buses in the City of Adelaide (DPTI Trial Buses)

- The study concluded that the 1905/micro hybrid bus significantly reduces GHG emissions, energy demand, PM and human health risks (cancerous and non-cancerous) compared to conventional internal combustion engine LSD buses, such as Scania, Volvo and Mercedes (see Chapter 8). The majority of GHG emissions/PM release and energy consumption is incurred during the operational phase (74%–79%), followed by upstream emissions (9–14%). However, the main contribution in the LCA to human toxicity, cancer (HTc) and non-cancerous diseases (HTnc) occurs during vehicle manufacturing, maintenance and disposal (48%–65%). Therefore, in order to consider public transport buses in South Australia sustainable (understood to mean non-harmful to the environment and human health), improvements to fuel economy, the bus's powertrain efficiency, the use of low-carbon fuel feedstock and driver behaviour/skills should be considered.

- The results presented in this thesis in relation to the DPTI trial buses mostly concur with the reviewed literature (Ercan and Tatari, 2015, Cooper et al., 2012, Kytö et al., 2012, Williamson, 2012, Victorian department of transport, 2010).

6) The Environmental Rating Scores of Vehicles

- Developing an approach for estimating vehicles' environmental rating scores is useful for consumers around the world. It involves exploring many issues related to the life-cycle-based environmental impacts of vehicles and how they can be communicated to people. Indeed, these ratings could help to foster a market for vehicle designs and technologies with reduced environmental burdens – this will be crucial for progress in terms the promotion of an environmentally sustainable transportation system. Advanced vehicles or vehicles powered by alternative fuels are listed as green vehicles (GVs). In other words, the highest star ratings are given to both advanced vehicles and alternative fuel-powered vehicles (four to five stars). Conventional internal combustion engine vehicles that run on petrol or LSD have much smaller rating scores (low ranking) (two to three stars) as they use high-carbon fuel feedstock (see Chapter 9).
- The environmental rating scores obtained for vehicles during this research match up with those in previous studies (Timmermans et al., 2006, Beer et al., 2001).

7) Uncertainty Analysis of LCA

- The study concludes that both passenger vehicles and public transit buses have small degrees of uncertainty in their LCA results in the categories of GWP, depletion in energy use and the influence of PM. However, the largest contributions to uncertainty in terms of the LCA findings came from the data pertaining to HTc and HTnc (3%–37% and 15%–39%, respectively) (see Chapter 5). Heavy-duty truck vehicles exhibited less uncertainty in the overall LCA results that arose with regard to GWP, depletion in energy use and human health influences compared to passenger vehicles and public transit buses.
- Regarding biofuel vehicles, there is higher variation within the LCA data in terms of GHG emissions for high levels of biofuel, including E85 and pure biodiesel. For vehicles running on low levels of biofuel, the largest contribution to uncertainty in the LCA results arises from the data about HTc and HTnc, (31%–34% and 30%–32%, respectively), while the energy demand and PM categories make much smaller contributions to uncertainty overall at a rate of 4%–10% and 1%–16%, respectively (see Chapter 7).
- In the case of public transport buses (the DPTI trial buses), there is higher deviation within the dataset. The gathered information pertaining to HTc and HTnc is more dispersed, and there is significant uncertainty arising from the categories of energy use with regard to HTc and HTnc, which exhibited values of 5%–6%, 36%–48% and 24%–37%, respectively (see Chapter 8).
- There has not been much work in this field; usually, uncertainty analysis was only covered in passing, including the uncertainty analysis in data only used to model the LCA during the use phase (Groen et al., 2017, Noshadravan et al., 2015, Wei et al., 2015, Cellura et al., 2011, Seager et al., 2008, Beer et al., 2001).

8) Sensitivity Analysis of LCA Results

- This study found that sensitivity analysis is the key driver of the impacts that could change the outcome of an LCA, and it provides useful insights about the level of contribution made by different inputs on the overall variations between LCA results. Parameters relating to the passenger occupancy rate, vehicular kilometres travelled, fuel consumption and vehicle manufacturing can significantly influence the LCA's overall energy use and emission levels (9%–11%, 7%–10%, 6%–8% and 1%–5%, respectively).
- Moreover, in advanced vehicles, the impact of the electricity mix consumption and production is clearly reflected in the outcomes (4%–6%). Meanwhile, for heavy-duty truck vehicles, the average load and fraction load factors significantly impact the categories of GWP, depletion in energy use and influence on human health (8%–11%). However, other strictures, including biofuel production and processing, crude oil extraction, vehicle maintenance and disposal, have a much smaller effect on life-cycle modelling; thus, their impact on the results can be ignored. Finally, the intensity of impacts depends heavily on where the electricity is derived from, fuel resources, advanced vehicle technologies and alternative vehicles. Nevertheless, many parameters, factors and assumptions also have a marked impact on the LCA results.
- There has not been much work in this area – the sensitivity analysis and its effect on the overall LCA results is not well understood. Earlier studies only focused on a few parameters that have significant, respective consequences on the overall LCA results (Huang et al., 2013, Boureima et al., 2009, Matheys et al., 2006, Beer et al., 2001).
- Finally, this study has found that among the most environmental impact enacted by categories of interest, the most important factor is the vehicle operation

phase. In terms of metal depletion in energy use and its influence on human health, the material intensity of the vehicles was shown to be of significance, yet the contribution analysis highlighted the operation phase as the biggest factor in relation to greenhouse gas emissions per passenger per kilometre travelled. On average, all types of public transport buses were shown to be more environmentally beneficial than passenger vehicles, including conventional and advanced technologies.

In light of all of this, this thesis represents a comprehensive study of the impacts of transport on the environment, focusing on exhaust emissions over vehicles' entire lifespans. The LCA was chosen as a suitable method to evaluate a comprehensive range of vehicles and fuel types. Alongside this evaluation is a detailed analysis of the sensitivity and the uncertainty of the data that has been used to feed into the LCA. As described below, it is hoped that this work will provide others with further directions for research in order to enrich the future body of knowledge and provide a sound scientific underpinning for sustainable transport solutions.

## 10.2 Recommendations and Suggestions for Future Work

Although LCA is unable to answer every question relating to vehicle emissions, it does provide insights into the environmental impact of transportation over a vehicle's entire lifetime. Such assessments may consider all stages of a vehicle's life, from the fuel pathway to the operational phase and from the vehicle's cradle to its grave, but there are still some stages that could not be fully evaluated due to a number of issues:

1. The data with regard to some stages is unavailable.
2. The information relating to the various impacts on human health is unreliable.

3. Some data, especially that relating to vehicle manufacture and fuel production, is difficult to access.
4. Some stages require data to be available over a long period of time in order to estimate impacts over a vehicle's lifetime.

The most vehement recommendation put forward here is to improve the LCA approach worldwide and make it an integral part of the automotive industry. Many industrial applications have been proposed for the LCA in terms of the environmental effects of certain products, including technology design, optimisation, technological strategies and marketing. Indeed, a good number of industries have developed LCA competences, and many have begun applying these to business decisions. Consequently, vehicle producers' patterns of adopting of life-cycle approaches must be analysed along with their impact on the environment.

Moreover, the LCA's methodology should be improved and standardised in terms of data use and the methods employed; this would mean it could be applied to various modes of transportation and deal with complex issues. Overall, to advance future research on LCA in the transport sector, the following recommendations and suggestions for future work have been made:

1. The sustainability assessment of alternative transport fuels should focus on narrowing the uncertainties in GHG emissions, criteria air pollutants and energy use in future research studies.
2. Filling critical gaps in terms of measuring emissions during the production, manufacturing, maintenance and disposal phases should be carried out using the LCA approach for both fuels and vehicles. Also, in order to increase accuracy regarding the fuel cycle's life-cycle emissions, it is important to update the LCA to encompass crude oil extraction and production, crude oil transportation, crude oil refinement or

esterification and fuel distribution (refuelling). Moreover, well-to-wheels (WTW) analysis should be improved upon. This is a part of the LCA as a whole and can provide pertinent information, especially on upstream energy and the operational phase.

3. The existing life cycle inventories should be updated to include data relating to biofuel feedstock production and processing in Australia.
4. Vehicles' life-cycle costs should be revised. The life-cycle cost includes outlays with regard to vehicle purchase, vehicle operation, fuel, electricity, servicing and maintenance and vehicle exhaust emissions. This will give customers crucial information, so they can decide how environmentally friendly a particular vehicle is.
5. The capital and operational costs of vehicles of both hydrogen fuel cell and BEVs should be updated. Additionally, fuel economy data relating to the vehicle powertrain in advanced vehicle technologies should also be reviewed in line with the life cycle inventory.
6. Life-cycle assessment modelling should be completed to ensure that the impact assessment is objectively and holistically approached.
7. The impact assessment of fuel should be extended to include the external influences of alternative fuel in terms of advanced vehicle powertrains, job creation and the consequences on biodiversity and water resources.
8. Vehicles' LCAs should be extended to include the impact of alternative fuel production on soil and water quality.
9. Future research should focus on sustainability assessments of efficient pathways for the production and transmission of electricity.

10. For more accurate overall LCA results, the environmental impact of each part of the vehicle’s manufacturing process should be estimated, including the body, chassis, traction system, powertrain and transmission.
11. LCAs should be updated to incorporate engine oil, brake and transmission fluids, powertrain coolant and refrigerant fluid.
12. LCAs should be made to include the vehicle recycling phase, so that the environmental impact of recycling vehicle components, such as the battery, steel and aluminium, can be evaluated.
13. LCAs should include many parameters, factors and assumptions, including tonnage and kilometres travelled in heavy-duty truck vehicles and vehicle recycling parameters, in order to see how they impact the outcomes.
14. LCAs should be updated with different sizes of vehicles (small, medium and large) and state whether the vehicles are lightweight or a conventional weight. This will give more opportunities for comparisons to be made between various sizes of automobiles.
15. Although the Australian driving cycle was used to estimate the LCA of vehicles in this PhD thesis, it is important to formulate a driving cycle that matches all of the equivalent counterparts around the world, including the American driving cycle, the European driving cycle and the Japanese driving cycle;
16. To check the data used for life-cycle modelling, it is important to employ in-depth uncertainty analysis; Doing so will increase confidence in the LCA results.
17. To determine the impact of each parameter, factor and assumption on life-cycle modelling, it is necessary to perform a sensitivity analysis, which is highly accurate. This will offer up more information on the parameters that have the most significant impact on the results or those that have little or no impact, meaning the outcome can be ignored.

18. Finally, future studies should investigate the effect of driver behaviour on LCAs, such as the consequences of electrified vehicle adoption on driving patterns and vehicular kilometres travelled.

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# APPENDICES

## APPENDIX A: SIMAPRO SOFTWARE

### A.1 Goal and Scope Definition in SimaPro Software

The goal and scope definition in SimaPro software can be established by text field and library sections according to the project to be built. For instance, if LCA is to be relevant only for Australia, the USA, Japanese, Middle East and Europe databases can be switched off.

### A.2 Data Inventory in SimaPro

The LCA data collection is considered an important task to evaluate an environmental impact assessment for products and services. SimaPro software has the advantage that it can collect missing data and distinguish between two types of data. The first type is foreground data which is considered important data that comes from different sources. There are two special websites on the internet that are relevant to the LCA foreground database: http://lca-data.org and www.life-cycle.org. The other type of data is background data which focuses on material extraction and production, energy resources, transportation and waste management, and includes current and future databases predicted.

### A.3 The Eco Invent Database

Eco invent database is one of the important databases worldwide that is focused on the website www.ecoinvent.org. The are many advantages of this database, as indicated below:

1. It covers a lot of data worldwide.
2. The application of system boundaries and allocation is included.

3. The ecoinvent background reports can be accessed via the SimaPro help menu, the ecoinvent website or the ecoinvent CD.
4. It includes specification of uncertainty data.
5. It includes different types of gas emissions. So, different methods to assess the environmental impact of products can be used.
6. It has capital goods as a default, which is important for energy systems such as wind and hydropower, but also for transportation systems.
7. It is updated regularly by the ecoinvent Centre.

The ecoinvent database has a lot of resources in most cases. Also, it satisfies all the background data requirements. In addition, version 3 of the ecoinvent database has a more international scope.

Further, SimaPro includes six dataset versions:

1. Allocation default, unit processes
2. Allocation default, system processes
3. Allocation recycled content, unit processes
4. Allocation recycled content, system processes
5. Consequential, unit processes
6. Consequential, system processes

### A.3.1 SimaPro Process

Each process in SimaPro software is provided in two versions: unit processes and system processes. A unit process version contains only emissions and resource inputs from one process step while a system process is the inventory result of an overall LCA that gives no insight into the inputs and outputs of the separate supply chains processed in the production system. A comparative summary of using unit and system processes is shown in Table A.1.

| Unit Process | System Process |
|---|---|
| It has a huge process tree and contribution of all individual unit processes | It has simple process tree |
| It includes uncertainty information and it allows to run statistical analysis (Monte Carlo) | It has no uncertainty information |
| It is slow for calculation | It is fast for calculation |

**Table A.1: Comparative Summary of Unit and System Processes**

## A.4 Input Output Data in SimaPro

SimaPro has a lot of data for many sectors including agriculture, transportation, energy, food, manufacture and others. All data is per economic sector rather than per process. Therefore, it is useful to have input output data in SimaPro software when assessing the economic side of products.

## A.5 Impact Assessment Methods in SimaPro

SimaPro has many standard impact assessment methods. Each method contains a number (usually 10 to 20) of impact categories; some allow aggregation into a single score and some do not. However, SimaPro does allow to add or delete impact categories from or to a method. Also, SimaPro allows the creation of completely new methods.

## A.6 Interpretation in SimaPro

The software is designed to examine the issues that are relevant to the specific application of SimaPro. Therefore, it is important to use the interpretation when the LCA is completed to check that results match the standard (ISO) results.

## A.7 Data Uncertainty in SimaPro

The ecoinvent database is divided into two versions:

- Version with unit processes
- Version with system processes

Almost all data points have a relationship with unit processes, and SimaPro comes with a specification of uncertainty data. It requires a lot of information to use uncertainty data. This includes how to interpret and specify uncertainty data in SimaPro software. Ecoinvent database always assumes a lognormal distribution which is characterized by a standard deviation. A typical property of a lognormal distribution is that the square of the geometric standard deviation covers the 95% confidence interval. This is an important difference from the normal distribution.

## A.8 Sensitivity Analysis in SimaPro Software

Sensitivity analysis is considered one of the most useful characteristics of SimaPro software. It evaluates the effect of different assumptions on total LCA results. So, it can give better results and it can compare results based on different resources. Therefore, sensitivity analysis is recommended when a particular assumption is changed, or it uses different impact assessment methods.

## A.9 Contribution Analysis in SimaPro Software

Contribution analysis is the method that addresses this case by finding which processes play a role in LCA results, and the most important assumptions within these processes. Therefore, it is important to understand the uncertainty of LCA results. SimaPro has two ways of finding the contribution analysis of LCA processes:

1. Tree process or network: this is an approach that has advantage and disadvantage. The advantage of this is that the role of the process can be seen exactly, while the disadvantage is that some processes can occur many times in an LCA.
2. Contribution analysis section of the result screen: This develops the total contribution analysis by adding significant numbers of single processes.

# APPENDIX B: GREET MODEL

## B. 1 The Introduction of GREET Model

The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. The most recent GREET versions are the GREET 1 2017 version for fuel-cycle analysis and GREET 2 2017 version for vehicle-cycle analysis. GREET software separately calculates the following:

1. GHG emissions including carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$).
2. Air pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide ($NO_x$), particulate matter with size smaller than 10 micron ($PM_{10}$), particulate matter with size smaller than 2.5 micron ($PM_{2.5}$), human toxicity cancer (HTc), human toxicity non cancer (HTnc), black carbon (BC), and sulphur oxides ($SO_x$).
3. Energy consumption whether this energy is derived from renewable sources or non-renewable sources.

Furthermore, GREET model is divided into two model types as listed below:

## B.2 Fuel Pathways Model

GREET includes more than 100 fuel pathway models including petroleum, natural gas, biofuel, hydrogen, and electricity. These fuels are produced from various energy feedstock sources. They are shown in Figure B.1.

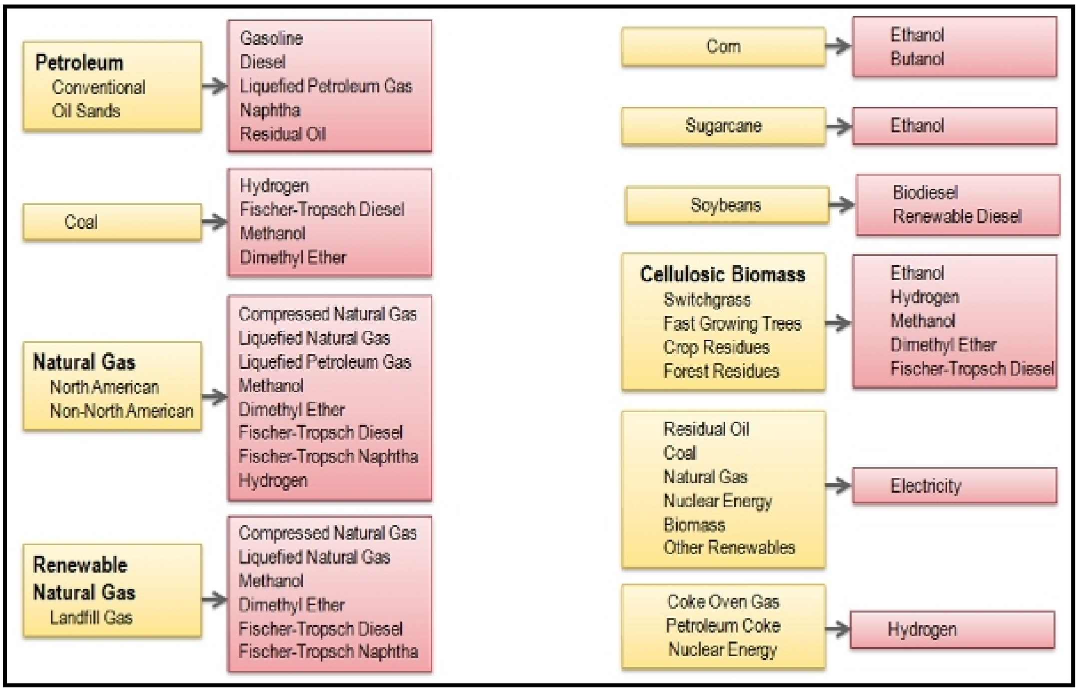


**Figure B.1: The Fuel Pathway in GREET Model**

## B.3 The Vehicle Technologies Model

GREET model simulates three classes of vehicles as listed below:

1. Passenger vehicle
2. Light duty truck 1 (gross weight < 6000 lb)
3. Light duty truck 2 (gross weight < 8500 lb)

Added to that, GREET model includes more than 80 combined fuel-use vehicles as listed below:

1. Spark ignition petrol vehicles
2. Compression ignition diesel Vehicles
3. Hybrid electric vehicles
4. Spark-ignition engines

5. Compression ignition engines

6. Plug-in hybrid electric vehicles

7. Spark ignition engines

8. Compression ignition engines

9. Battery electric vehicles

10. Fuel cell vehicles

## B.4 GREET Model Guides

GREET model is divided into four start guides as listed below:

### B.4.1 Well to Product (WTT or WTP)

Figure B.2 shows well to tank or well to pump. It includes life cycle of fuel production (upstream energy) and it considers the energy consumption and emissions during fuel production or electricity generation from different resources.

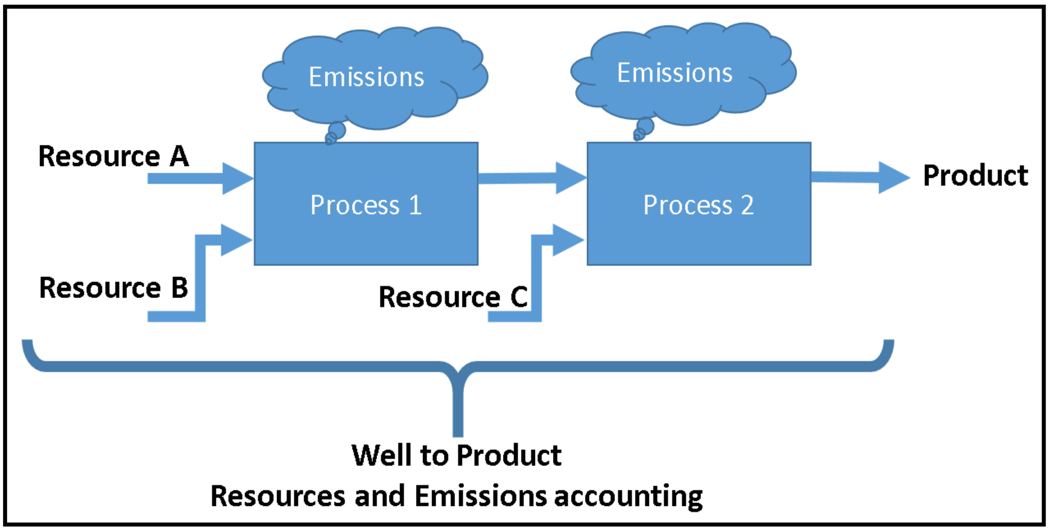


**Figure B.2: The Well to Product**

The GREET model includes significant numbers of fuel pathways such as the electricity production pathway, the electricity production mix, and fuel production from biomass or from crude oil etc.

### B.4.2 Well to Wheels Analysis (WTW)

Well to wheel (WTW) results combines GHG emissions, air pollutants and energy consumption during well to tank (WTT-fuel pathway) and tank to wheel (TTW-tailpipe emissions) over vehicle lifetime. The diagram in Figure B.3, represents the total life cycle analysis of fuel production, material production and they are combined in order to estimate the cradle to grave impact of different transportation technologies.

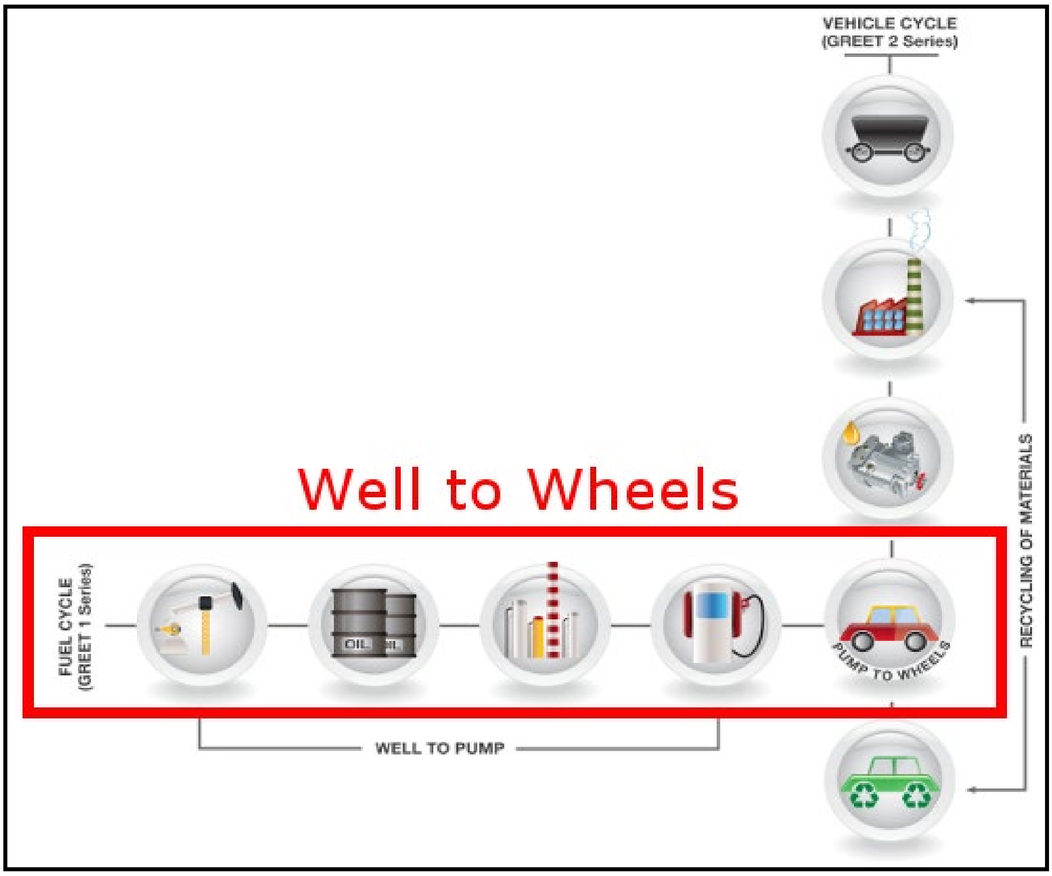


**Figure B.3: The Well to Wheel (WTW) Analysis of Vehicle/Fuel Combined Use**

Further, the GREET model includes many vehicle/fuel WTW results such as WTW results explorer/grid independent vehicle and WTW results explorer/grid connected vehicle.

### B.4.3 Data Editors

It is necessary to modify the database and add new databases to match Australian databases. Figure B.4 shows the building blocks of the GREET model.

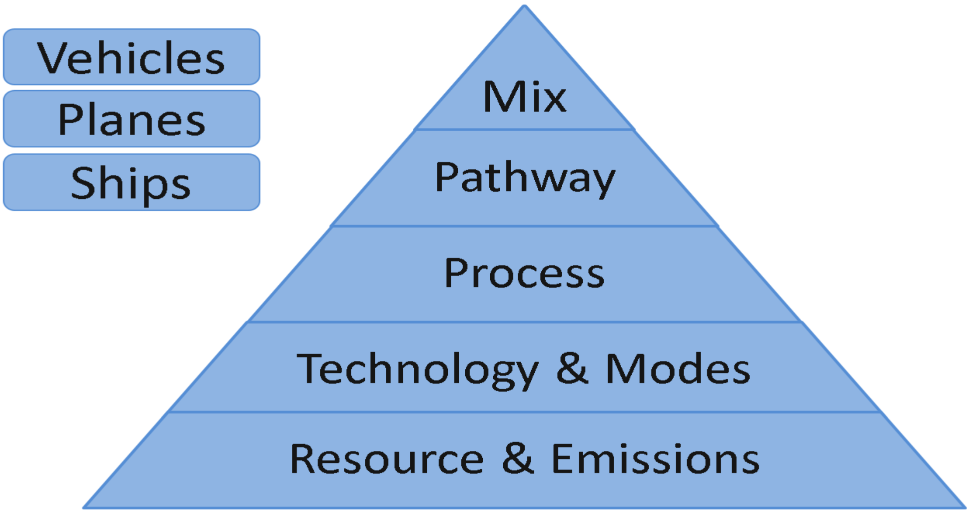
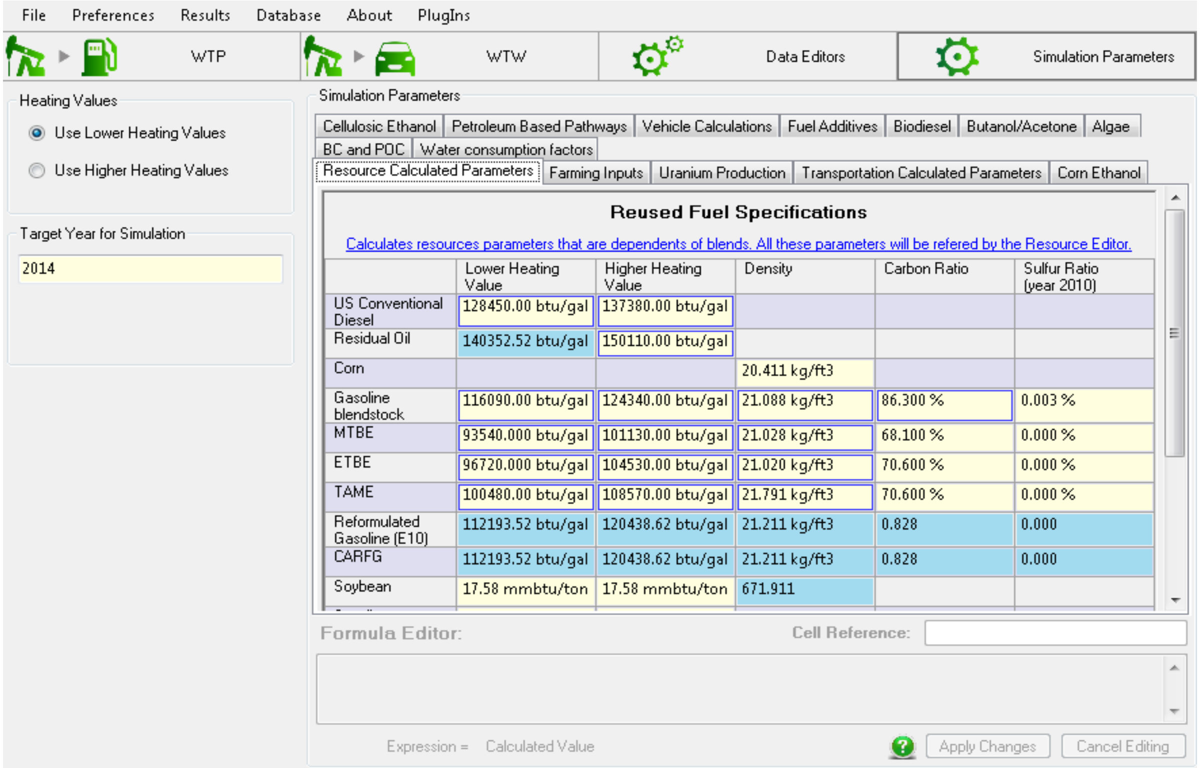


**Figure B.4: Building Blocks of GREET Model**

Therefore, the following processes, including stationery and transportation are considered a part of the data editor: resources, emissions, technologies, processes, pathway, mix and vehicles.

### B.4.4 Simulation Parameters

The changing place of input parameters is done by the section (simulation parameters). It can be edited, reused across the model in a similar way and accessed by clicking the last large button in the main GREET banner, as shown in Figure B.5.



Heating Values

● Use Lower Heating Values

○ Use Higher Heating Values

Target Year for Simulation: 2014

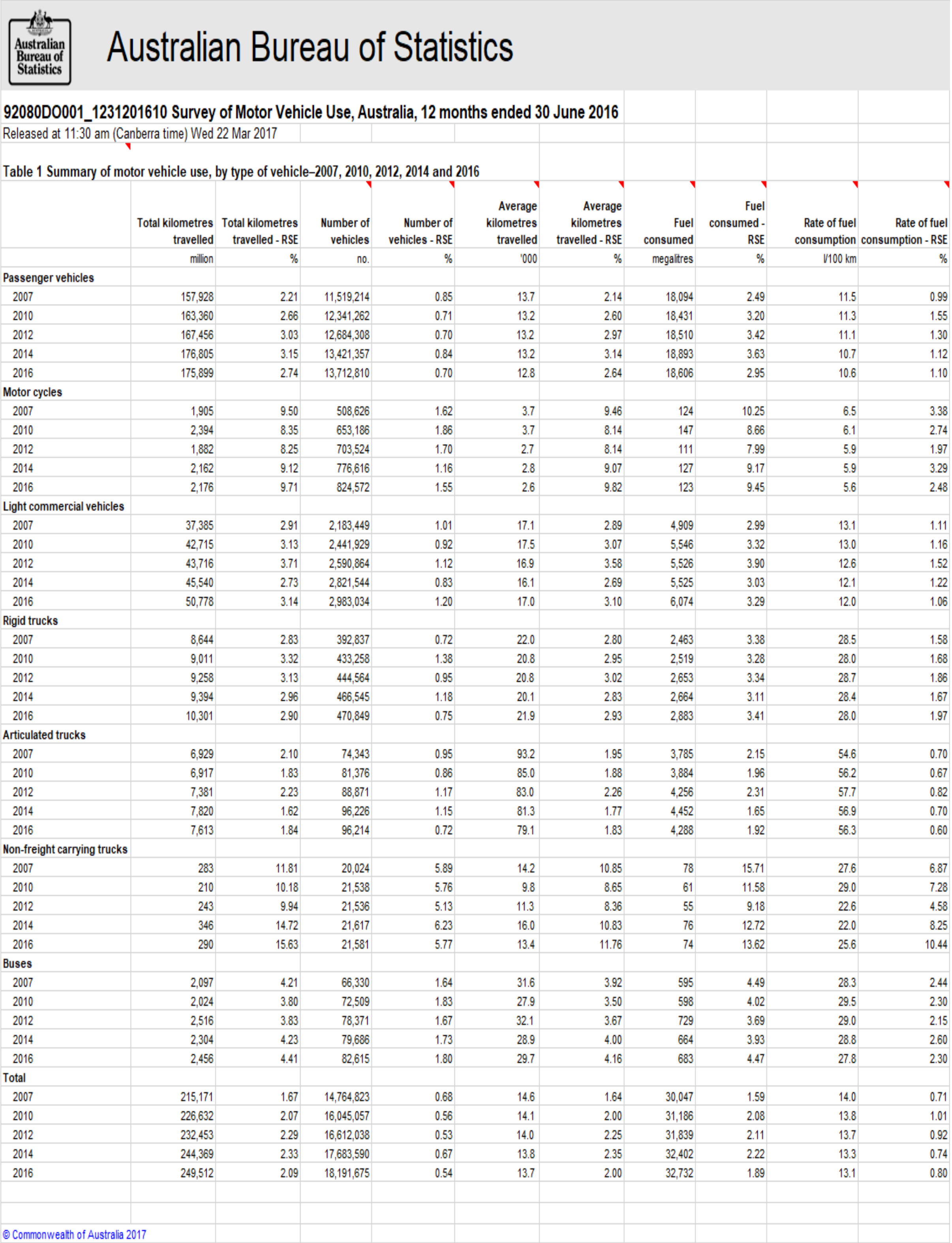
**Reused Fuel Specifications**

Calculates resources parameters that are dependents of blends. All these parameters will be refered by the Resource Editor.

| | Lower Heating Value | Higher Heating Value | Density | Carbon Ratio | Sulfur Ratio (year 2010) |
|---|---|---|---|---|---|
| US Conventional Diesel | 128450.00 btu/gal | 137380.00 btu/gal | | | |
| Residual Oil | 140352.52 btu/gal | 150110.00 btu/gal | | | |
| Corn | | | 20.411 kg/ft3 | | |
| Gasoline blendstock | 116090.00 btu/gal | 124340.00 btu/gal | 21.088 kg/ft3 | 86.300 % | 0.003 % |
| MTBE | 93540.000 btu/gal | 101130.00 btu/gal | 21.028 kg/ft3 | 68.100 % | 0.000 % |
| ETBE | 96720.000 btu/gal | 104530.00 btu/gal | 21.020 kg/ft3 | 70.600 % | 0.000 % |
| TAME | 100480.00 btu/gal | 108570.00 btu/gal | 21.791 kg/ft3 | 70.600 % | 0.000 % |
| Reformulated Gasoline (E10) | 112193.52 btu/gal | 120438.62 btu/gal | 21.211 kg/ft3 | 0.828 | 0.000 |
| CARFG | 112193.52 btu/gal | 120438.62 btu/gal | 21.211 kg/ft3 | 0.828 | 0.000 |
| Soybean | 17.58 mmbtu/ton | 17.58 mmbtu/ton | 671.911 | | |

Figure B.5: Simulation Parameters Section

# APPENDIX C: VEHICLE KILOMETRES TRAVELLED



Australian Bureau of Statistics

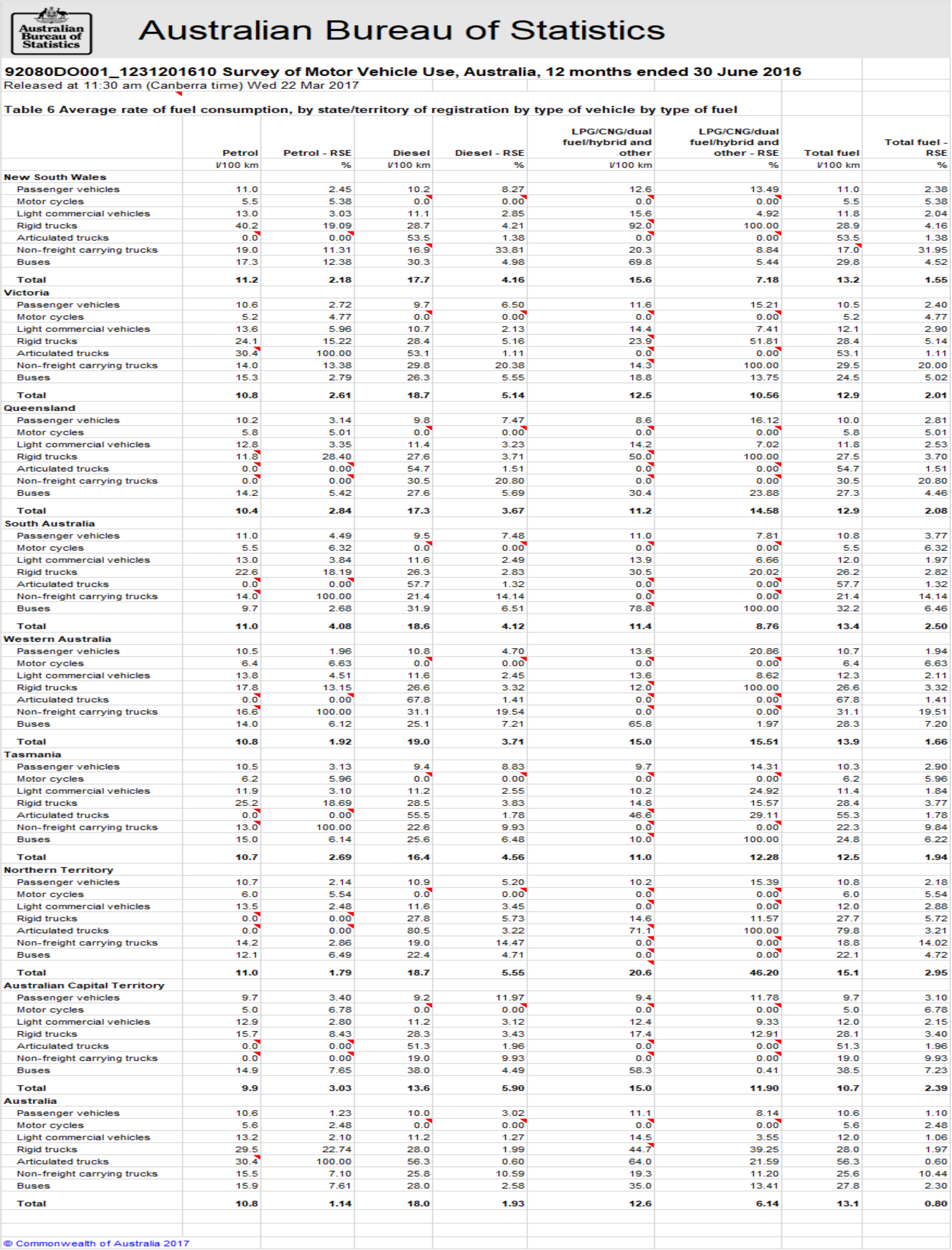
**92080DO001_1231201610 Survey of Motor Vehicle Use, Australia, 12 months ended 30 June 2016**

Released at 11:30 am (Canberra time) Wed 22 Mar 2017

**Table 1 Summary of motor vehicle use, by type of vehicle–2007, 2010, 2012, 2014 and 2016**

| | Total kilometres travelled | Total kilometres travelled - RSE | Number of vehicles | Number of vehicles - RSE | Average kilometres travelled | Average kilometres travelled - RSE | Fuel consumed | Fuel consumed - RSE | Rate of fuel consumption | Rate of fuel consumption - RSE |
|---|---|---|---|---|---|---|---|---|---|---|
| | million | % | no. | % | '000 | % | megalitres | % | l/100 km | % |
| **Passenger vehicles** | | | | | | | | | | |
| 2007 | 157,928 | 2.21 | 11,519,214 | 0.85 | 13.7 | 2.14 | 18,094 | 2.49 | 11.5 | 0.99 |
| 2010 | 163,360 | 2.66 | 12,341,262 | 0.71 | 13.2 | 2.60 | 18,431 | 3.20 | 11.3 | 1.55 |
| 2012 | 167,456 | 3.03 | 12,684,308 | 0.70 | 13.2 | 2.97 | 18,510 | 3.42 | 11.1 | 1.30 |
| 2014 | 176,805 | 3.15 | 13,421,357 | 0.84 | 13.2 | 3.14 | 18,893 | 3.63 | 10.7 | 1.12 |
| 2016 | 175,899 | 2.74 | 13,712,810 | 0.70 | 12.8 | 2.64 | 18,606 | 2.95 | 10.6 | 1.10 |
| **Motor cycles** | | | | | | | | | | |
| 2007 | 1,905 | 9.50 | 508,626 | 1.62 | 3.7 | 9.46 | 124 | 10.25 | 6.5 | 3.38 |
| 2010 | 2,394 | 8.35 | 653,186 | 1.86 | 3.7 | 8.14 | 147 | 8.66 | 6.1 | 2.74 |
| 2012 | 1,882 | 8.25 | 703,524 | 1.70 | 2.7 | 8.14 | 111 | 7.99 | 5.9 | 1.97 |
| 2014 | 2,162 | 9.12 | 776,616 | 1.16 | 2.8 | 9.07 | 127 | 9.17 | 5.9 | 3.29 |
| 2016 | 2,176 | 9.71 | 824,572 | 1.55 | 2.6 | 9.82 | 123 | 9.45 | 5.6 | 2.48 |
| **Light commercial vehicles** | | | | | | | | | | |
| 2007 | 37,385 | 2.91 | 2,183,449 | 1.01 | 17.1 | 2.89 | 4,909 | 2.99 | 13.1 | 1.11 |
| 2010 | 42,715 | 3.13 | 2,441,929 | 0.92 | 17.5 | 3.07 | 5,546 | 3.32 | 13.0 | 1.16 |
| 2012 | 43,716 | 3.71 | 2,590,864 | 1.12 | 16.9 | 3.58 | 5,526 | 3.90 | 12.6 | 1.52 |
| 2014 | 45,540 | 2.73 | 2,821,544 | 0.83 | 16.1 | 2.69 | 5,525 | 3.03 | 12.1 | 1.22 |
| 2016 | 50,778 | 3.14 | 2,983,034 | 1.20 | 17.0 | 3.10 | 6,074 | 3.29 | 12.0 | 1.06 |
| **Rigid trucks** | | | | | | | | | | |
| 2007 | 8,644 | 2.83 | 392,837 | 0.72 | 22.0 | 2.80 | 2,463 | 3.38 | 28.5 | 1.58 |
| 2010 | 9,011 | 3.32 | 433,258 | 1.38 | 20.8 | 2.95 | 2,519 | 3.28 | 28.0 | 1.68 |
| 2012 | 9,258 | 3.13 | 444,564 | 0.95 | 20.8 | 3.02 | 2,653 | 3.34 | 28.7 | 1.86 |
| 2014 | 9,394 | 2.96 | 466,545 | 1.18 | 20.1 | 2.83 | 2,664 | 3.11 | 28.4 | 1.67 |
| 2016 | 10,301 | 2.90 | 470,849 | 0.75 | 21.9 | 2.93 | 2,883 | 3.41 | 28.0 | 1.97 |
| **Articulated trucks** | | | | | | | | | | |
| 2007 | 6,929 | 2.10 | 74,343 | 0.95 | 93.2 | 1.95 | 3,785 | 2.15 | 54.6 | 0.70 |
| 2010 | 6,917 | 1.83 | 81,376 | 0.86 | 85.0 | 1.88 | 3,884 | 1.96 | 56.2 | 0.67 |
| 2012 | 7,381 | 2.23 | 88,871 | 1.17 | 83.0 | 2.26 | 4,256 | 2.31 | 57.7 | 0.82 |
| 2014 | 7,820 | 1.62 | 96,226 | 1.15 | 81.3 | 1.77 | 4,452 | 1.65 | 56.9 | 0.70 |
| 2016 | 7,613 | 1.84 | 96,214 | 0.72 | 79.1 | 1.83 | 4,288 | 1.92 | 56.3 | 0.60 |
| **Non-freight carrying trucks** | | | | | | | | | | |
| 2007 | 283 | 11.81 | 20,024 | 5.89 | 14.2 | 10.85 | 78 | 15.71 | 27.6 | 6.87 |
| 2010 | 210 | 10.18 | 21,538 | 5.76 | 9.8 | 8.65 | 61 | 11.58 | 29.0 | 7.28 |
| 2012 | 243 | 9.94 | 21,536 | 5.13 | 11.3 | 8.36 | 55 | 9.18 | 22.6 | 4.58 |
| 2014 | 346 | 14.72 | 21,617 | 6.23 | 16.0 | 10.83 | 76 | 12.72 | 22.0 | 8.25 |
| 2016 | 290 | 15.63 | 21,581 | 5.77 | 13.4 | 11.76 | 74 | 13.62 | 25.6 | 10.44 |
| **Buses** | | | | | | | | | | |
| 2007 | 2,097 | 4.21 | 66,330 | 1.64 | 31.6 | 3.92 | 595 | 4.49 | 28.3 | 2.44 |
| 2010 | 2,024 | 3.80 | 72,509 | 1.83 | 27.9 | 3.50 | 598 | 4.02 | 29.5 | 2.30 |
| 2012 | 2,516 | 3.83 | 78,371 | 1.67 | 32.1 | 3.67 | 729 | 3.69 | 29.0 | 2.15 |
| 2014 | 2,304 | 4.23 | 79,686 | 1.73 | 28.9 | 4.00 | 664 | 3.93 | 28.8 | 2.60 |
| 2016 | 2,456 | 4.41 | 82,615 | 1.80 | 29.7 | 4.16 | 683 | 4.47 | 27.8 | 2.30 |
| **Total** | | | | | | | | | | |
| 2007 | 215,171 | 1.67 | 14,764,823 | 0.68 | 14.6 | 1.64 | 30,047 | 1.59 | 14.0 | 0.71 |
| 2010 | 226,632 | 2.07 | 16,045,057 | 0.56 | 14.1 | 2.00 | 31,186 | 2.08 | 13.8 | 1.01 |
| 2012 | 232,453 | 2.29 | 16,612,038 | 0.53 | 14.0 | 2.25 | 31,839 | 2.11 | 13.7 | 0.92 |
| 2014 | 244,369 | 2.33 | 17,683,590 | 0.67 | 13.8 | 2.35 | 32,402 | 2.22 | 13.3 | 0.74 |
| 2016 | 249,512 | 2.09 | 18,191,675 | 0.54 | 13.7 | 2.00 | 32,732 | 1.89 | 13.1 | 0.80 |

# APPENDIX D: THE AVERAGE VEHICLE FUEL CONSUMPTION



Australian Bureau of Statistics

**92080DO001_1231201610 Survey of Motor Vehicle Use, Australia, 12 months ended 30 June 2016**

Released at 11:30 am (Canberra time) Wed 22 Mar 2017

**Table 6 Average rate of fuel consumption, by state/territory of registration by type of vehicle by type of fuel**

| | Petrol | Petrol - RSE | Diesel | Diesel - RSE | LPG/CNG/dual fuel/hybrid and other | LPG/CNG/dual fuel/hybrid and other - RSE | Total fuel | Total fuel - RSE |
|---|---|---|---|---|---|---|---|---|
| | l/100 km | % | l/100 km | % | l/100 km | % | l/100 km | % |
| **New South Wales** | | | | | | | | |
| Passenger vehicles | 11.0 | 2.45 | 10.2 | 8.27 | 12.6 | 13.49 | 11.0 | 2.38 |
| Motor cycles | 5.5 | 5.38 | 0.0 | 0.00 | 0.0 | 0.00 | 5.5 | 5.38 |
| Light commercial vehicles | 13.0 | 3.03 | 11.1 | 2.85 | 15.6 | 4.92 | 11.8 | 2.04 |
| Rigid trucks | 40.2 | 19.09 | 28.7 | 4.21 | 92.0 | 100.00 | 28.9 | 4.16 |
| Articulated trucks | 0.0 | 0.00 | 53.5 | 1.38 | 0.0 | 0.00 | 53.5 | 1.38 |
| Non-freight carrying trucks | 19.0 | 11.31 | 16.9 | 33.81 | 20.3 | 8.84 | 17.0 | 31.95 |
| Buses | 17.3 | 12.38 | 30.3 | 4.98 | 69.8 | 5.44 | 29.8 | 4.52 |
| **Total** | **11.2** | **2.18** | **17.7** | **4.16** | **15.6** | **7.18** | **13.2** | **1.55** |
| **Victoria** | | | | | | | | |
| Passenger vehicles | 10.6 | 2.72 | 9.7 | 6.50 | 11.6 | 15.21 | 10.5 | 2.40 |
| Motor cycles | 5.2 | 4.77 | 0.0 | 0.00 | 0.0 | 0.00 | 5.2 | 4.77 |
| Light commercial vehicles | 13.6 | 5.96 | 10.7 | 2.13 | 14.4 | 7.41 | 12.1 | 2.90 |
| Rigid trucks | 24.1 | 15.22 | 28.4 | 5.16 | 23.9 | 51.81 | 28.4 | 5.14 |
| Articulated trucks | 30.4 | 100.00 | 53.1 | 1.11 | 0.0 | 0.00 | 53.1 | 1.11 |
| Non-freight carrying trucks | 14.0 | 13.38 | 29.8 | 20.38 | 14.3 | 100.00 | 29.5 | 20.00 |
| Buses | 15.3 | 2.79 | 26.3 | 5.55 | 18.8 | 13.75 | 24.5 | 5.02 |
| **Total** | **10.8** | **2.61** | **18.7** | **5.14** | **12.5** | **10.56** | **12.9** | **2.01** |
| **Queensland** | | | | | | | | |
| Passenger vehicles | 10.2 | 3.14 | 9.8 | 7.47 | 8.6 | 16.12 | 10.0 | 2.81 |
| Motor cycles | 5.8 | 5.01 | 0.0 | 0.00 | 0.0 | 0.00 | 5.8 | 5.01 |
| Light commercial vehicles | 12.8 | 3.35 | 11.4 | 3.23 | 14.2 | 7.02 | 11.8 | 2.53 |
| Rigid trucks | 11.8 | 28.40 | 27.6 | 3.71 | 50.0 | 100.00 | 27.5 | 3.70 |
| Articulated trucks | 0.0 | 0.00 | 54.7 | 1.51 | 0.0 | 0.00 | 54.7 | 1.51 |
| Non-freight carrying trucks | 0.0 | 0.00 | 30.5 | 20.80 | 0.0 | 0.00 | 30.5 | 20.80 |
| Buses | 14.2 | 5.42 | 27.6 | 5.69 | 30.4 | 23.88 | 27.3 | 4.46 |
| **Total** | **10.4** | **2.84** | **17.3** | **3.67** | **11.2** | **14.58** | **12.9** | **2.08** |
| **South Australia** | | | | | | | | |
| Passenger vehicles | 11.0 | 4.49 | 9.5 | 7.48 | 11.0 | 7.81 | 10.8 | 3.77 |
| Motor cycles | 5.5 | 6.32 | 0.0 | 0.00 | 0.0 | 0.00 | 5.5 | 6.32 |
| Light commercial vehicles | 13.0 | 3.84 | 11.6 | 2.49 | 13.9 | 6.66 | 12.0 | 1.97 |
| Rigid trucks | 22.6 | 18.19 | 26.3 | 2.83 | 30.5 | 20.02 | 26.2 | 2.82 |
| Articulated trucks | 0.0 | 0.00 | 57.7 | 1.32 | 0.0 | 0.00 | 57.7 | 1.32 |
| Non-freight carrying trucks | 14.0 | 100.00 | 21.4 | 14.14 | 0.0 | 0.00 | 21.4 | 14.14 |
| Buses | 9.7 | 2.68 | 31.9 | 6.51 | 78.8 | 100.00 | 32.2 | 6.46 |
| **Total** | **11.0** | **4.08** | **18.6** | **4.12** | **11.4** | **8.76** | **13.4** | **2.50** |
| **Western Australia** | | | | | | | | |
| Passenger vehicles | 10.5 | 1.96 | 10.8 | 4.70 | 13.6 | 20.86 | 10.7 | 1.94 |
| Motor cycles | 6.4 | 6.63 | 0.0 | 0.00 | 0.0 | 0.00 | 6.4 | 6.63 |
| Light commercial vehicles | 13.8 | 4.51 | 11.6 | 2.45 | 13.6 | 8.62 | 12.3 | 2.11 |
| Rigid trucks | 17.8 | 13.15 | 26.6 | 3.32 | 12.0 | 100.00 | 26.6 | 3.32 |
| Articulated trucks | 0.0 | 0.00 | 67.8 | 1.41 | 0.0 | 0.00 | 67.8 | 1.41 |
| Non-freight carrying trucks | 16.6 | 100.00 | 31.1 | 19.54 | 0.0 | 0.00 | 31.1 | 19.51 |
| Buses | 14.0 | 6.12 | 25.1 | 7.21 | 65.8 | 1.97 | 28.3 | 7.20 |
| **Total** | **10.8** | **1.92** | **19.0** | **3.71** | **15.0** | **15.51** | **13.9** | **1.66** |
| **Tasmania** | | | | | | | | |
| Passenger vehicles | 10.5 | 3.13 | 9.4 | 8.83 | 9.7 | 14.31 | 10.3 | 2.90 |
| Motor cycles | 6.2 | 5.96 | 0.0 | 0.00 | 0.0 | 0.00 | 6.2 | 5.96 |
| Light commercial vehicles | 11.9 | 3.10 | 11.2 | 2.55 | 10.2 | 24.92 | 11.4 | 1.84 |
| Rigid trucks | 25.2 | 18.69 | 28.5 | 3.83 | 14.8 | 15.57 | 28.4 | 3.77 |
| Articulated trucks | 0.0 | 0.00 | 55.5 | 1.78 | 46.6 | 29.11 | 55.3 | 1.78 |
| Non-freight carrying trucks | 13.0 | 100.00 | 22.6 | 9.93 | 0.0 | 0.00 | 22.3 | 9.84 |
| Buses | 15.0 | 6.14 | 25.6 | 6.48 | 10.0 | 100.00 | 24.8 | 6.22 |
| **Total** | **10.7** | **2.69** | **16.4** | **4.56** | **11.0** | **12.28** | **12.5** | **1.94** |
| **Northern Territory** | | | | | | | | |
| Passenger vehicles | 10.7 | 2.14 | 10.9 | 5.20 | 10.2 | 15.39 | 10.8 | 2.18 |
| Motor cycles | 6.0 | 5.54 | 0.0 | 0.00 | 0.0 | 0.00 | 6.0 | 5.54 |
| Light commercial vehicles | 13.5 | 2.48 | 11.6 | 3.45 | 0.0 | 0.00 | 12.0 | 2.88 |
| Rigid trucks | 0.0 | 0.00 | 27.8 | 5.73 | 14.6 | 11.57 | 27.7 | 5.72 |
| Articulated trucks | 0.0 | 0.00 | 80.5 | 3.22 | 71.1 | 100.00 | 79.8 | 3.21 |
| Non-freight carrying trucks | 14.2 | 2.86 | 19.0 | 14.47 | 0.0 | 0.00 | 18.8 | 14.02 |
| Buses | 12.1 | 6.49 | 22.4 | 4.71 | 0.0 | 0.00 | 22.1 | 4.72 |
| **Total** | **11.0** | **1.79** | **18.7** | **5.55** | **20.6** | **46.20** | **15.1** | **2.95** |
| **Australian Capital Territory** | | | | | | | | |
| Passenger vehicles | 9.7 | 3.40 | 9.2 | 11.97 | 9.4 | 11.78 | 9.7 | 3.10 |
| Motor cycles | 5.0 | 6.78 | 0.0 | 0.00 | 0.0 | 0.00 | 5.0 | 6.78 |
| Light commercial vehicles | 12.9 | 2.80 | 11.2 | 3.12 | 12.4 | 9.33 | 12.0 | 2.15 |
| Rigid trucks | 15.7 | 8.43 | 28.3 | 3.43 | 17.4 | 12.91 | 28.1 | 3.40 |
| Articulated trucks | 0.0 | 0.00 | 51.3 | 1.96 | 0.0 | 0.00 | 51.3 | 1.96 |
| Non-freight carrying trucks | 0.0 | 0.00 | 19.0 | 9.93 | 0.0 | 0.00 | 19.0 | 9.93 |
| Buses | 14.9 | 7.65 | 38.0 | 4.49 | 58.3 | 0.41 | 38.5 | 7.23 |
| **Total** | **9.9** | **3.03** | **13.6** | **5.90** | **15.0** | **11.90** | **10.7** | **2.39** |
| **Australia** | | | | | | | | |
| Passenger vehicles | 10.6 | 1.23 | 10.0 | 3.02 | 11.1 | 8.14 | 10.6 | 1.10 |
| Motor cycles | 5.6 | 2.48 | 0.0 | 0.00 | 0.0 | 0.00 | 5.6 | 2.48 |
| Light commercial vehicles | 13.2 | 2.10 | 11.2 | 1.27 | 14.5 | 3.55 | 12.0 | 1.06 |
| Rigid trucks | 29.5 | 22.74 | 28.0 | 1.99 | 44.7 | 39.25 | 28.0 | 1.97 |
| Articulated trucks | 30.4 | 100.00 | 56.3 | 0.60 | 64.0 | 21.59 | 56.3 | 0.60 |
| Non-freight carrying trucks | 15.5 | 7.10 | 25.8 | 10.59 | 19.3 | 11.20 | 25.6 | 10.44 |
| Buses | 15.9 | 7.61 | 28.0 | 2.58 | 35.0 | 13.41 | 27.8 | 2.30 |
| **Total** | **10.8** | **1.14** | **18.0** | **1.93** | **12.6** | **6.14** | **13.1** | **0.80** |

# APPENDIX E: FUEL COMBUSTION EMISSION FACTORS

| Transport equipment type | Fuel combusted | Energy content factor (GJ/kL unless otherwise indicated) | Emission factor kg $CO_2$-e/GJ (relevant oxidation factors incorporated) | | |
|---|---|---|---|---|---|
| | | | $CO_2$ | $CH_4$ | $N_2O$ |
| General transport | | | | | |
| | Gasoline (other than for use as fuel in an aircraft) | 34.2 | 67.4 | 0.5 | 1.8 |
| | Diesel oil | 38.6 | 69.9 | 0.1 | 0.5 |
| | Gasoline for use as fuel in an aircraft | 33.1 | 67.0 | 0.05 | 0.7 |
| | Kerosene for use as fuel in an aircraft | 36.8 | 69.6 | 0.01 | 0.6 |
| | Fuel oil | 39.7 | 73.6 | 0.07 | 0.6 |
| | Liquefied petroleum gas | 26.2 | 60.2 | 0.6 | 0.7 |
| | Biodiesel | 34.6 | 0.0 | 0.7 | 1.9 |
| | Ethanol for use as fuel in an internal combustion engine | 23.4 | 0.0 | 0.7 | 1.9 |
| | Biofuels other than those mentioned in items above | 23.4 | 0.0 | 0.7 | 1.9 |
| | Compressed natural gas that has converted to standard conditions (light duty vehicles) | $39.3 \times 10^{-3}$ GJ/m$^3$ | 51.4 | 6.5 | 0.3 |
| | Compressed natural gas that has converted to standard conditions (heavy duty vehicles) | $39.3 \times 10^{-3}$ GJ/m$^3$ | 51.4 | 2.5 | 0.3 |
| | Liquefied natural gas (light duty vehicles) | 25.3 | 51.4 | 6.5 | 0.3 |
| | Liquefied natural gas (heavy duty vehicles) | 25.3 | 51.4 | 2.5 | 0.3 |
| Post-2004 vehicles | | | | | |
| | Gasoline (other than for use as fuel in an aircraft) | 34.2 | 67.4 | 0.02 | 0.2 |
| | Diesel oil | 38.6 | 69.9 | 0.01 | 0.6 |
| | Liquefied petroleum gas | 26.2 | 60.2 | 0.4 | 0.3 |
| | Ethanol for use as fuel in an internal combustion engine | 23.4 | 0 | 0.2 | 0.2 |
| Heavy vehicles conforming to Euro design standards | | | | | |
| Euro iv or higher | Diesel oil | 38.6 | 69.9 | 0.06 | 0.5 |
| Euro iii | Diesel oil | 38.6 | 69.9 | 0.1 | 0.5 |
| Euro i | Diesel oil | 38.6 | 69.9 | 0.2 | 0.5 |

**Table E.1: Fuel Combustion Emission Factors/fuels Used for Transport Energy Purposes (Australian Government, 2019)**

# APPENDIX F: THE UNCERTAINTY ANALYSIS FOR LCA OF TRANSPORTATION

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.897258 | 0.135185 | 5 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.240427 | 0.003593 | 1 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.54E-09 | 5.15E-10 | 33 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 6.10E-09 | 2.03E-09 | 33 |
| **Particulate Matter(kg/pkm)** | 0.000228 | 6.48E-06 | 3 |

**Table F.1: Uncertainty Analysis of LSDV' LCA**

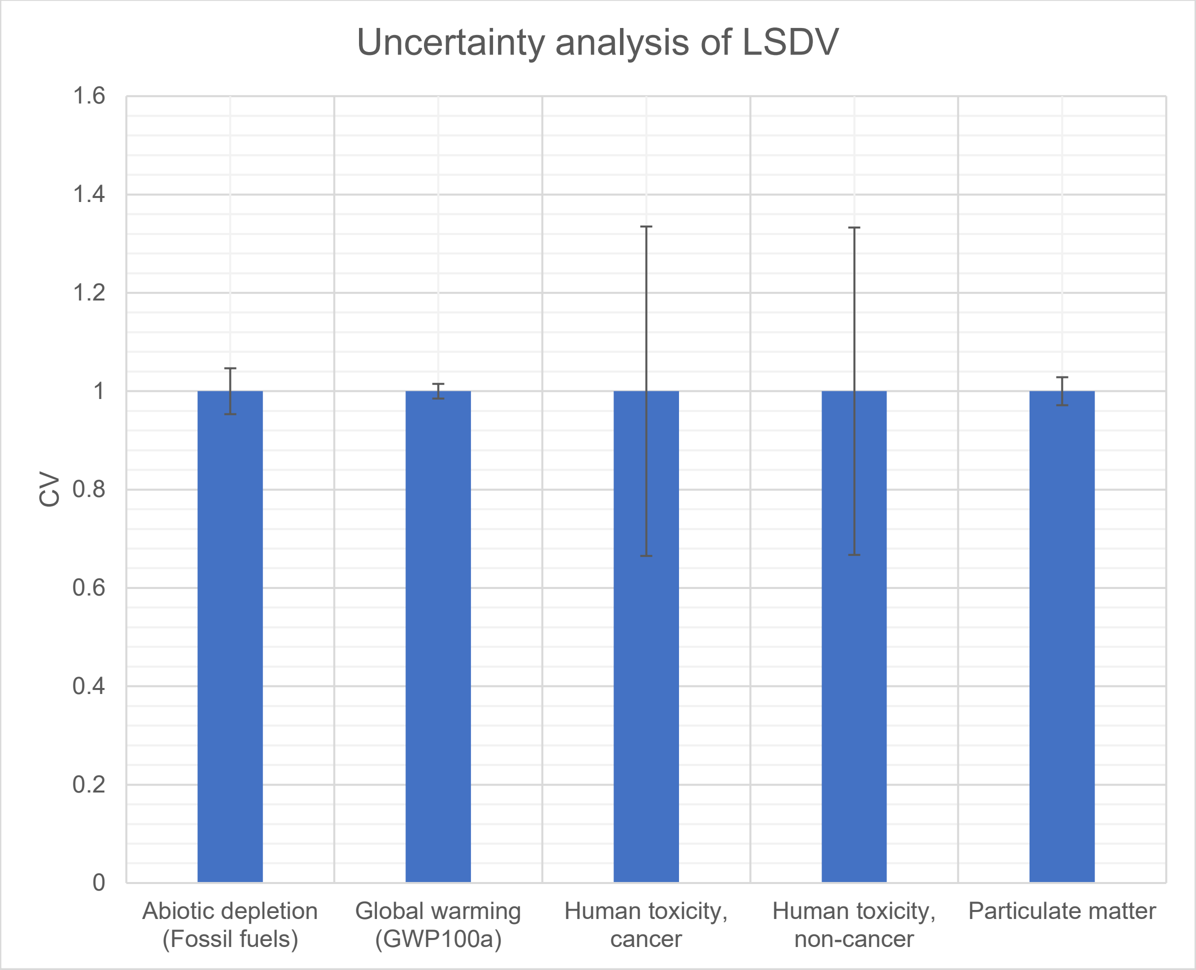


**Figure F.1: Uncertainty Analysis of LSDV' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.562629 | 0.023157 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.037329 | 0.001666 | 4 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.40E-09 | 4.48E-10 | 32 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 5.52E-09 | 2.45E-09 | 44 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.24E-06 | 9% |

**Table F.2: Uncertainty Analysis of CNGV' LCA**

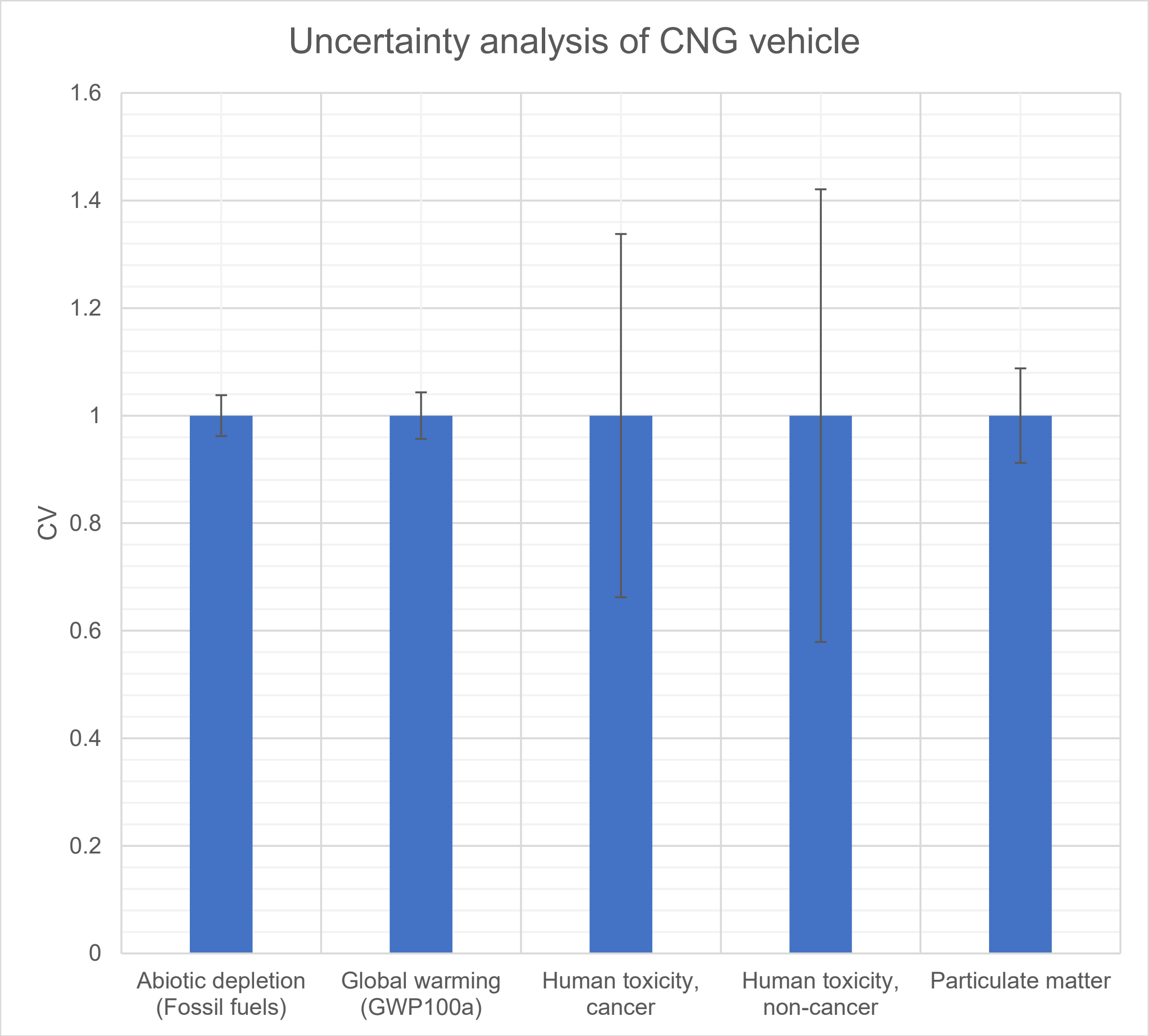


**Figure F.2: Uncertainty Analysis of CNGV' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic depletion (Fossil Fuels) (MJ/pkm)** | 2.467786 | 0.066184 | 3 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.198984 | 0.002257 | 1 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.53E-09 | 6.22E-10 | 41 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 6.75E-09 | 2.16E-09 | 32 |
| **Particulate Matter(kg/pkm)** | 2.50E-05 | 2.09E-06 | 8 |

**Table F.3: Uncertainty Analysis of LPGV' LCA**

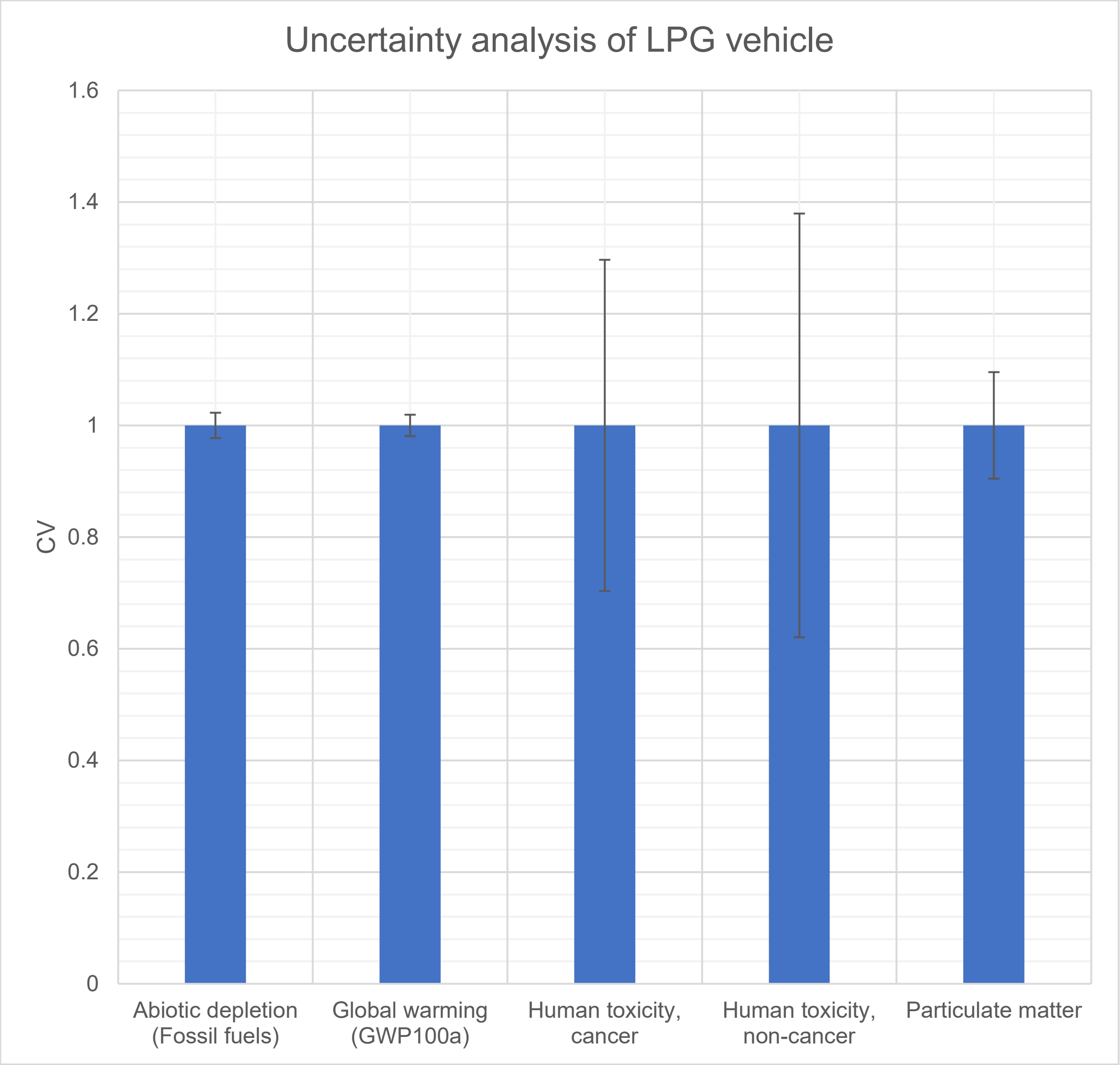


**Figure F.3: Uncertainty Analysis of LPGV' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.7308 | 0.02799 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.12776 | 0.002065 | 2 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.71E-09 | 6.30E-10 | 37 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 8.20E-09 | 3.47E-09 | 42 |
| **Particulate Matter (kg/pkm)** | 4.75E-05 | 6.67E-06 | 14 |

**Table F.4: Uncertainty Analysis of HEV' LCA**

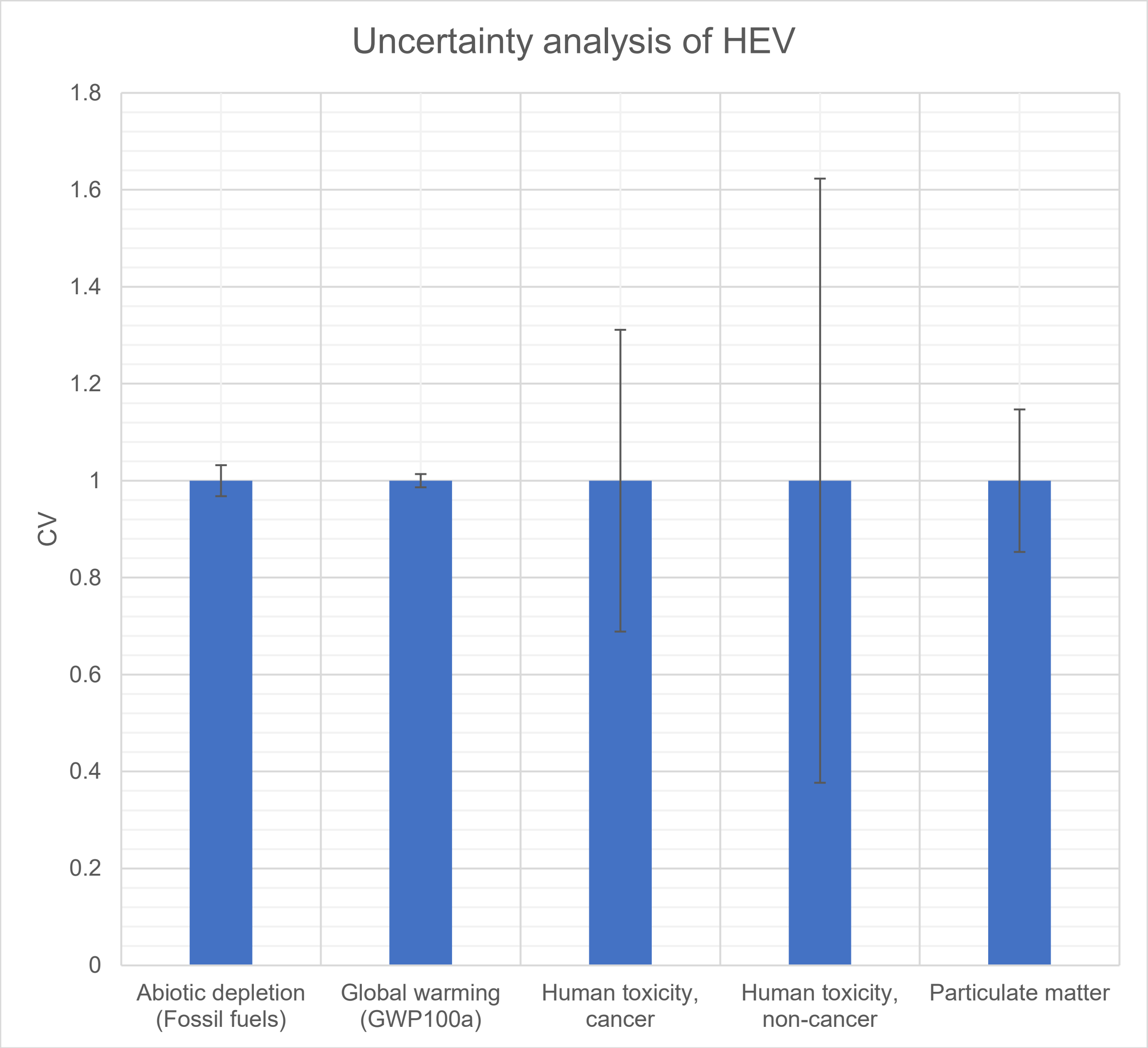


**Figure F.4: Uncertainty Analysis of HEV' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.5718362 | 0.037999975 | 2 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.15949965 | 0.003257546 | 2 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.89E-09 | 5.06E-10 | 27 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 2.45E-08 | 6.51E-09 | 27 |
| **Particulate Matter(kg/pkm)** | 5.65E-05 | 5.01E-06 | 9 |

**Table F.5: Uncertainty Analysis of PHEV' LCA**

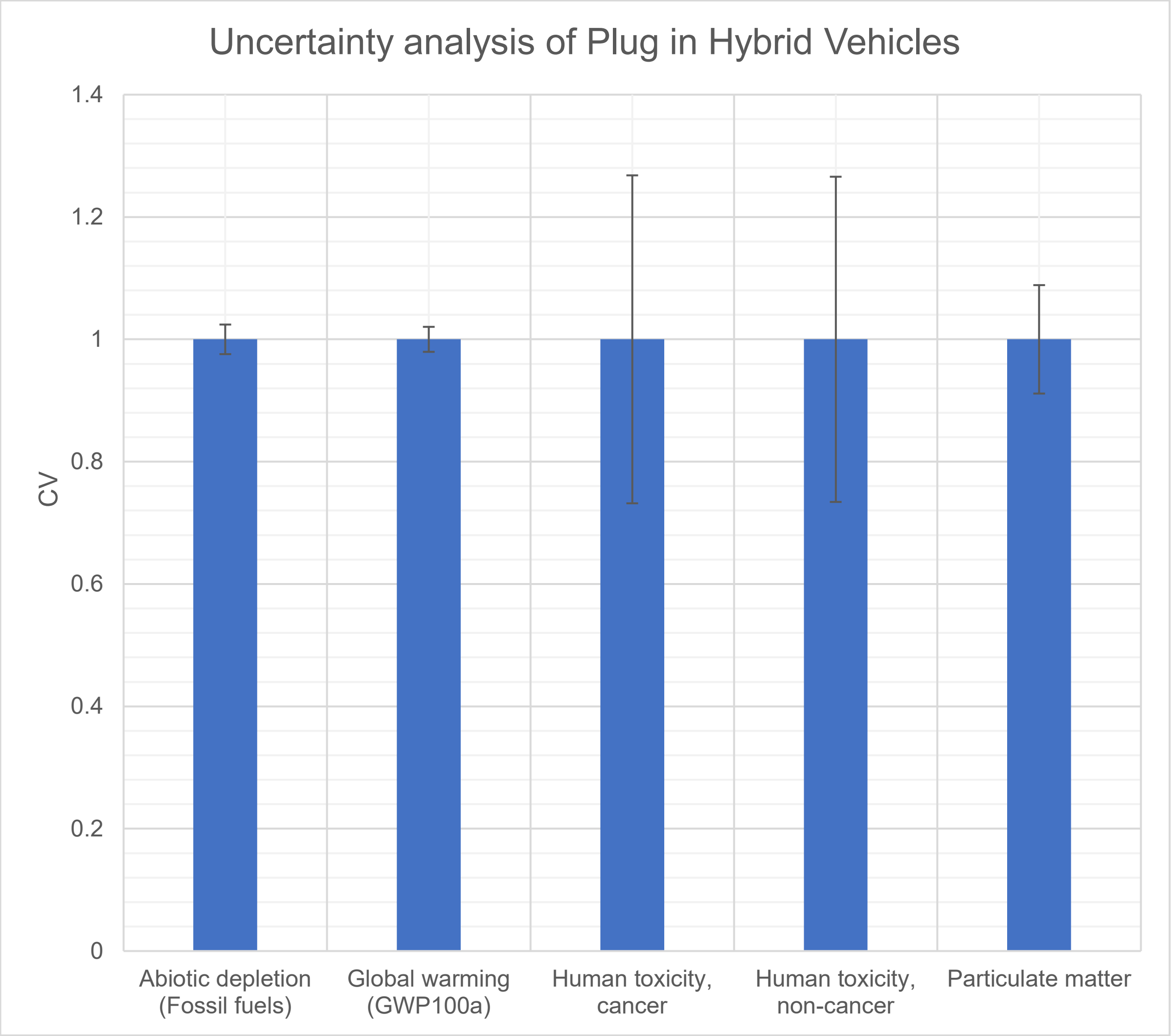


**Figure F.5: Uncertainty Analysis of PHEV' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.622206 | 0.025716 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.045223 | 0.001836 | 4 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.54E-09 | 4.29E-10 | 28 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 7.91E-09 | 4.90E-09 | 62 |
| **Particulate Matter(kg/pkm)** | 1.44E-05 | 1.29E-06 | 9 |

**Table F.6: Uncertainty Analysis of FCV' LCA**

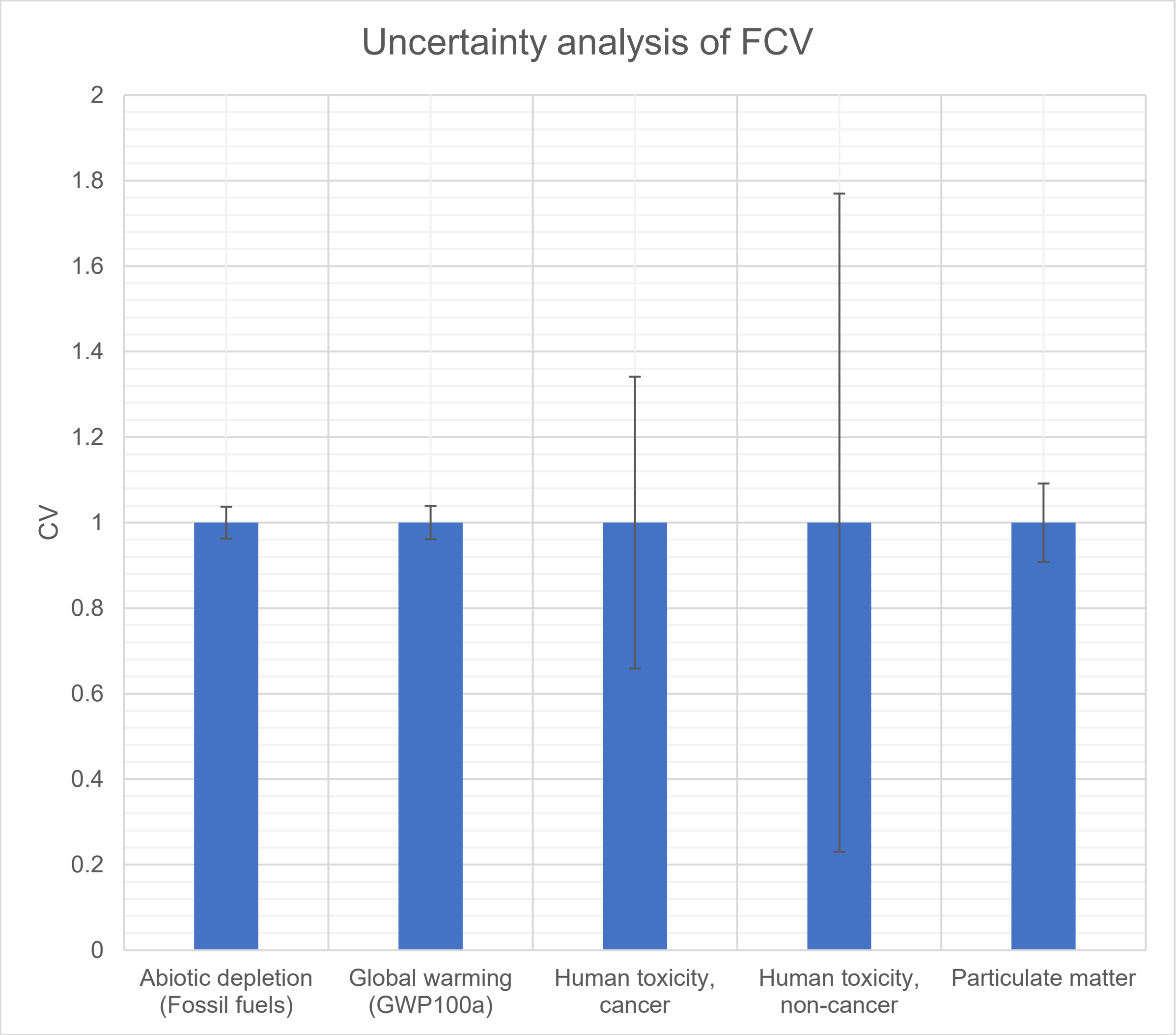


**Figure F.6: Uncertainty Analysis of FCV' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.879665 | 0.062421 | 3 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.153739 | 0.00507 | 3 |
| **Human Toxicity, Cancer(kg/pkm)** | 2.20E-09 | 1.04E-09 | 47 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 1.76E-08 | 3.74E-09 | 21 |
| **Particulate Matter(kg/pkm)** | 3.60E-05 | 4.11E-06 | 11 |

**Table F.7: Uncertainty Analysis of BEV' LCA**

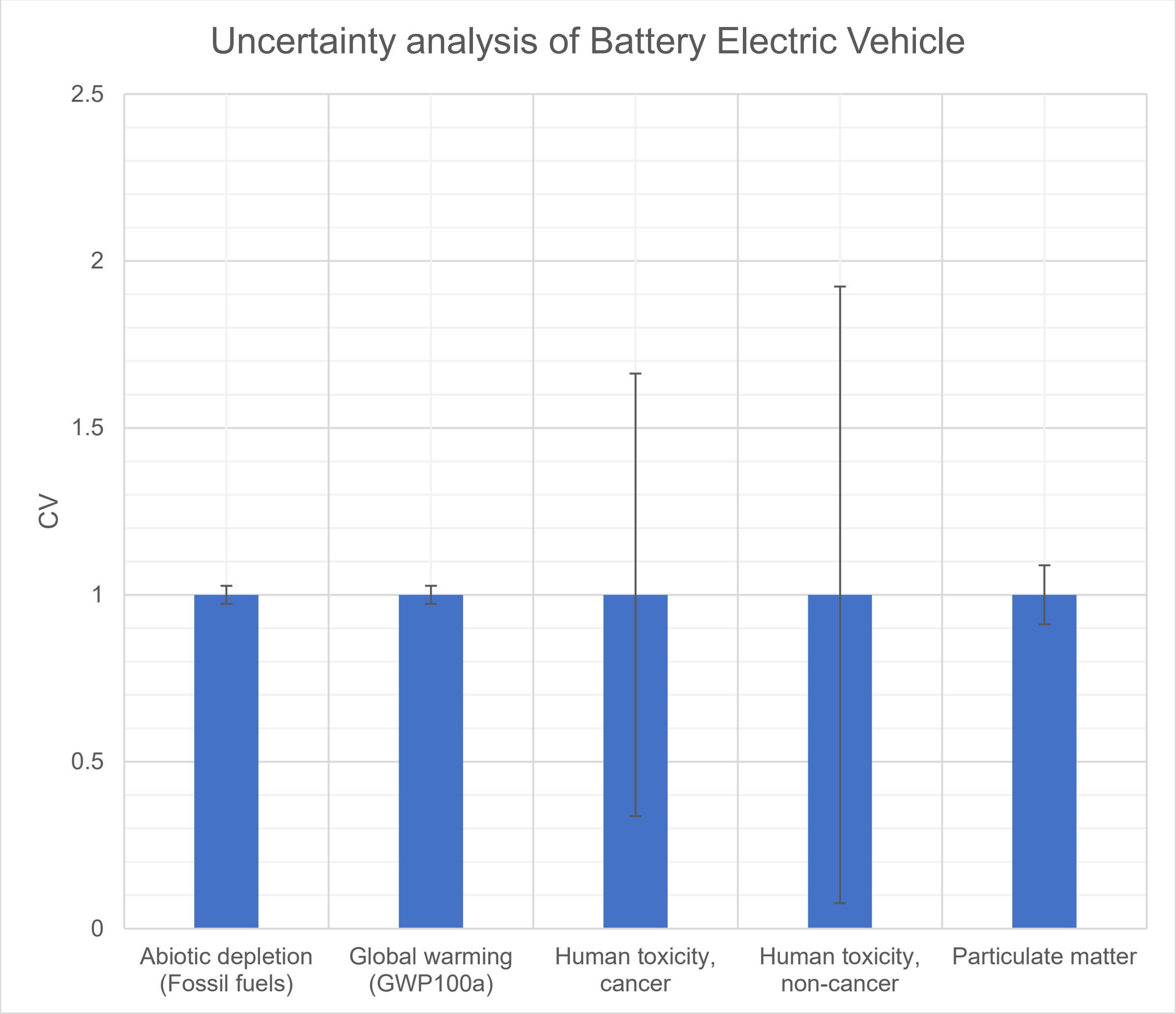


**Figure F.7: Uncertainty Analysis of BEV' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.74590935 | 0.042374001 | 6 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.061591682 | 0.004106045 | 7 |
| **Human Toxicity, Cancer(kg/pkm)** | 3.86E-10 | 9.94E-11 | 26 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 1.88E-09 | 5.17E-10 | 2 |
| **Particulate Matter (kg/pkm)** | 7.70E-06 | 8.96E-07 | 12 |

**Table F.8: Uncertainty Analysis of LPG Buses' LCA**

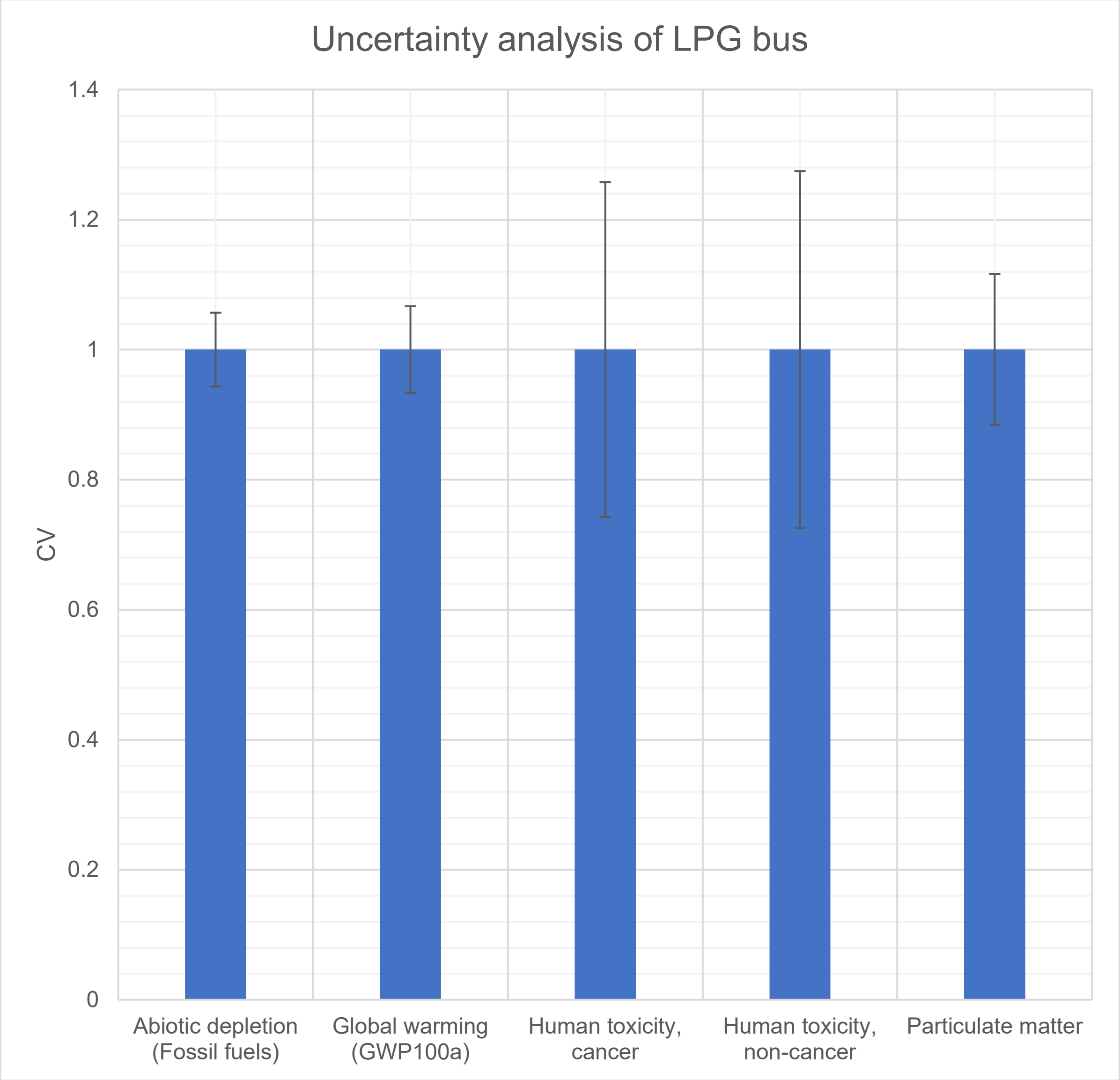


**Figure F.8: Uncertainty Analysis of LPG Buses' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92414087 | 0.048217157 | 5 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.077258214 | 0.003445644 | 4 |
| **Human Toxicity, Cancer(kg/pkm)** | 4.55E-10 | 1.56E-10 | 34 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 2.14E-09 | 5.15E-10 | 24 |
| **Particulate Matter (kg/pkm)** | 6.65E-05 | 4.90E-06 | 7 |

**Table F.9: Uncertainty Analysis of Hybrid Electric Buses' LCA**

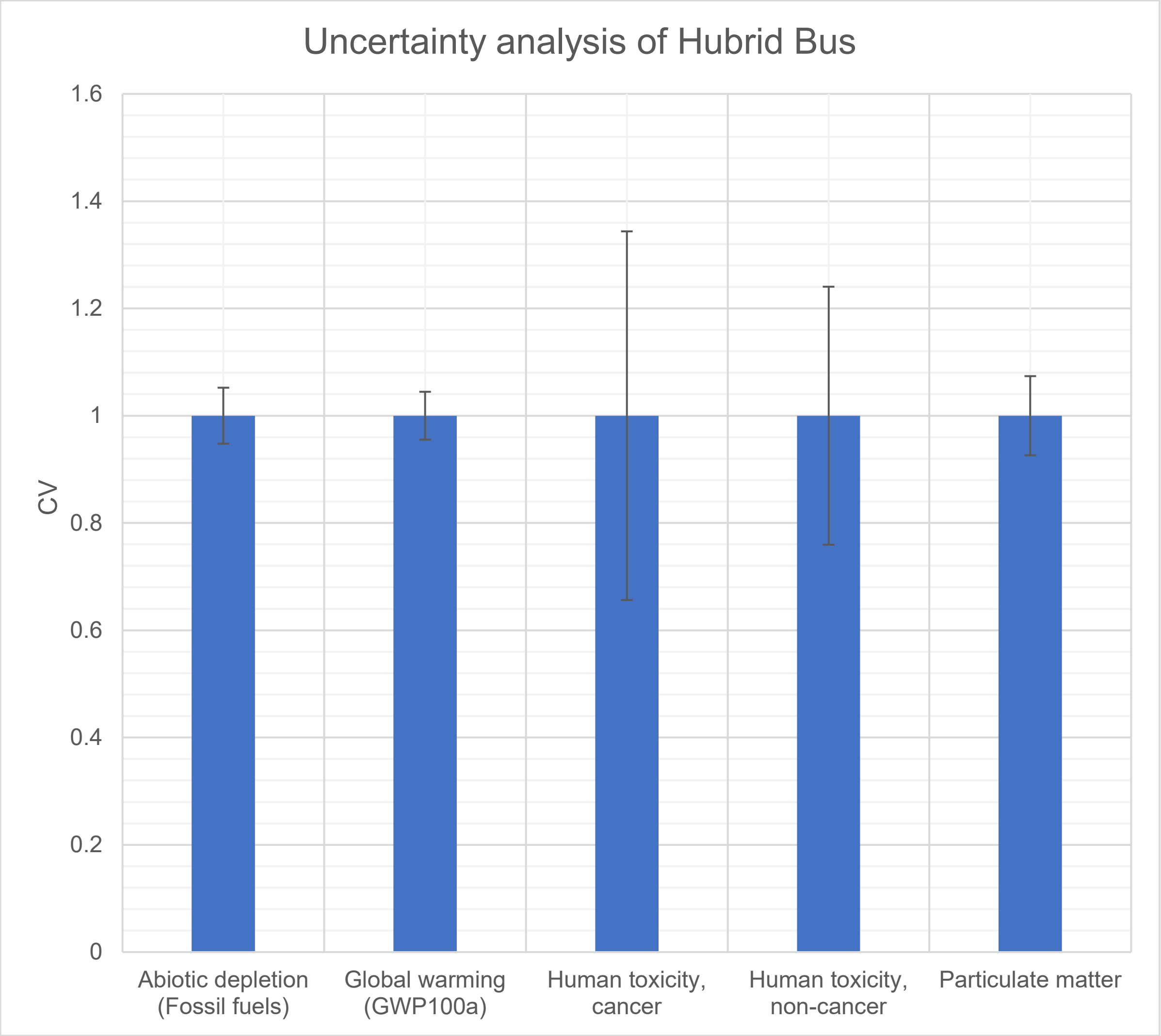


**Figure F.9: Uncertainty Analysis of Hybrid Electric Buses' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28203213 | 0.046692279 | 17 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.022736701 | 0.004089922 | 18 |
| **Human Toxicity, Cancer(kg/pkm)** | 4.85E-10 | 1.71E-10 | 35 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 2.28E-09 | 5.11E-10 | 22 |
| **Particulate Matter (kg/pkm)** | 5.18E-06 | 6.55E-07 | 13 |

**Table F.10: Uncertainty Analysis of Fuel Cell Buses' LCA**

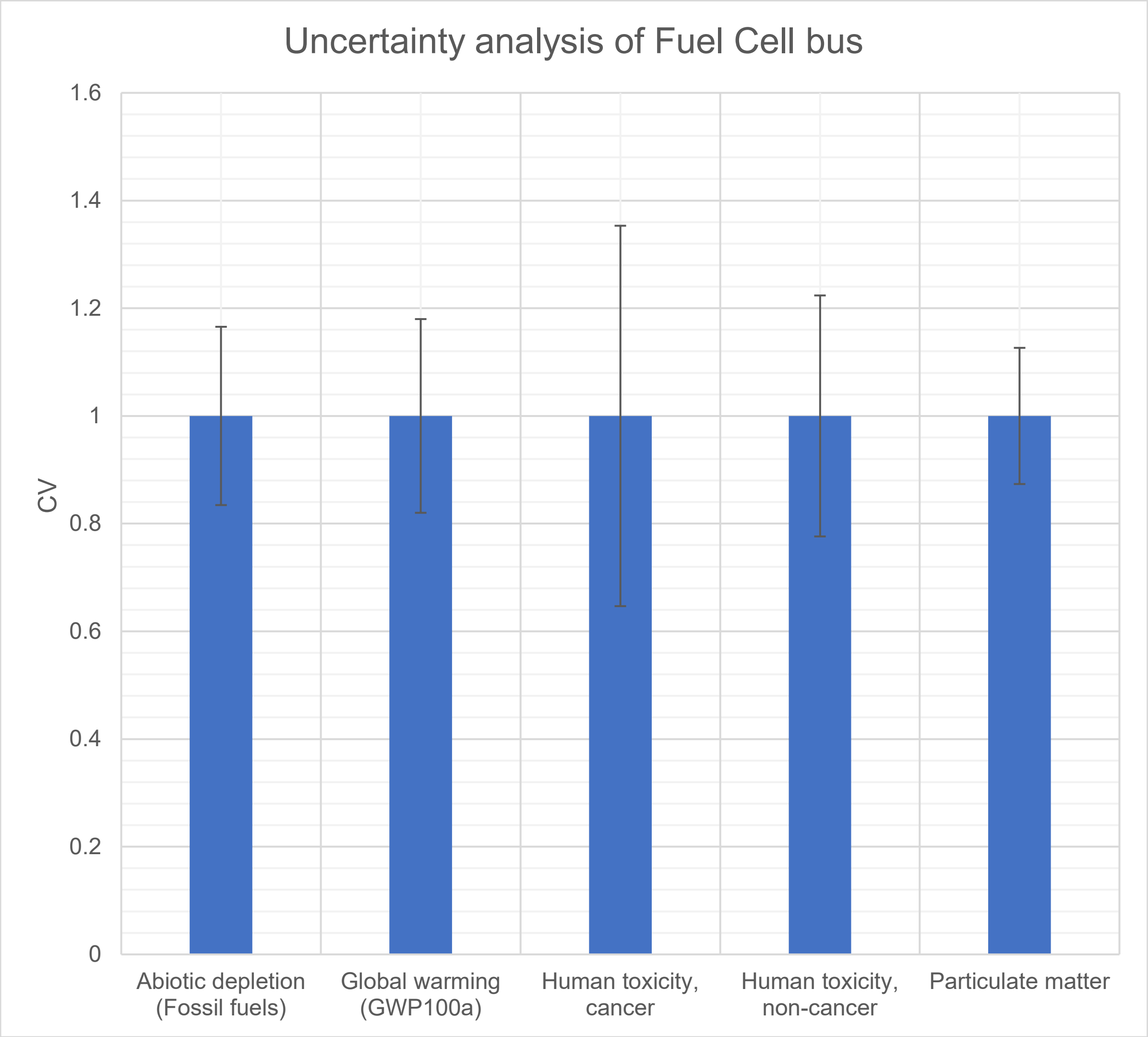


**Figure F.10: Uncertainty Analysis of Fuel Cell Buses' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.1060441 | 0.042934296 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.095186719 | 0.003711812 | 4 |
| **Human Toxicity, Cancer(kg/pkm)** | 7.53E-10 | 3.86E-10 | 51 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 5.86E-09 | 1.41E-09 | 24 |
| **Particulate Matter (kg/pkm)** | 1.52E-05 | 1.24E-06 | 8 |

**Table F.11: Uncertainty Analysis of Battery Electric Buses' LCA**

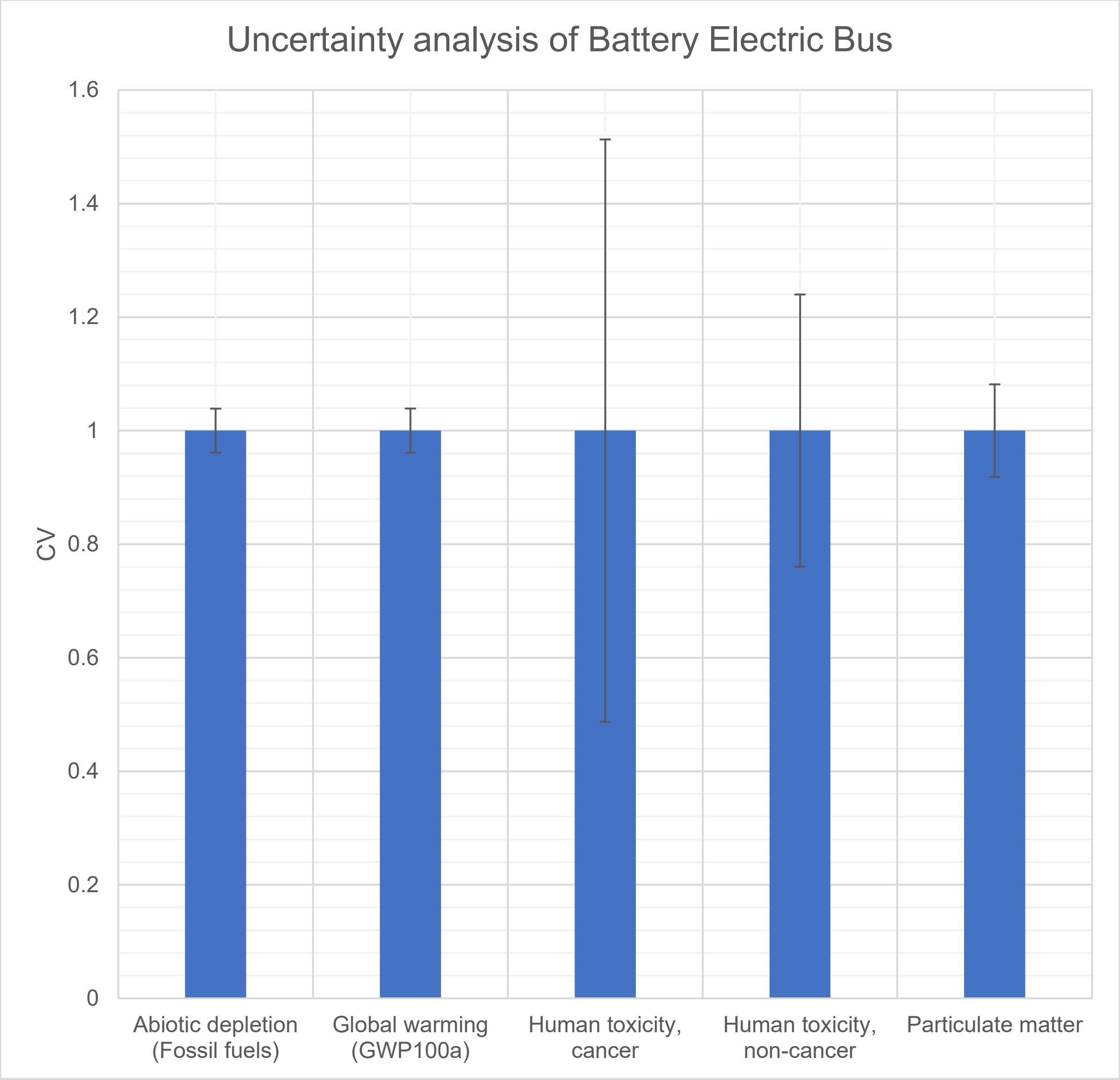


**Figure F.11: Uncertainty Analysis of Battery Electric Buses'** LCA

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | 5.7928767 | 0.28529392 | 5 |
| **Global Warming (GWP100a) (kg/tkm)** | 0.47908639 | 0.008013562 | 2 |
| **Human Toxicity, Cancer(kg/tkm)** | 1.51E-09 | 5.40E-10 | 36 |
| **Human Toxicity, Non-Cancer(kg/tkm)** | 8.24E-09 | 2.67E-09 | 32 |
| **Particulate Matter (kg/tkm)** | 0.000406244 | 1.17E-05 | 3 |

**Table F.12: Uncertainty Analysis of Hybrid Rigid Trucks' LCA**

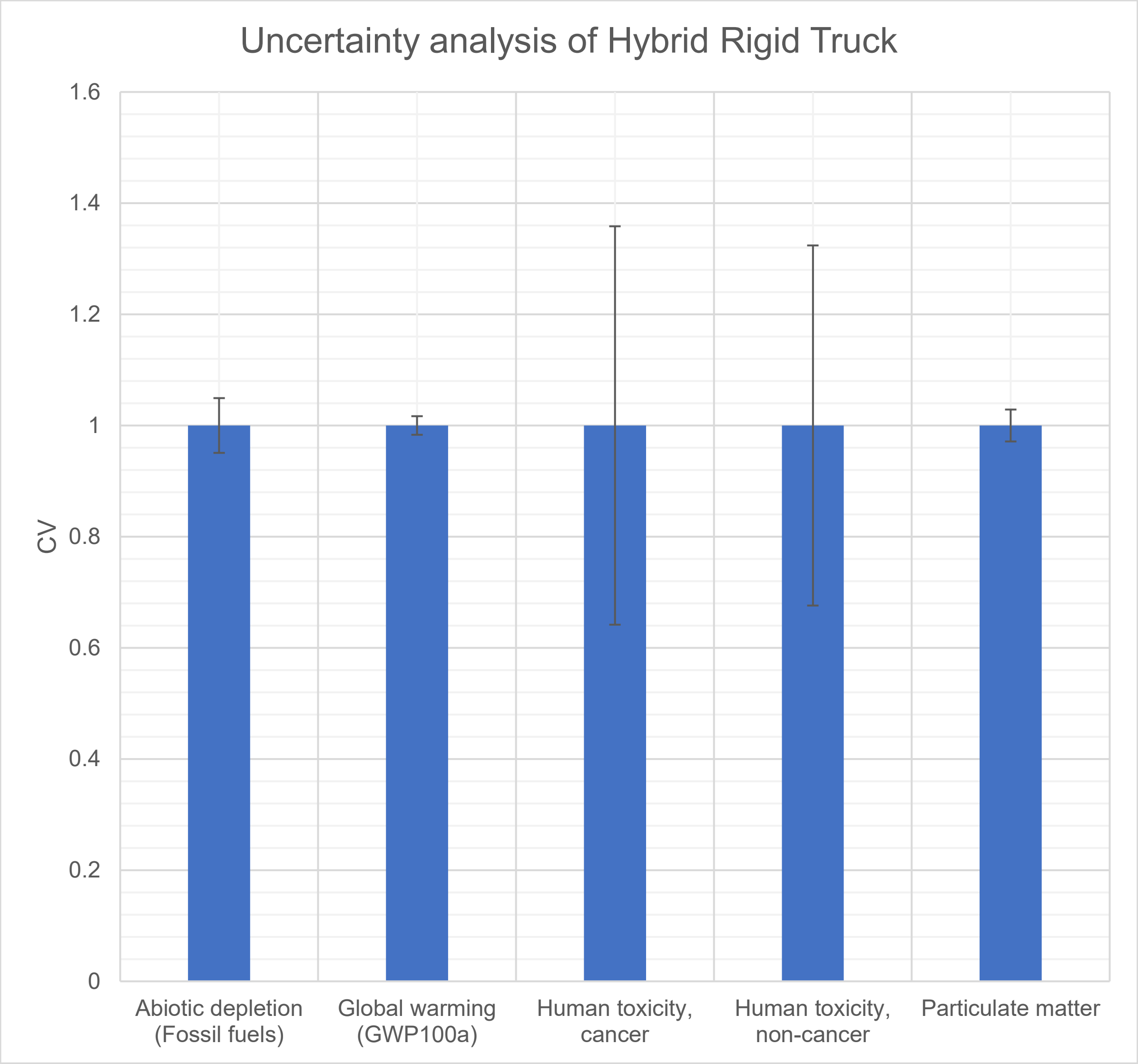


**Figure F.12: Uncertainty Analysis of Hybrid Rigid Trucks' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | 3.3736775 | 0.067743606 | 2 |
| **Global Warming (GWP100a) (kg/tkm)** | 0.27941971 | 0.005917522 | 2 |
| **Human Toxicity, Cancer(kg/tkm)** | 2.28E-09 | 8.48E-10 | 37 |
| **Human Toxicity, Non-Cancer(kg/tkm)** | 2.00E-08 | 4.22E-09 | 21 |
| **Particulate Matter (kg/tkm)** | 4.88E-05 | 4.10E-06 | 8 |

**Table F.13: Uncertainty Analysis of Battery Electric rigid trucks' LCA**

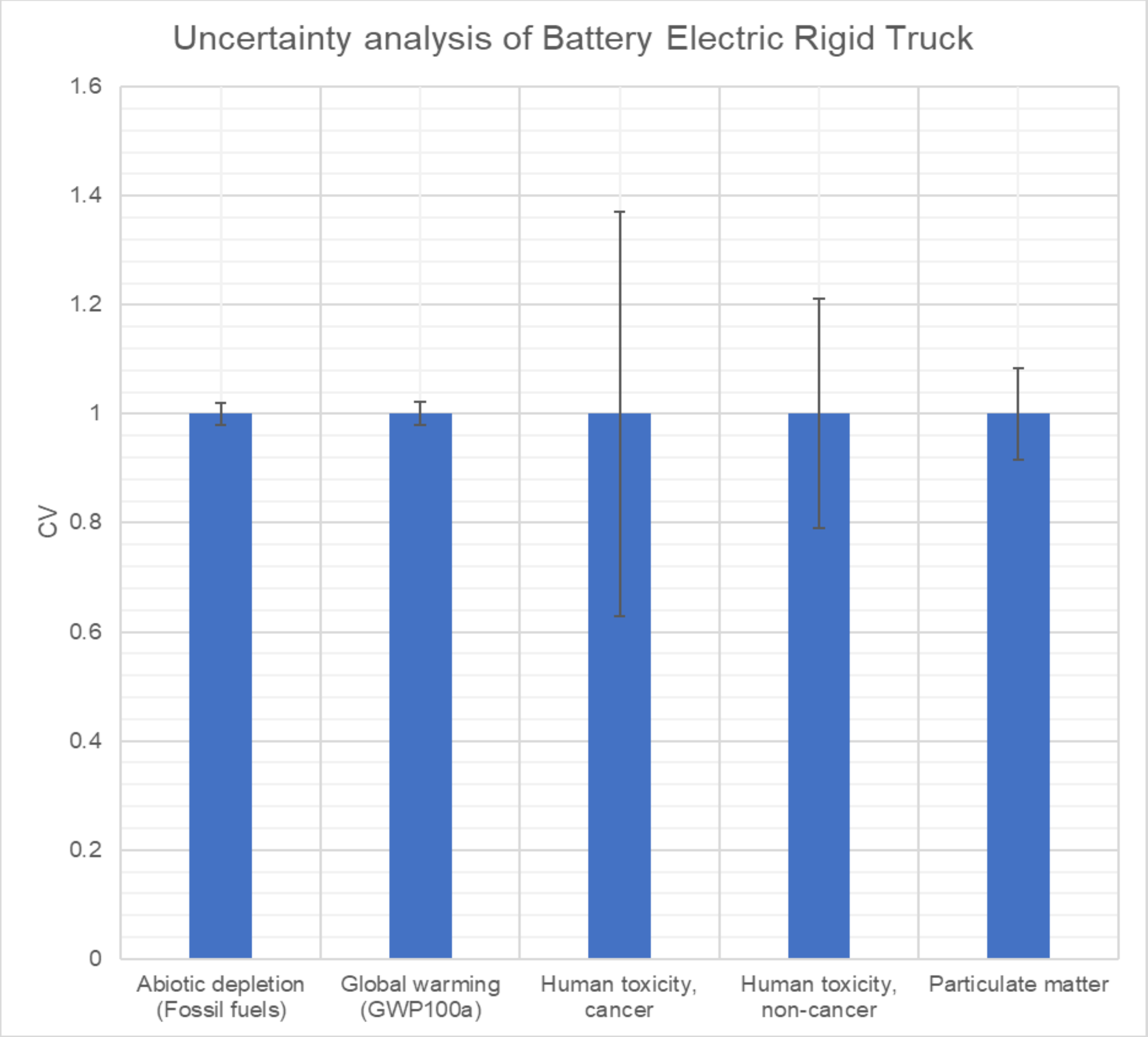


**Figure F.13: Uncertainty Analysis of Battery Electric rigid trucks' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | 1.4753118 | 0.077610146 | 5 |
| **Global Warming (GWP100a) (kg/tkm)** | 0.12359686 | 0.001868402 | 2 |
| **Human Toxicity, Cancer(kg/tkm)** | 2.48E-10 | 8.52E-11 | 34 |
| **Human Toxicity, Non-Cancer(kg/tkm)** | 1.53E-09 | 3.52E-10 | 23 |
| **Particulate Matter (kg/tkm)** | 7.53E-05 | 3.93E-06 | 5 |

**Table F.14: Uncertainty Analysis of LSD Articulated Trucks' LCA**

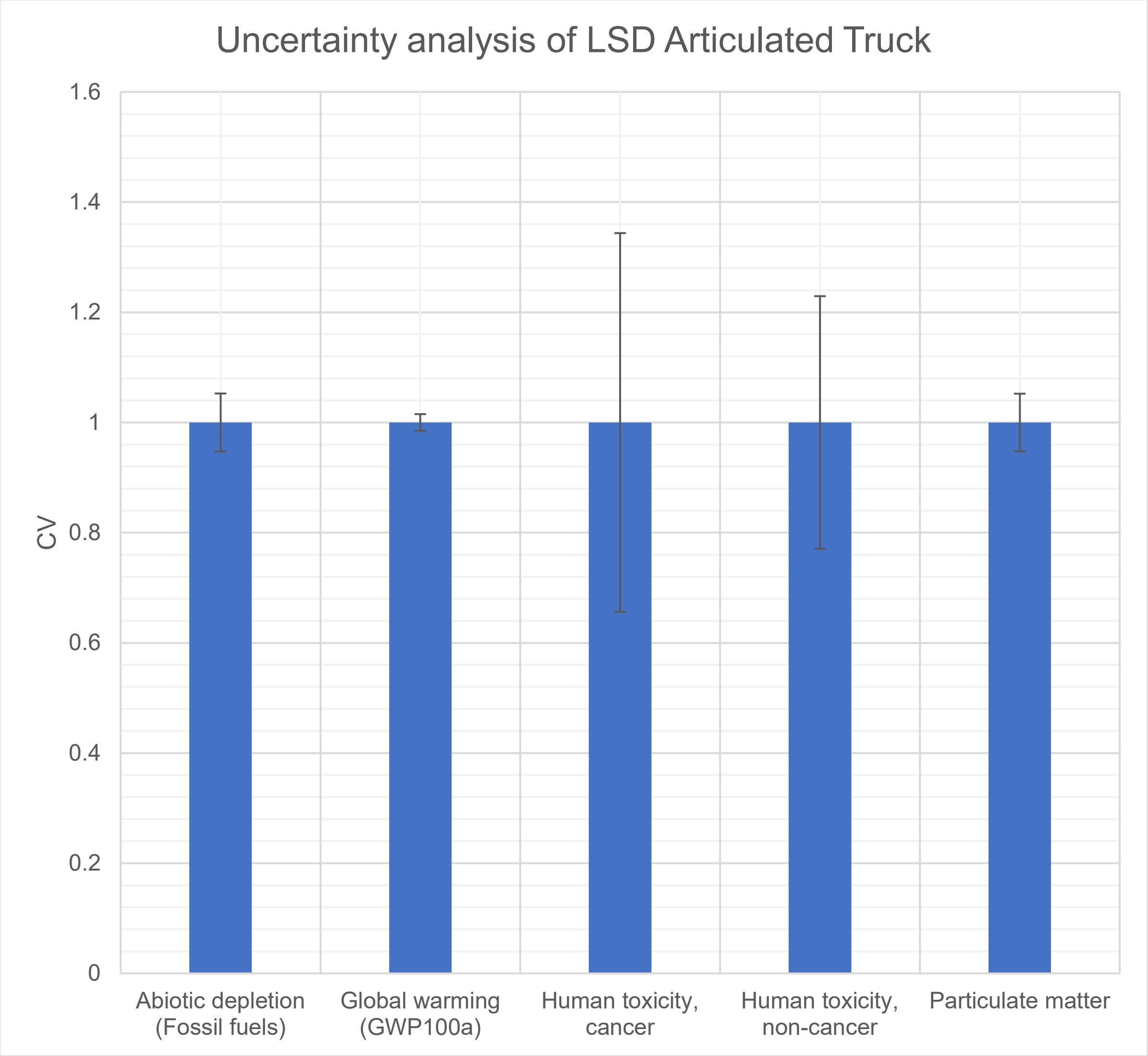


**Figure F.14: Uncertainty Analysis of LSD Articulated Trucks' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | 1.6662774 | 0.085124364 | 5 |
| **Global Warming (GWP100a) (kg/tkm)** | 0.13988353 | 0.002023069 | 1 |
| **Human Toxicity, Cancer(kg/tkm)** | 2.81E-10 | 9.40E-11 | 33 |
| **Human Toxicity, Non-Cancer(kg/tkm)** | 1.79E-09 | 7.12E-10 | 40 |
| **Particulate Matter (kg/tkm)** | 8.51E-05 | 3.79E-06 | 4 |

**Figure F.15: Uncertainty Analysis of Hybrid Electric Articulated Trucks' LCA**

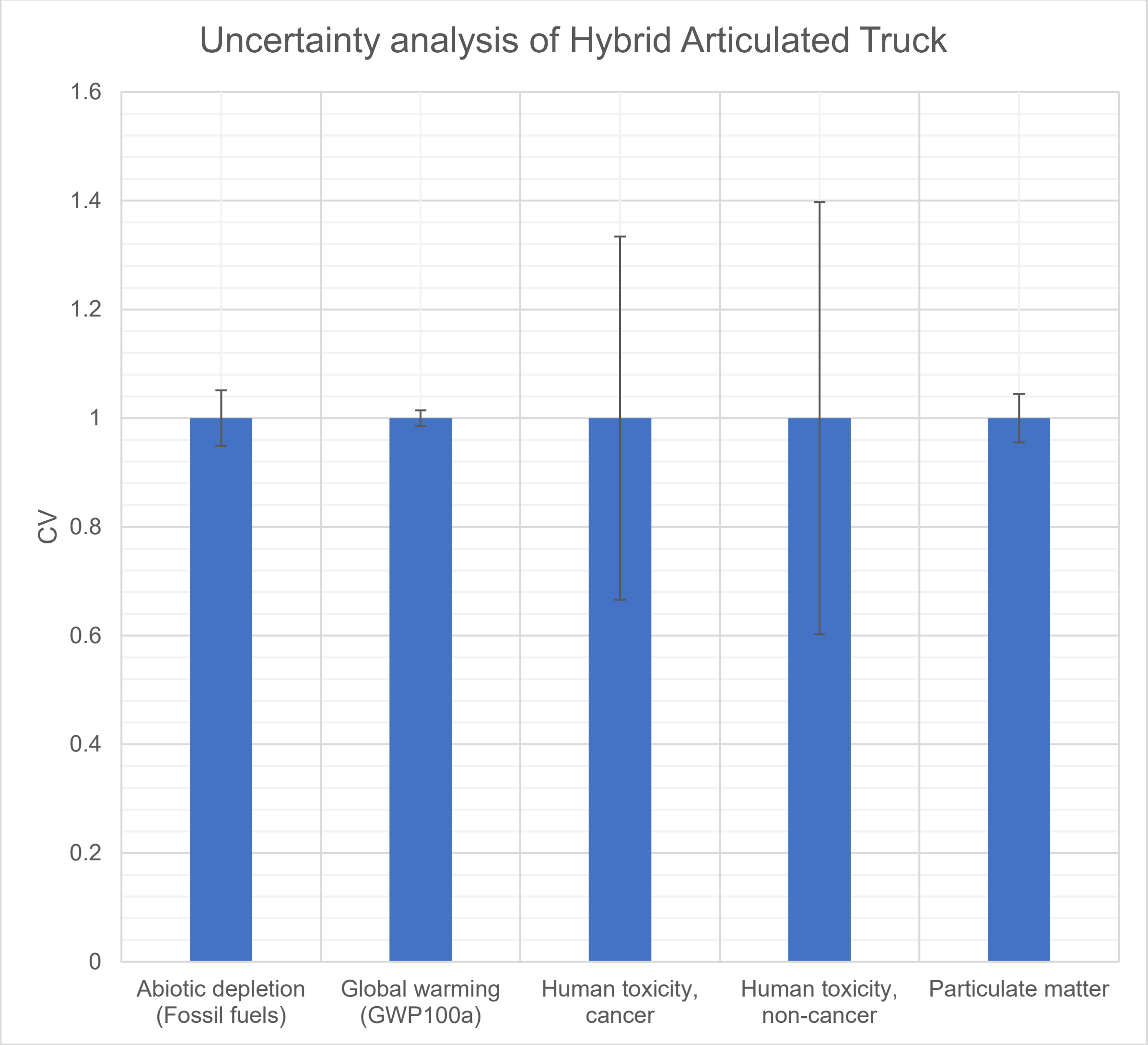


**Figure F.15: Uncertainty Analysis of Hybrid Electric Articulated Trucks' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/tkm)** | 0.85611871 | 0.02117 | 2 |
| **Global Warming (GWP100a) (kg/tkm)** | 0.07323398 | 0.001740375 | 2 |
| **Human Toxicity, Cancer (kg/tkm)** | 2.97E-10 | 7.00E-11 | 24 |
| **Human Toxicity, Non-Cancer (kg/tkm)** | 3.58E-09 | 8.07E-10 | 23 |
| **Particulate Matter (kg/tkm)** | 9.85E-06 | 7.29E-07 | 7 |

**Table F.16: Uncertainty Analysis of Battery Electric Articulated Trucks' LCA**

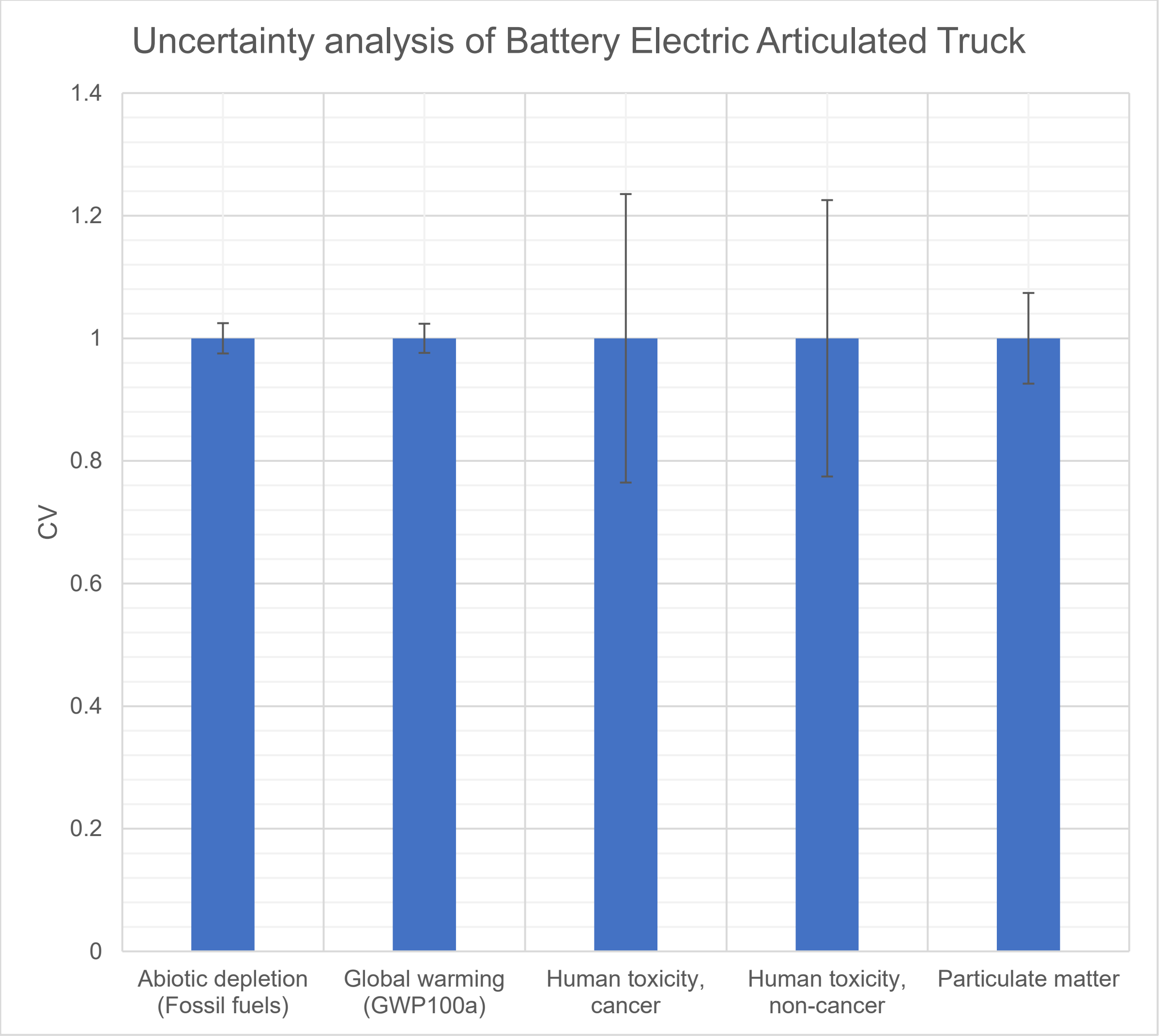


**Figure F.16: Uncertainty Analysis of Battery Electric Articulated Trucks' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.960088 | 0.1113437 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.17971315 | 0.003746367 | 2 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.56E-09 | 7.14E-10 | 46 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 9.29E-09 | 1.66E-09 | 18 |
| **Particulate Matter(kg/pkm)** | 5.79E-05 | 6.73E-06 | 12 |

**Table F.17: Uncertainty Analysis of $E_{25}$ Passenger Vehicles' LCA**

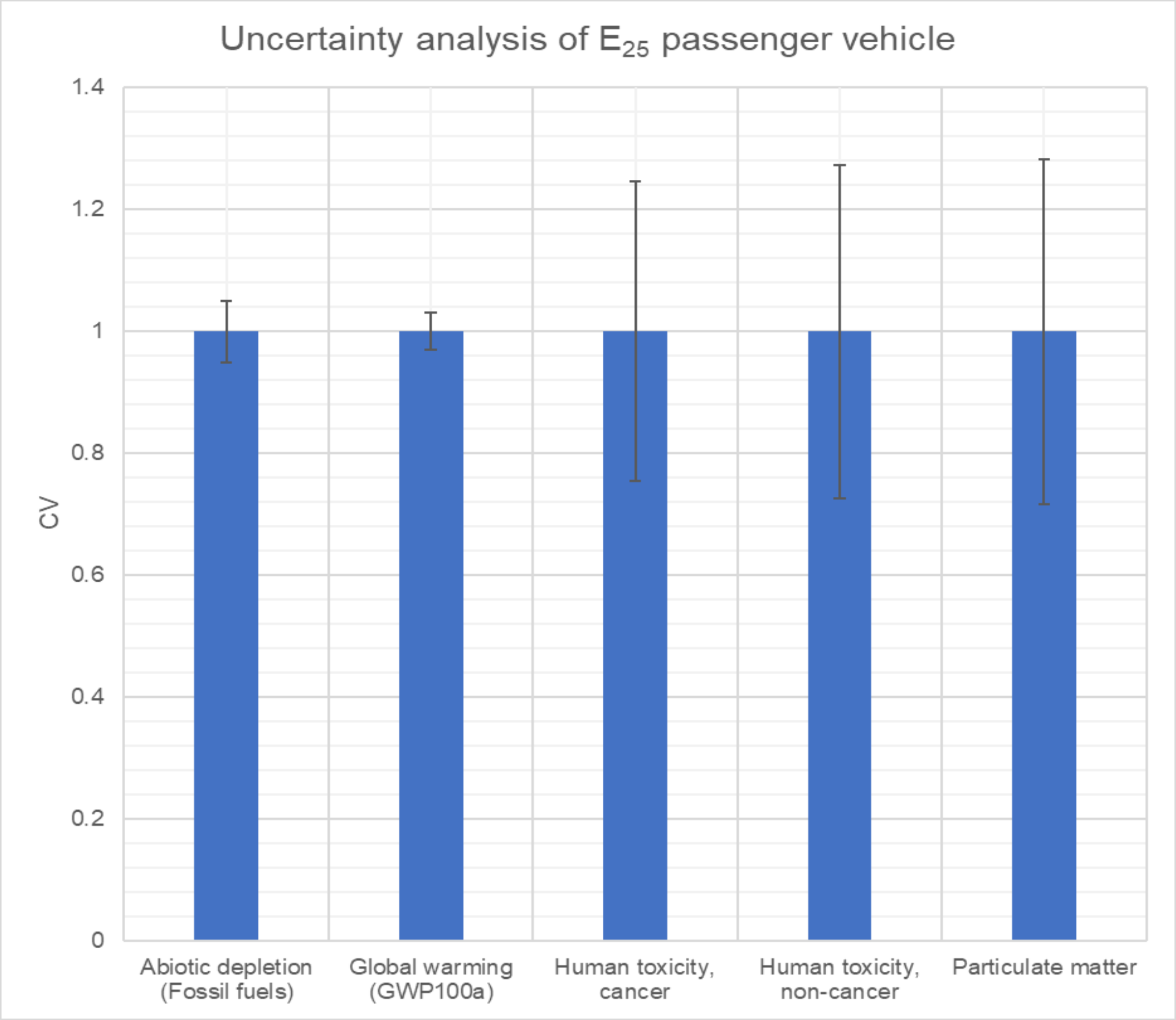


**Figure F.17: Uncertainty Analysis of $E_{25}$ Passenger Vehicles' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6481343 | 0.11801558 | 4 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.12953134 | 0.00629599 | 5 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.64E-09 | 6.31E-10 | 39 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 1.16E-08 | 1.86E-09 | 16 |
| **Particulate Matter(kg/pkm)** | 5.97E-05 | 7.92E-06 | 13 |

**Table F.18: Uncertainty Analysis of $E_{40}$ Passenger Vehicles' LCA**

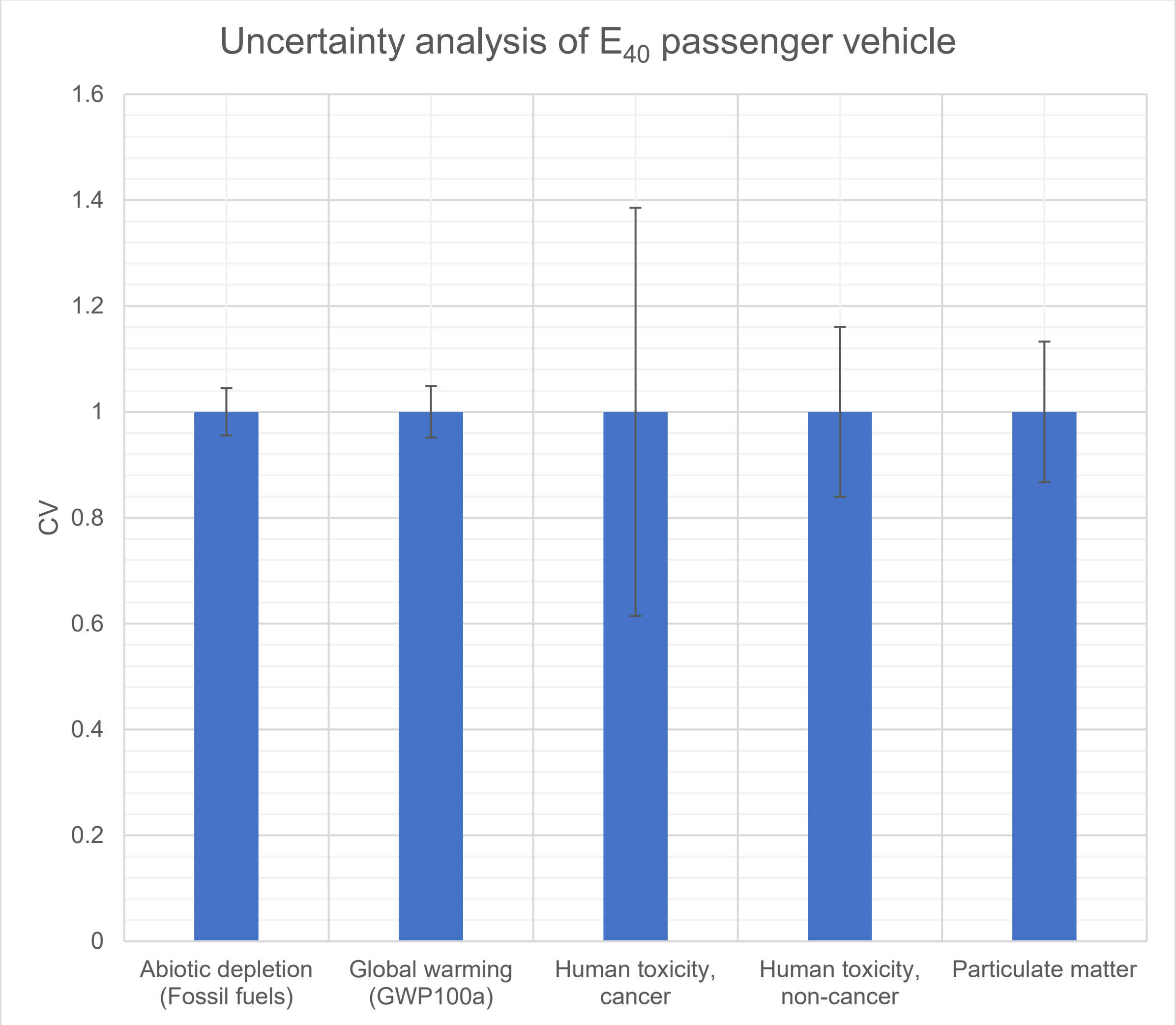


**Figure F.18: Uncertainty Analysis of $E_{40}$ Passenger Vehicles' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.666607 | 0.049709713 | 3 |
| **Global Warming (GWP100a) (kg/pkm)** | -0.012145238 | 0.011448569 | -94 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.60E-09 | 4.95E-10 | 31 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 1.77E-08 | 3.18E-09 | 18 |
| **Particulate Matter(kg/pkm)** | 6.26E-05 | 8.23E-06 | 13 |

**Table F.19: Uncertainty Analysis of E$_{85}$ Passenger Vehicles' LCA**

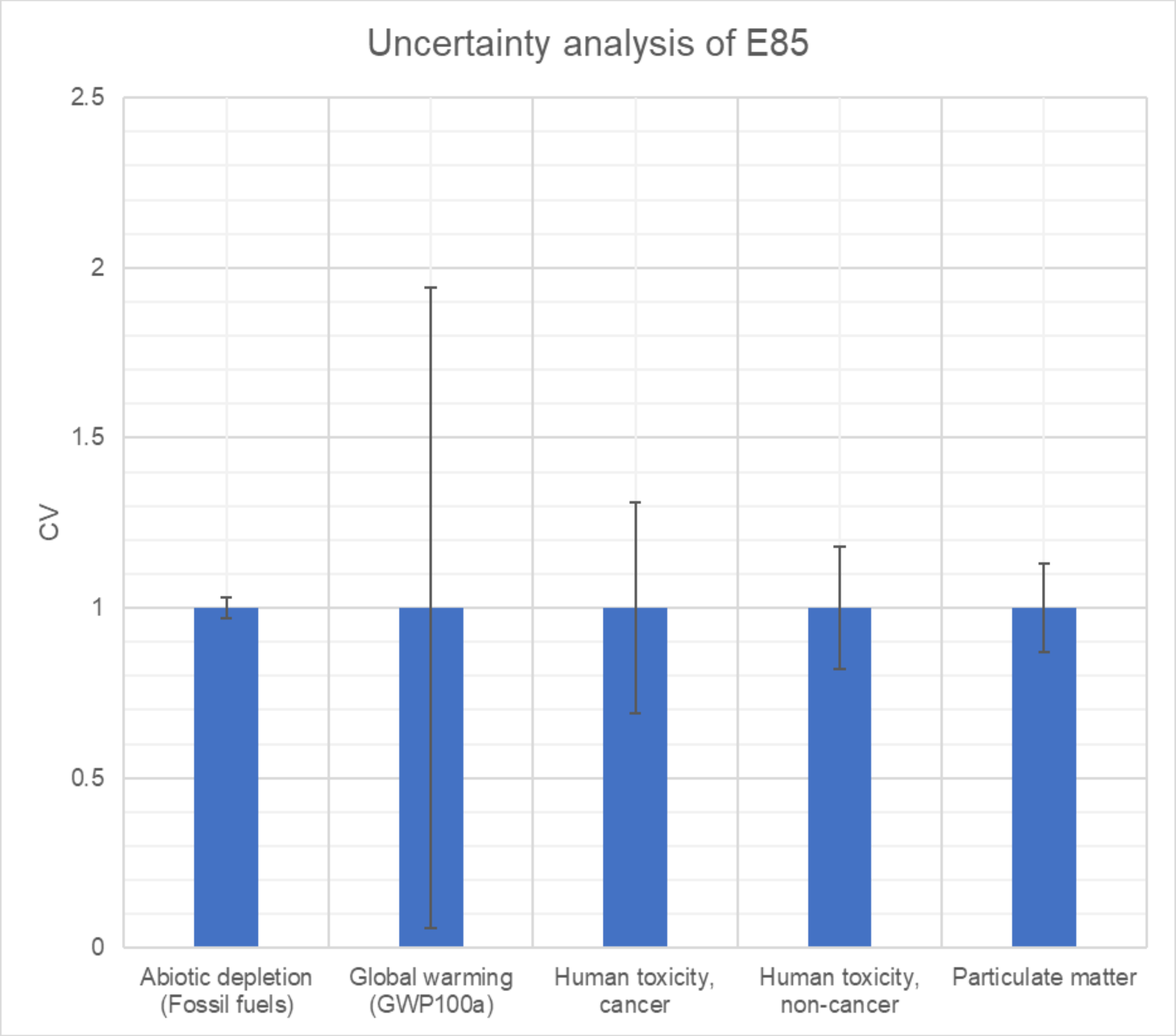


**Figure F.19: Uncertainty Analysis of E$_{85}$ Passenger Vehicles' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.89673929 | 0.050656204 | 6 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.073336019 | 0.003305012 | 5 |
| **Human Toxicity, Cancer(kg/pkm)** | 4.31E-10 | 1.31E-10 | 30 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 2.20E-09 | 6.43E-10 | 29 |
| **Particulate Matter(kg/pkm)** | 6.49E-05 | 2.28E-06 | 4 |

**Table F.20: Uncertainty Analysis of $BD_5$ Buses' LCA**

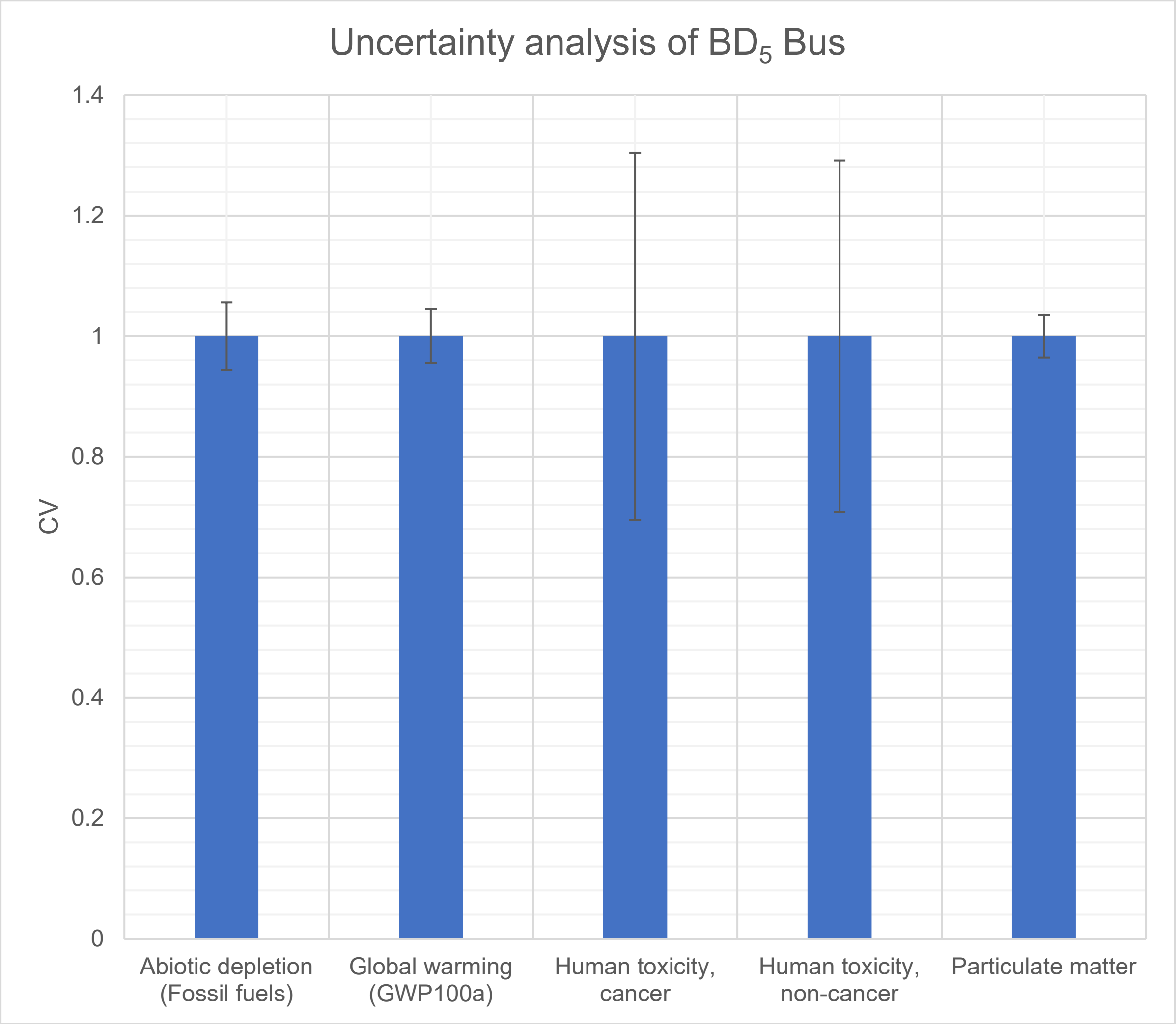


**Figure F.20: Uncertainty Analysis of $BD_5$ Buses' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.8448015 | 0.050287629 | 6% |
| **Global Warming (GWP100a) (kg/pkm)** | 0.061932673 | 0.004194153 | 7% |
| **Human Toxicity, Cancer(kg/pkm)** | 4.33E-10 | 1.22E-10 | 28% |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 2.57E-09 | 1.02E-09 | 40% |
| **Particulate Matter(kg/pkm)** | 6.33E-05 | 1.33E-06 | 2% |

**Table F.21: Uncertainty Analysis of BD20 Buses' LCA**

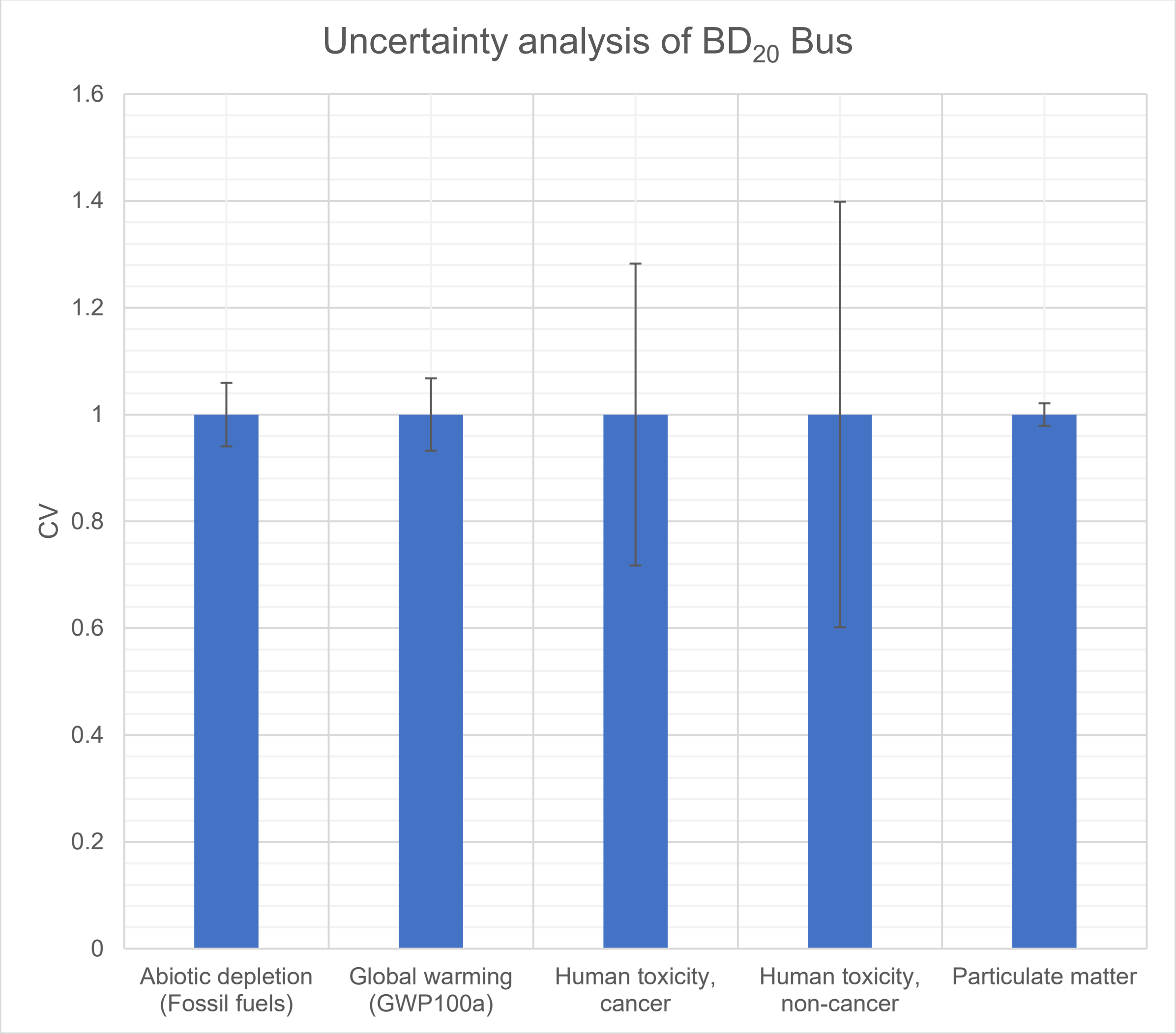


**Figure F.21: Uncertainty Analysis of BD20 Buses' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76205007 | 0.040273495 | 5 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.064197613 | 0.002293339 | 4 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.33E-10 | 4.38E-11 | 33 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 6.74E-10 | 1.48E-10 | 22 |
| **Particulate Matter(kg/pkm)** | 8.39E-06 | 2.51E-06 | 30 |

**Table F.22: Uncertainty Analysis of 2450/Scania Buses' LCA**

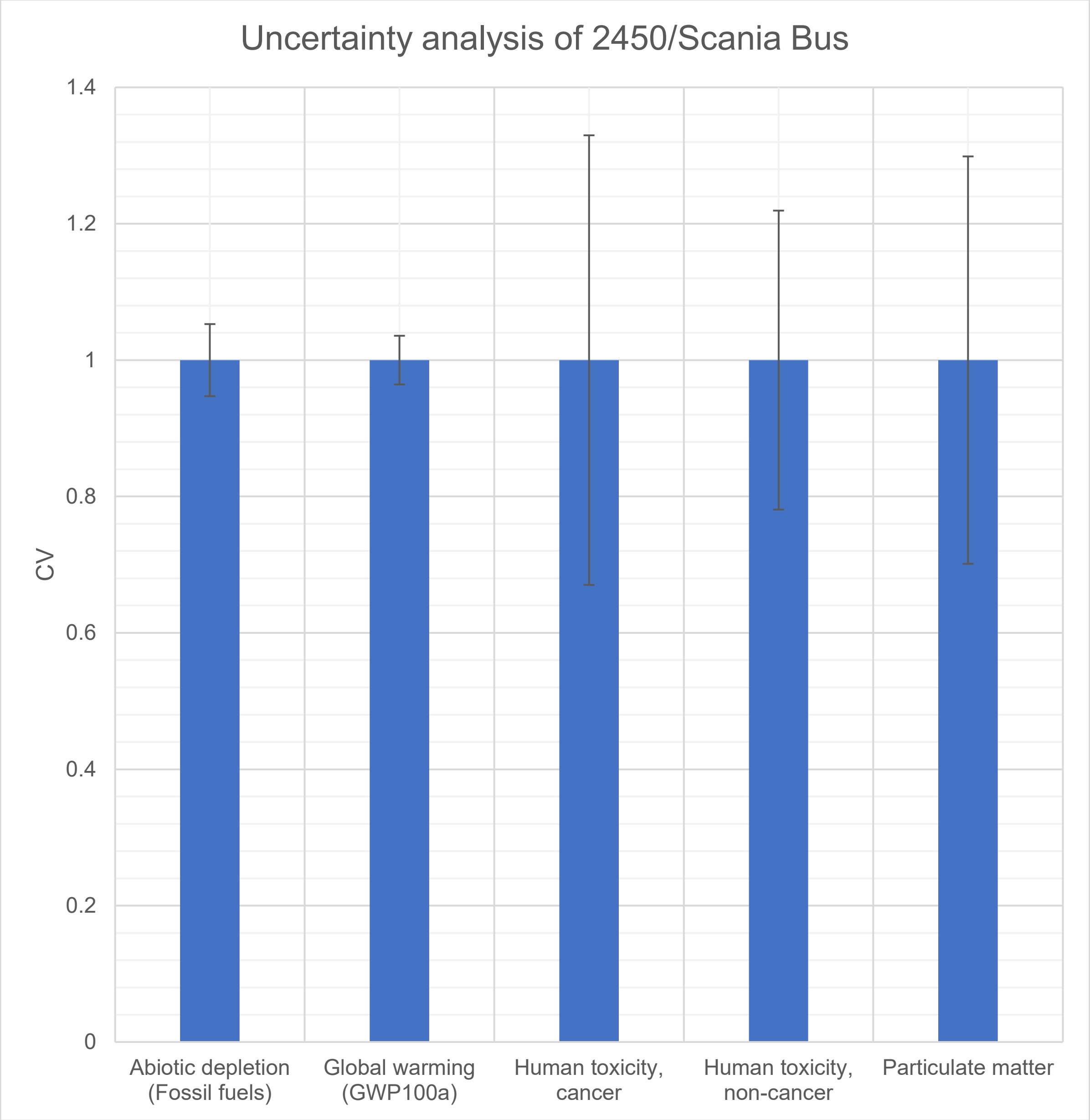


**Figure F.22: Uncertainty Analysis of 2450/Scania Buses' LCA**

| **Impact Category** | **Mean** | **SD** | **%CV** |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76085032 | 0.036285487 | 5 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.063575828 | 0.002131245 | 3 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.19E-10 | 4.10E-11 | 34 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 6.99E-10 | 1.72E-10 | 25 |
| **Particulate Matter(kg/pkm)** | 7.94E-06 | 1.87E-06 | 24 |

**Table F.23: Uncertainty Analysis of 2451/Volvo Buses' LCA**

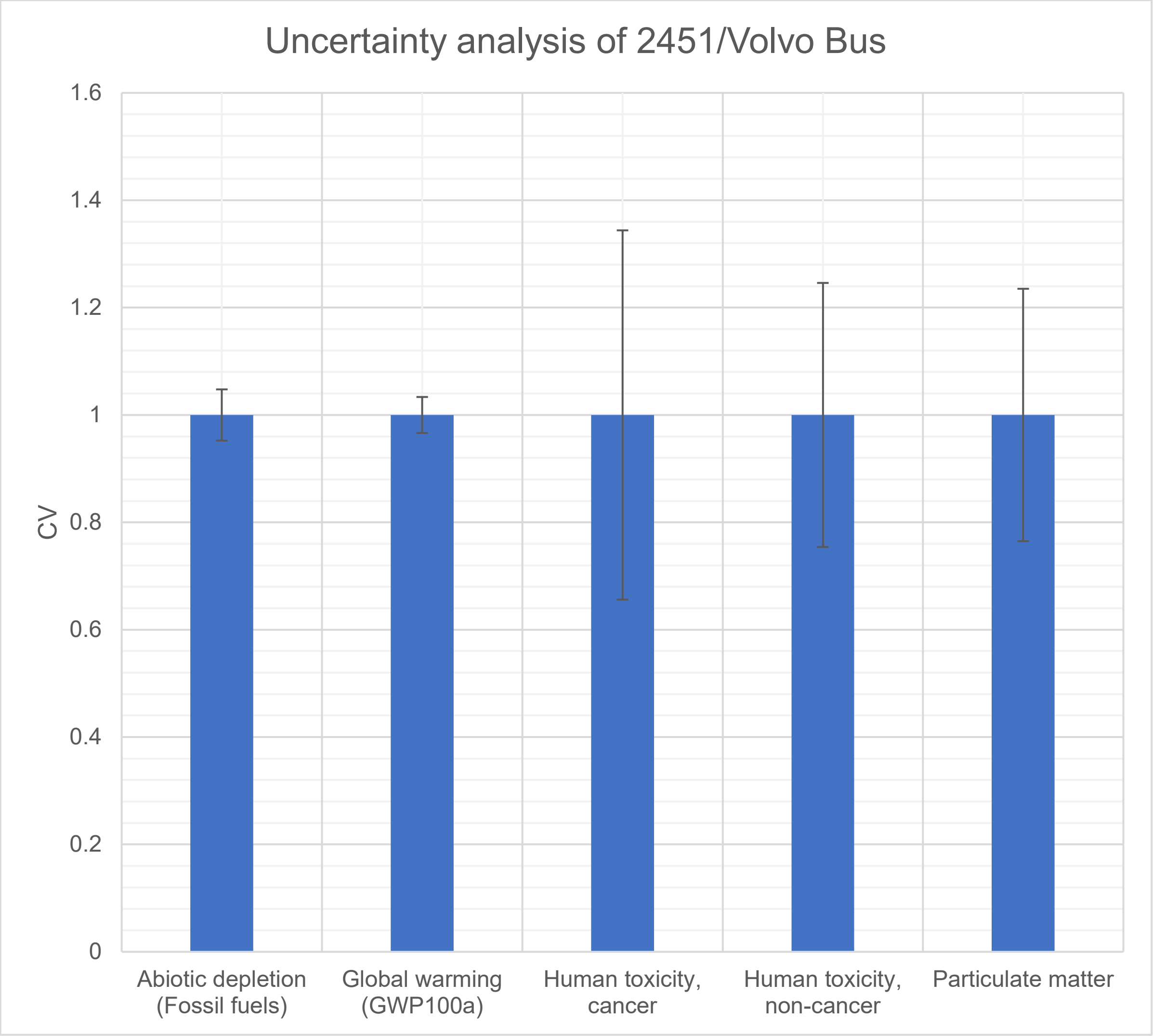


**Figure F.23: Uncertainty Analysis of 2451/Volvo Buses' LCA**

| Impact Category | Mean | SD | %CV |
|---|---|---|---|
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.83596151 | 0.052859964 | 6 |
| **Global Warming (GWP100a) (kg/pkm)** | 0.070020622 | 0.002405917 | 3 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.14E-10 | 3.47E-11 | 30 |
| **Human toxicity, Non-Cancer(kg/pkm)** | 7.30E-10 | 2.20E-10 | 30 |
| **Particulate Matter(kg/pkm)** | 9.17E-06 | 2.27E-06 | 25 |

**Table F.24: Uncertainty Analysis of 2452/Mercedes Buses' LCA**

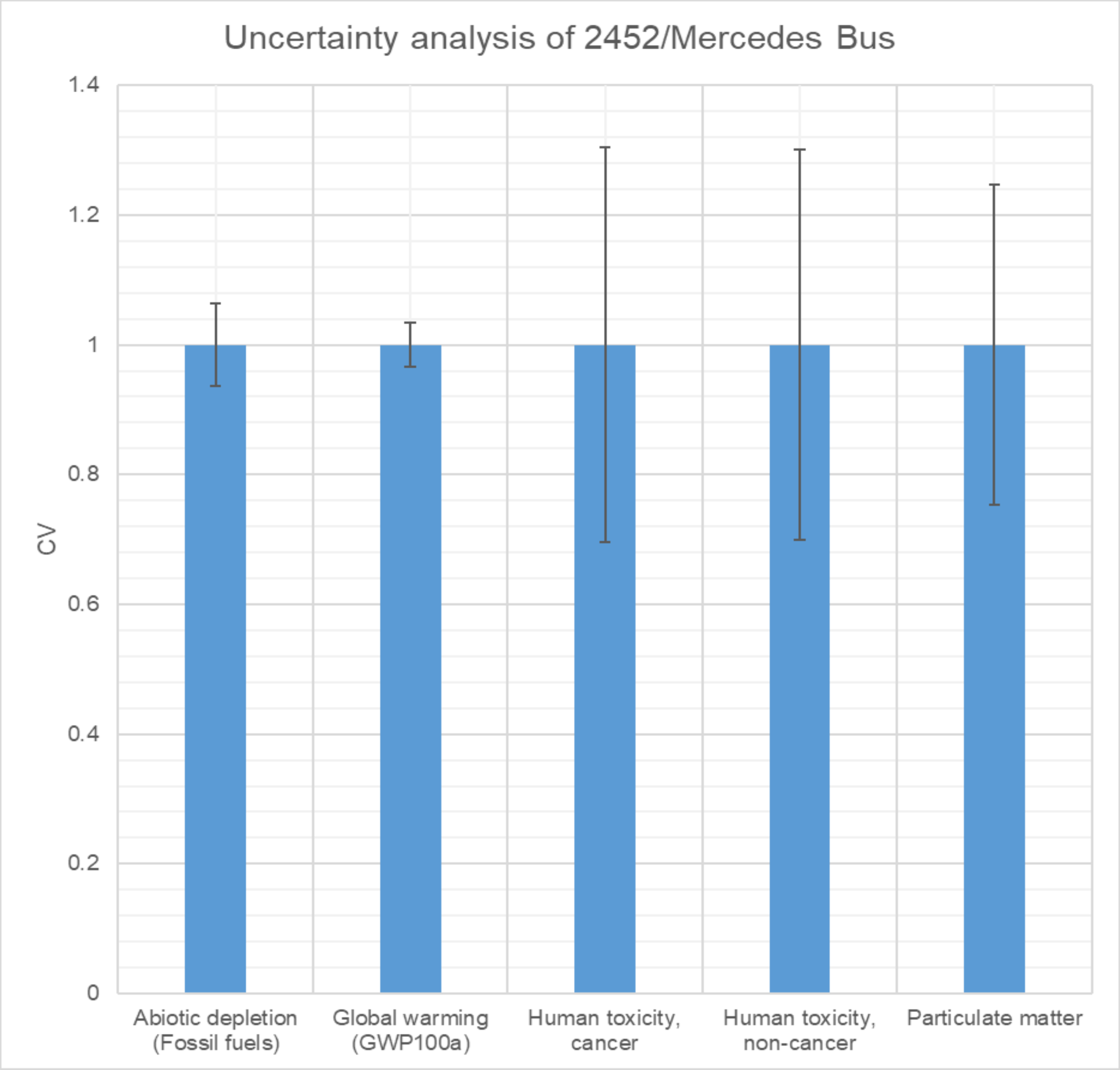


**Figure F.24: Uncertainty Analysis of 2452/Mercedes Buses' LCA**

# APPENDIX G: SENSITIVITY ANALYSIS FOR LCA OF TRANSPORTATION

### Petrol Passenger Vehicle

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.25912601 | 0.28378924 | 0.23894701 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.6835211 | 3.110027 | 9 | -8 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 0.000106857 | 8.97E-05 | 10 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.59E-09 | 1.56E-09 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 7.09E-09 | 6.79E-09 | 2 | -2 |

**Table G.1: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Kilometres Travelled Parameter)**

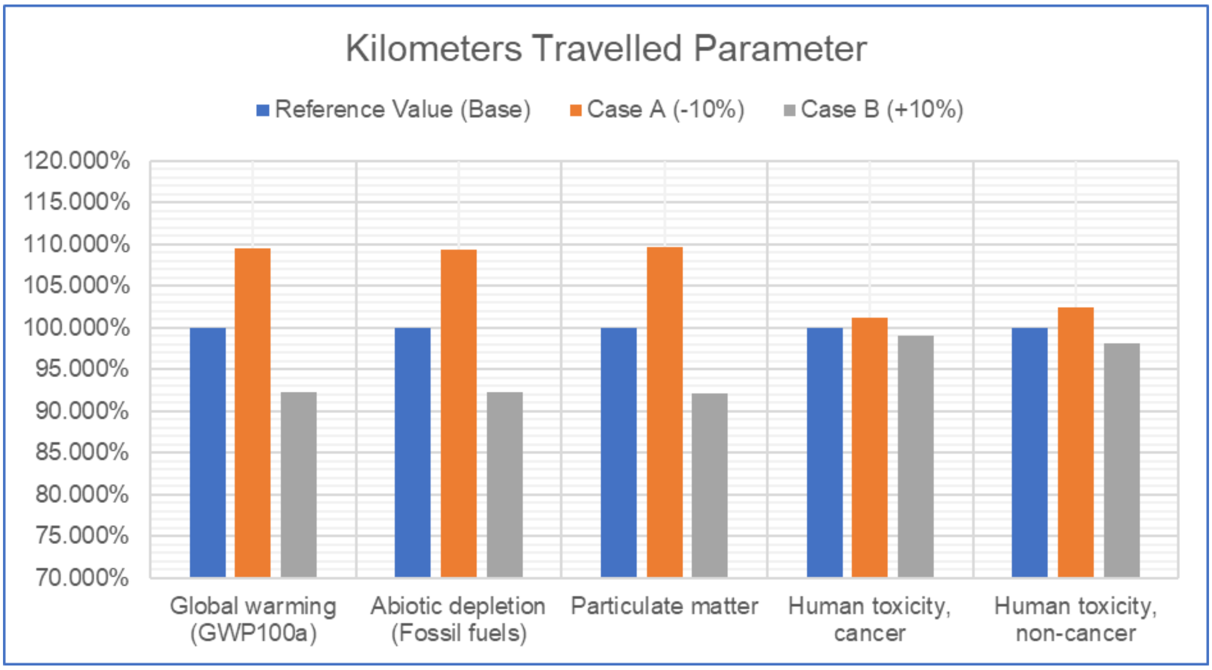


**Figure G.1: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.23692911 | 0.28132291 | -9 | 9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.0842198 | 3.6519789 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 8.89E-05 | 0.000105911 | -9 | 9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.56E-09 | 1.59E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 6.78E-09 | 7.07E-09 | -2 | 2 |

**Table G.2: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Fuel Consumption Parameter)**

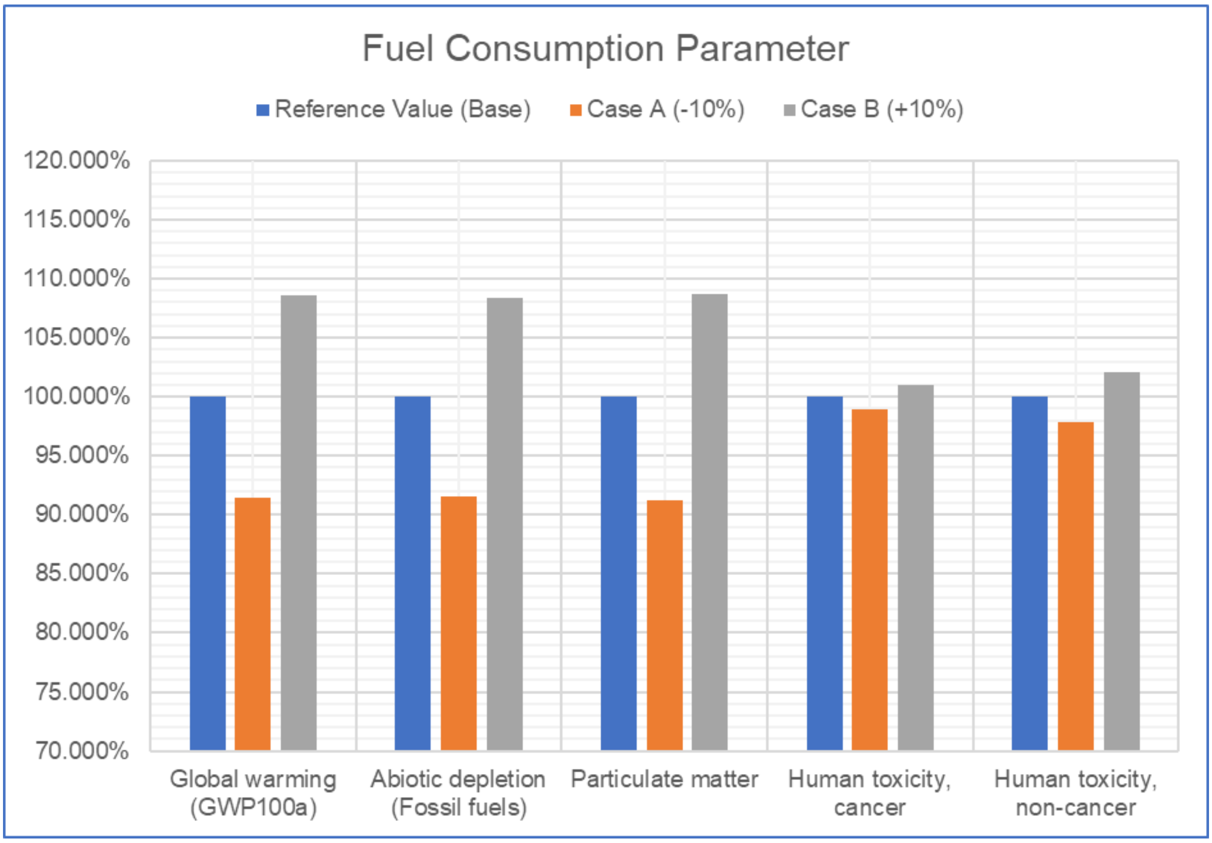


**Figure G.2: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.28791779 | 0.2355691 | 11% | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.7423326 | 3.0619085 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 0.000108216 | 8.85E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.75E-09 | 1.43E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 7.69E-09 | 6.29E-09 | 11 | -9 |

**Table G.3: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Occupancy Rate Parameter)**

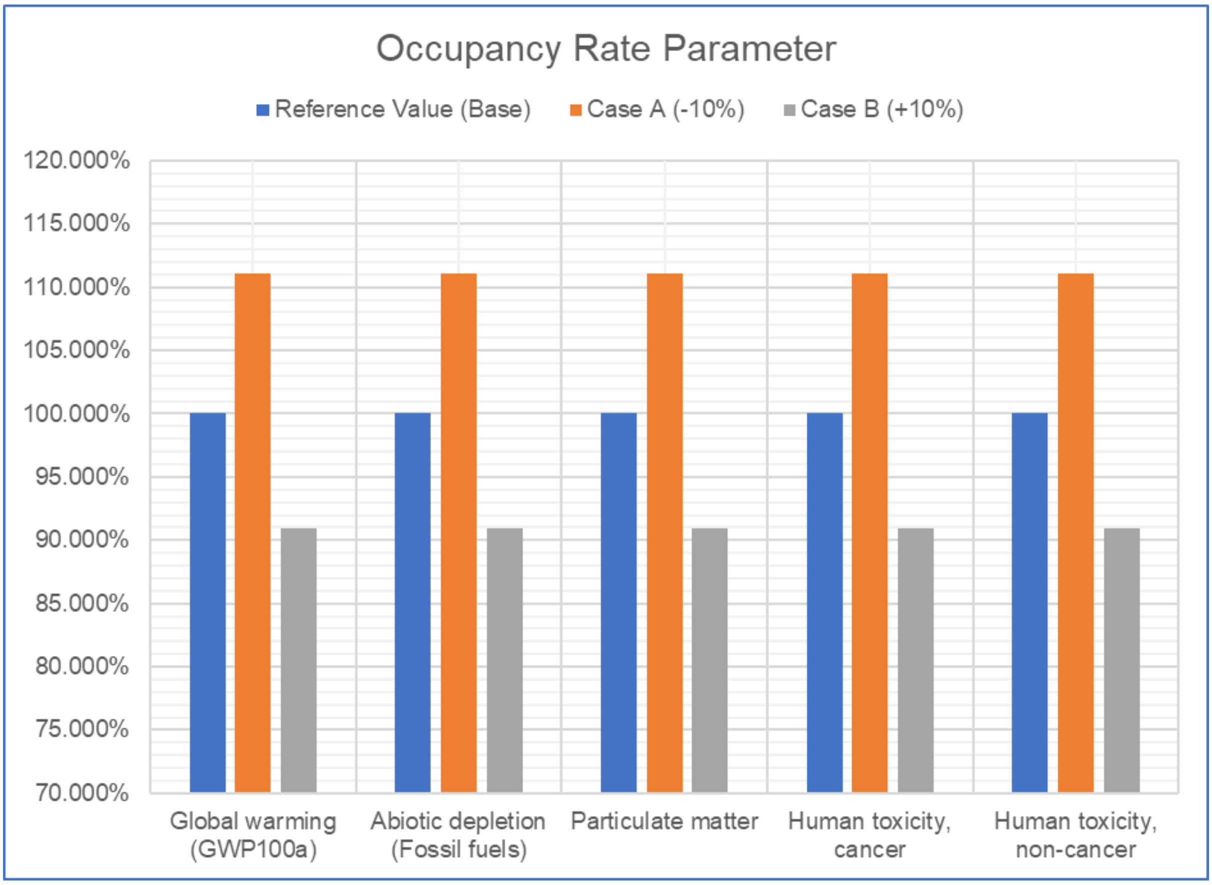


**Figure G.3: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| Global Warming (GWP100a) | 0.25912601 | 0.25622509 | 0.26202694 | -1 | 1 |
| Abiotic Depletion (Fossil Fuels) (MJ/pkm) | 3.3680994 | 3.3276639 | 3.4085349 | -1 | 1 |
| Particulate Matter (kg/pkm) | 9.74E-05 | 9.64E-05 | 9.84E-05 | -1 | 1 |
| Human Toxicity, Cancer (kg/pkm) | 1.57E-09 | 1.44E-09 | 1.71E-09 | -9 | 9 |
| Human Toxicity, Non-Cancer (kg/pkm) | 6.92E-09 | 6.49E-09 | 7.36E-09 | -6 | 6 |

Table G.4: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Vehicle Manufacture Parameter)

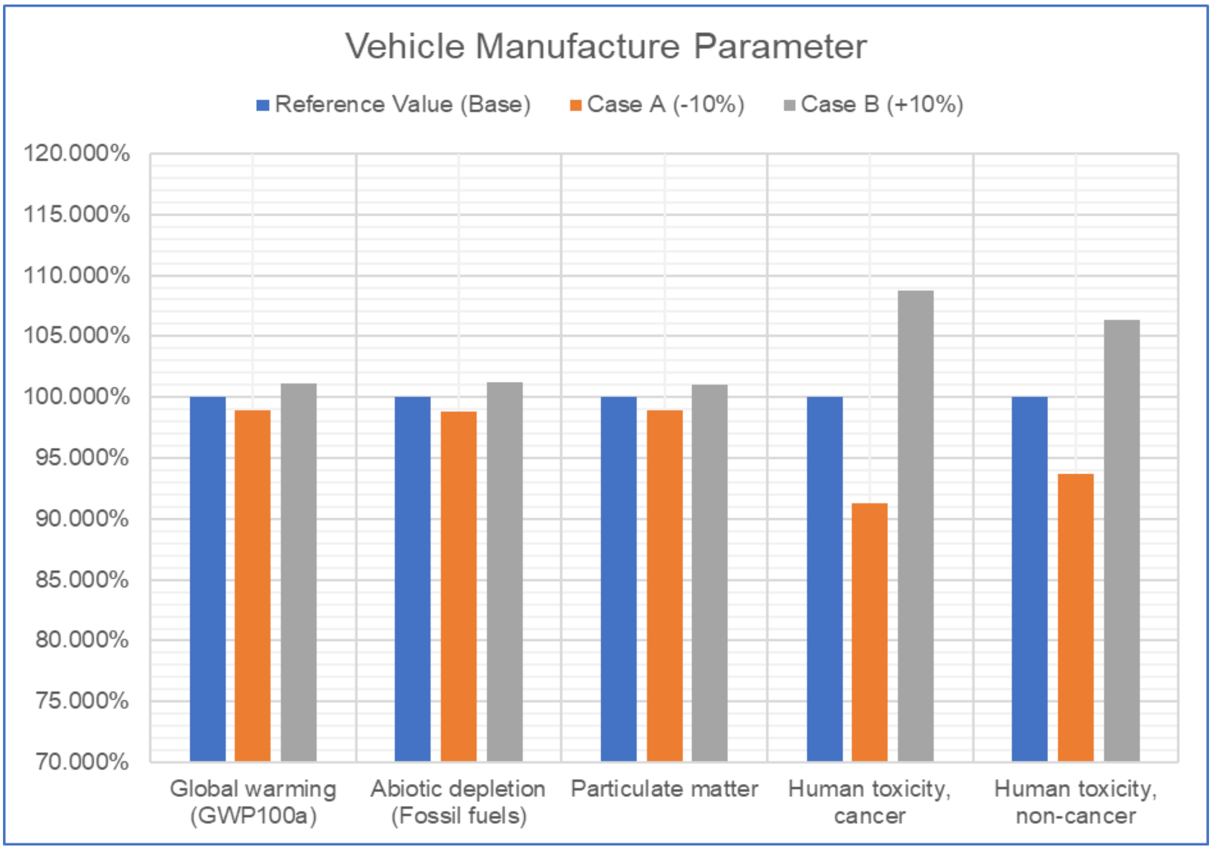


Figure G.4: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Vehicle Manufacture Parameter)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.25895912 | 0.25929291 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.3126977 | 3.423501 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 9.73E-05 | 9.75E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.57E-09 | 1.57E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 6.92E-09 | 6.93E-09 | 0 | 0 |

**Table G.5: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Crude Oil Extraction Parameter)**

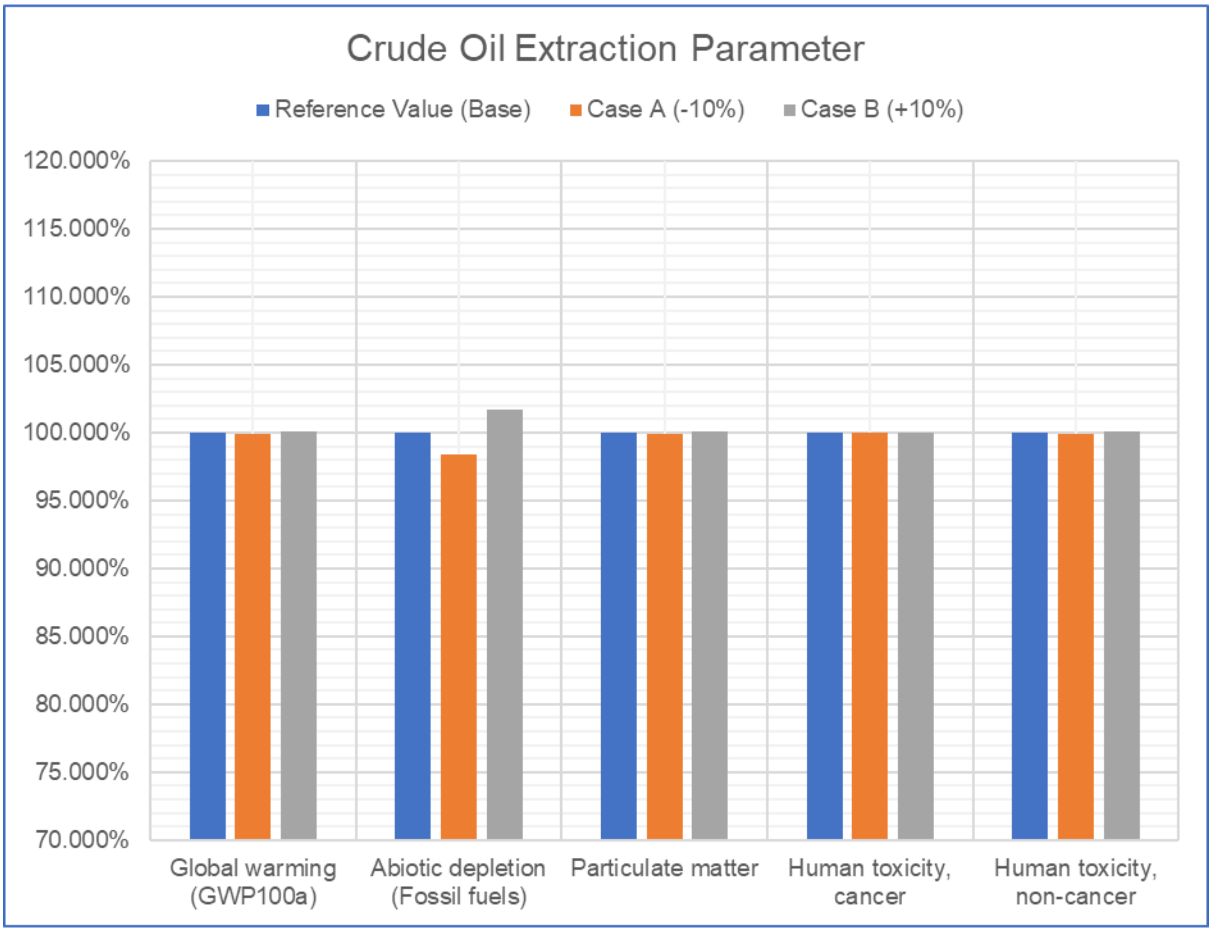


**Figure G.5: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.25878923 | 0.25946279 | 0% | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.3104404 | 3.4257583 | -2% | 2 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 9.72E-05 | 9.76E-05 | 0% | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.57E-09 | 1.57E-09 | 0% | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 6.91E-09 | 6.94E-09 | 0% | 0 |

**Table G.6: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Crude Oil Refining Parameter)**

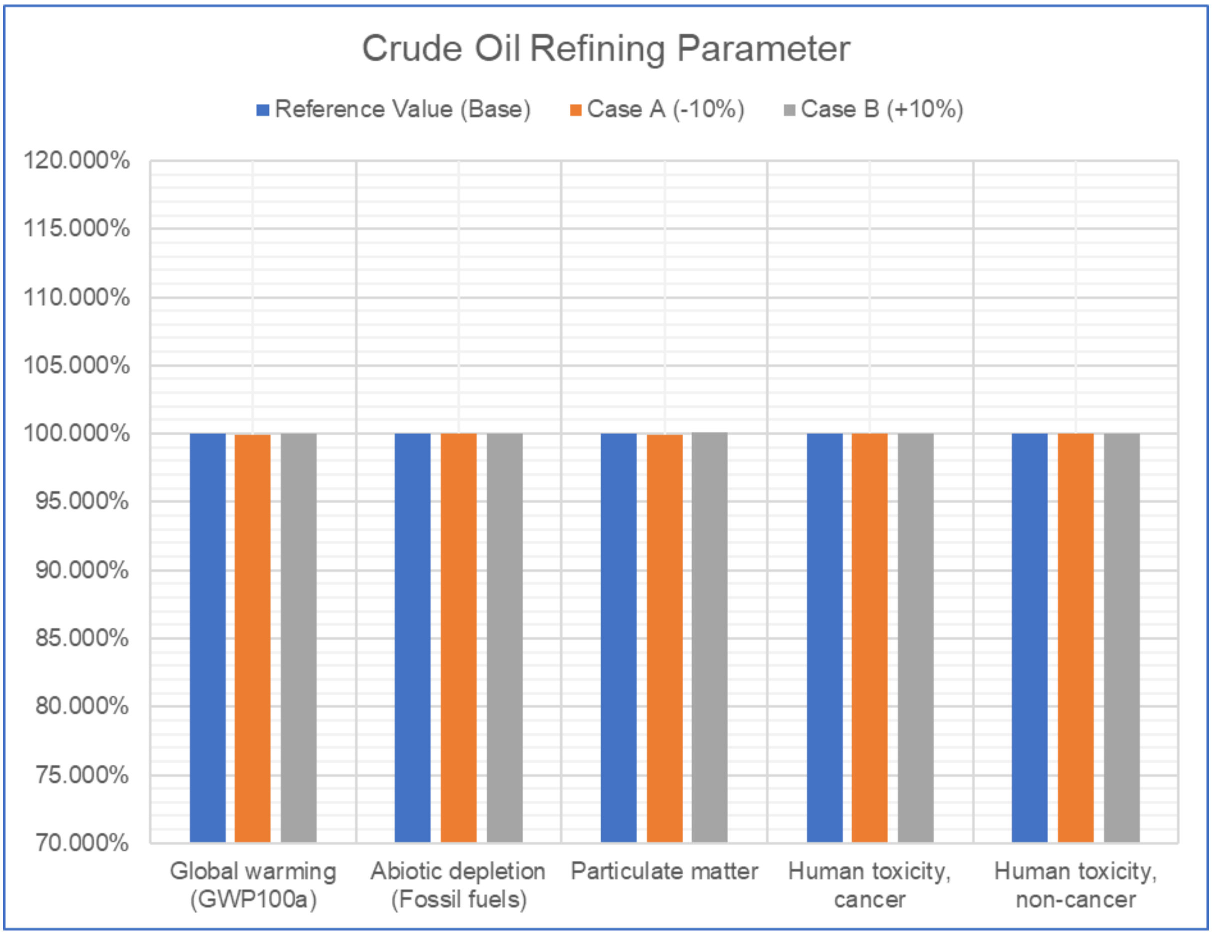


**Figure G.6: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.25852358 | 0.25972844 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.3567754 | 3.3794233 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 9.72E-05 | 9.76E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.57E-09 | 1.58E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 6.88E-09 | 6.96E-09 | -1 | 1 |

**Table G.7: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Vehicle Maintenance Parameter)**

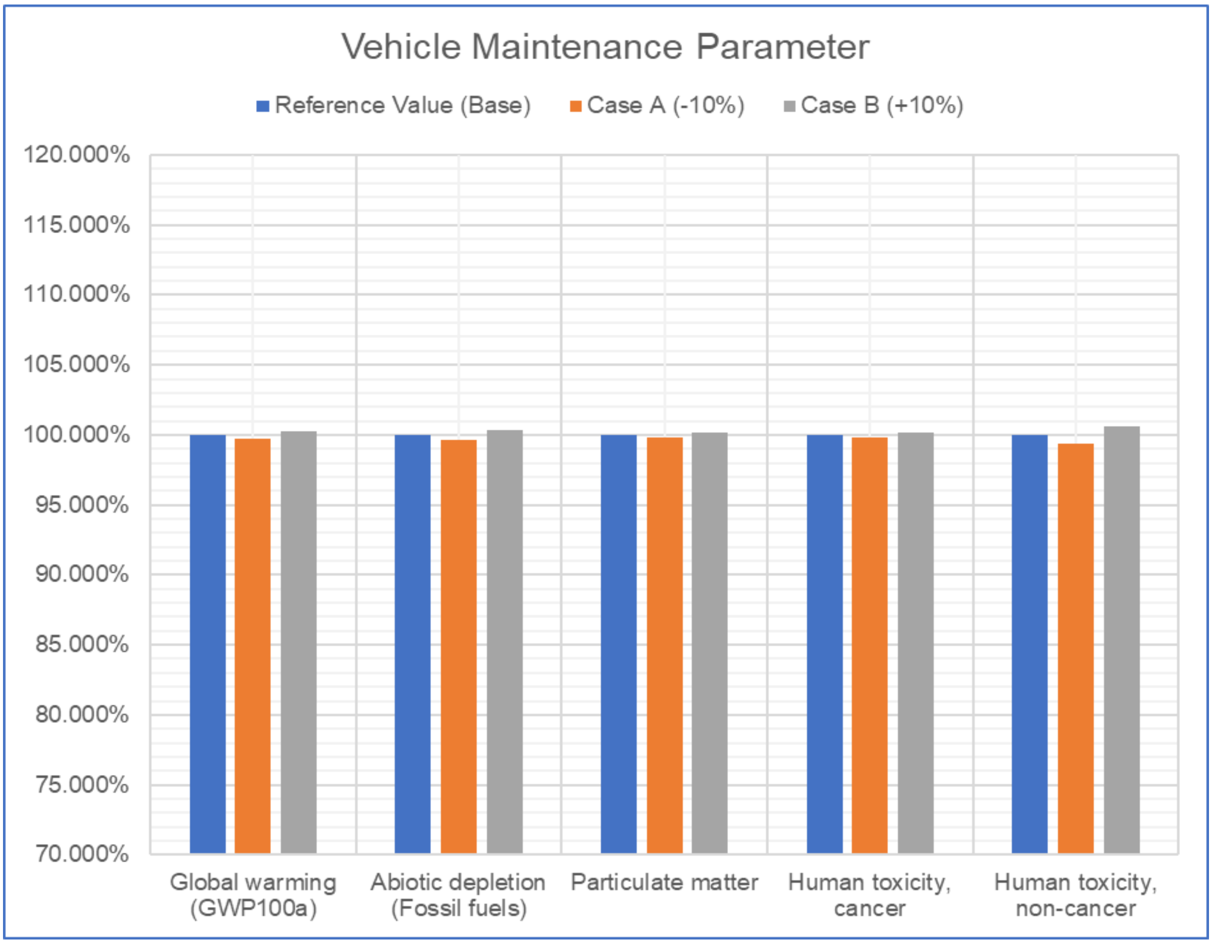


**Figure G.7: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.25912601 | 0.25891367 | 0.25933836 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.3680994 | 3.3669284 | 3.3692703 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 9.74E-05 | 9.74E-05 | 9.74E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.57E-09 | 1.57E-09 | 1.57E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.92E-09 | 6.86E-09 | 6.99E-09 | -1 | 1 |

**Table G.8: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Vehicle Disposal Parameter)**

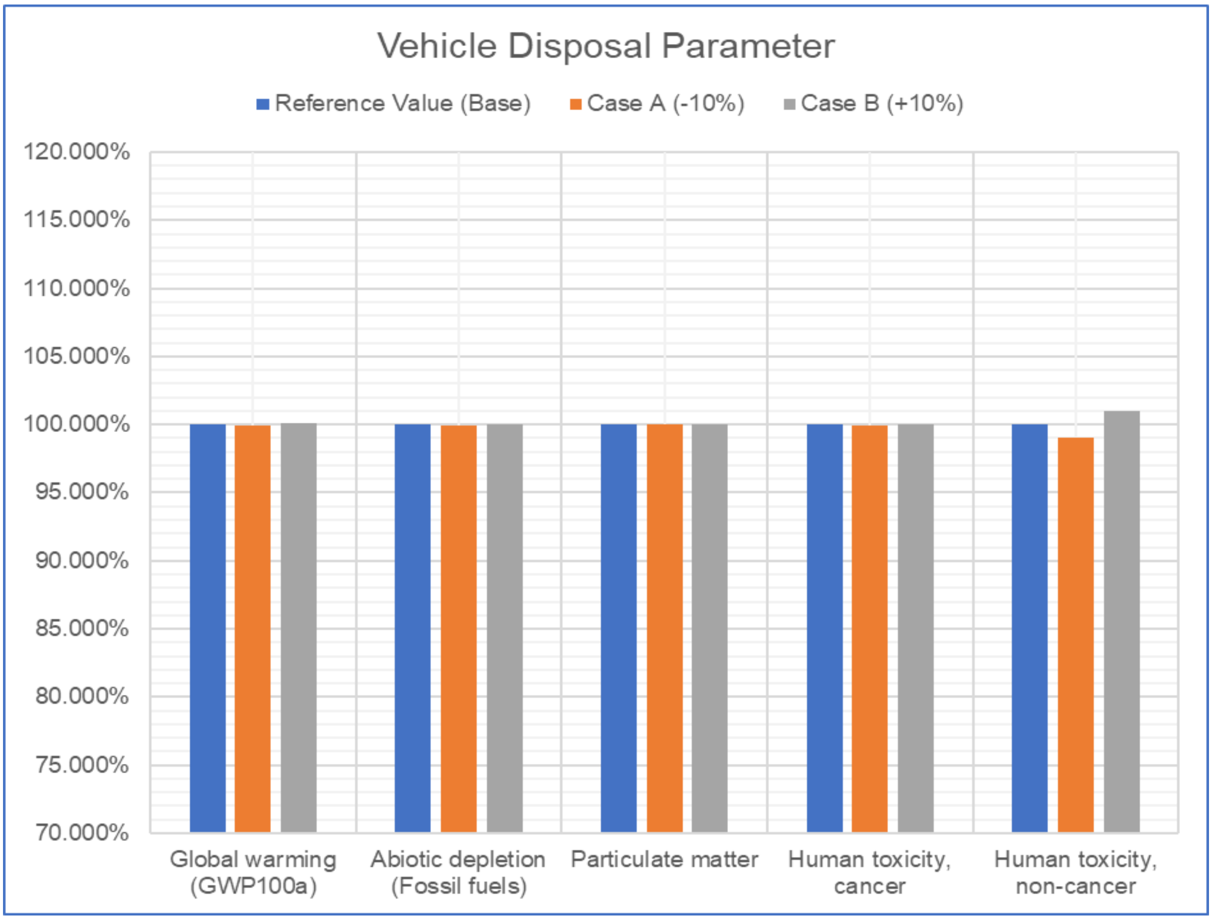


**Figure G.8: Sensitivity Analysis for LCA of Petrol Passenger Vehicles (Vehicle Disposal Parameter)**

### Low sulphur diesel vehicle (LSD)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.269358 | 0.220384 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 3.269865 | 2.675344 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000253 | 0.000207 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.72E-09 | 1.41E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 7.37E-09 | 6.03E-09 | 11 | -9 |

**Table G.9: Sensitivity Analysis for LCA of LSDV (Occupancy Rate Parameter)**

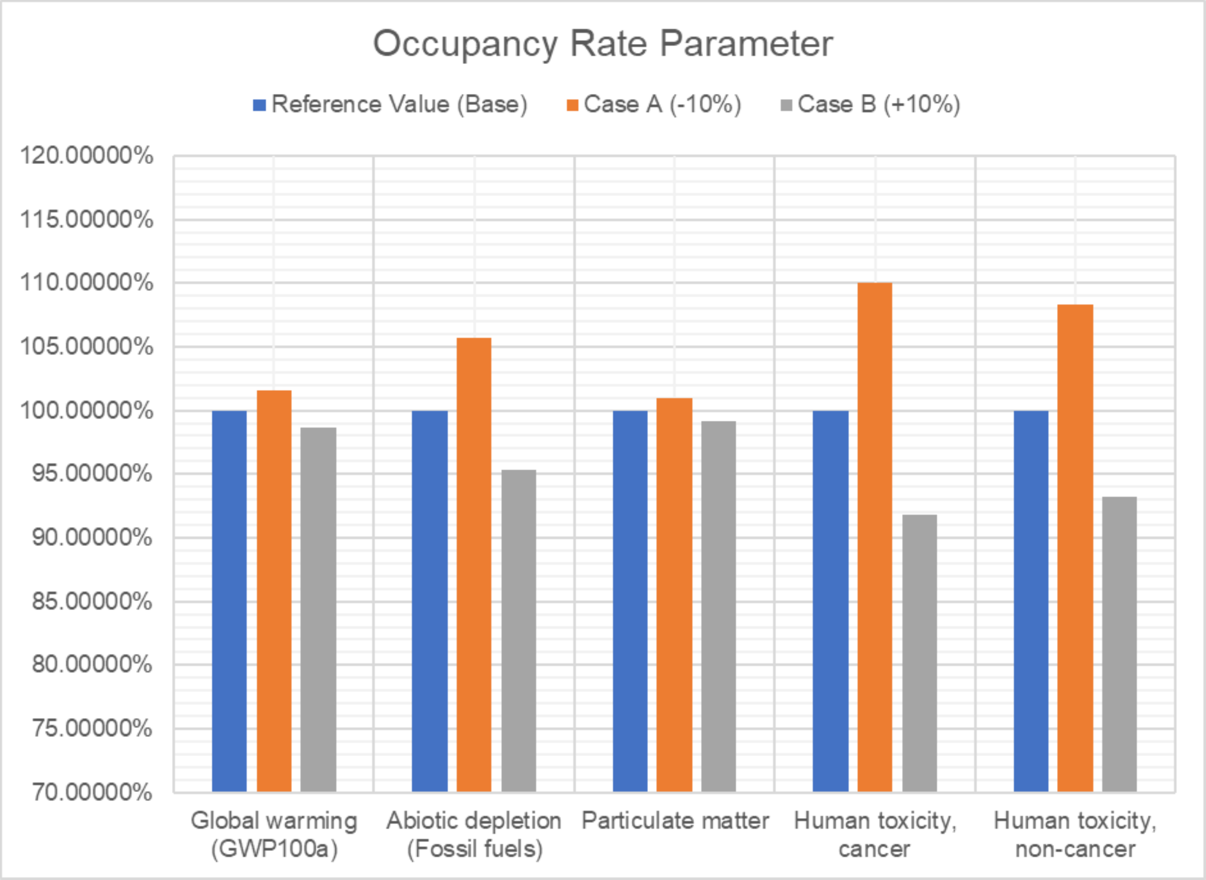


**Figure G.9: Sensitivity Analysis for LCA of LSDV (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.265229 | 0.223761 | 9 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 3.211054 | 2.723463 | 9 | -7 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000251 | 0.000208 | 11 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.57E-09 | 1.54E-09 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 6.76E-09 | 6.53E-09 | 2 | -2 |

**Table G.10: Sensitivity Analysis for LCA of LSDV (Kilometres Travelled Parameter)**

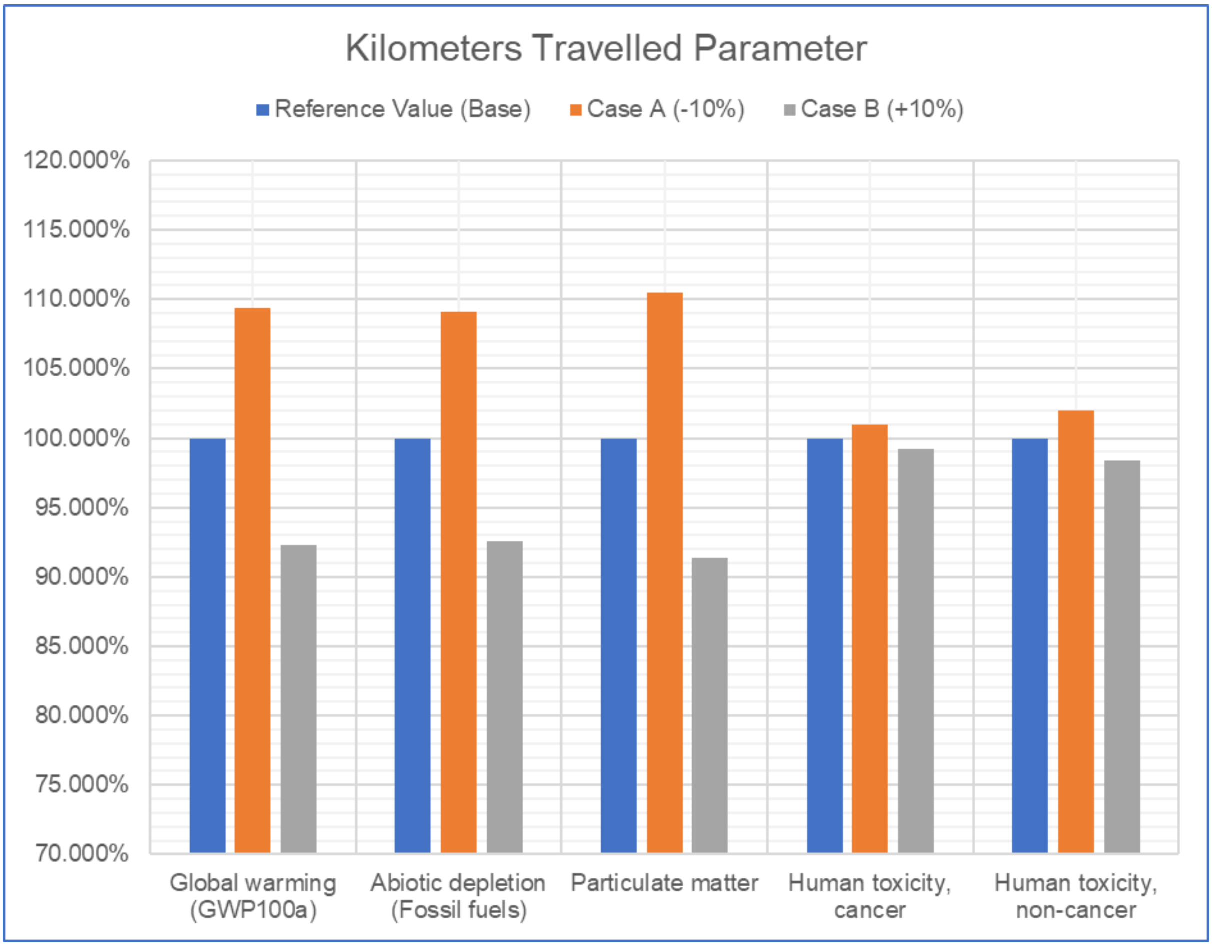


**Figure G.10: Sensitivity Analysis for LCA of LSDV (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.221895 | 0.262948 | -8 | 8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 2.701521 | 3.184236 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000206 | 0.000249 | -9 | 10 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.54E-09 | 1.57E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 6.52E-09 | 6.75E-09 | -2 | 2 |

**Table G.11: Sensitivity Analysis for LCA of LSDV (Fuel Consumption Parameter)**

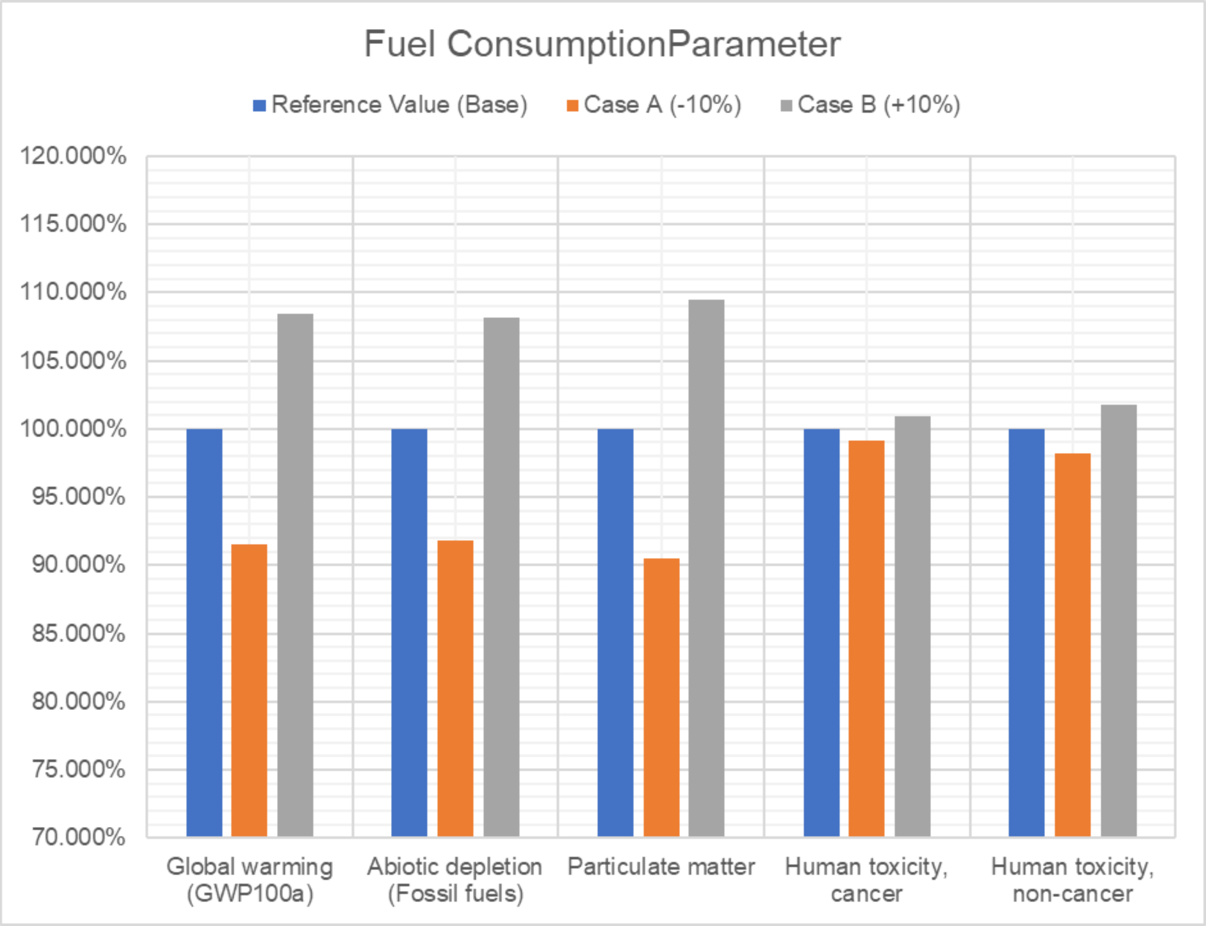


**Figure G.11: Sensitivity Analysis for LCA of LSDV (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.239521 | 0.245323 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 2.902443 | 2.983314 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000226 | 0.000228 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.41E-09 | 1.69E-09 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 6.20E-09 | 7.07E-09 | -6 | 7 |

**Table G.12: Sensitivity Analysis for LCA of LSDV (Vehicle Manufacture Parameter)**

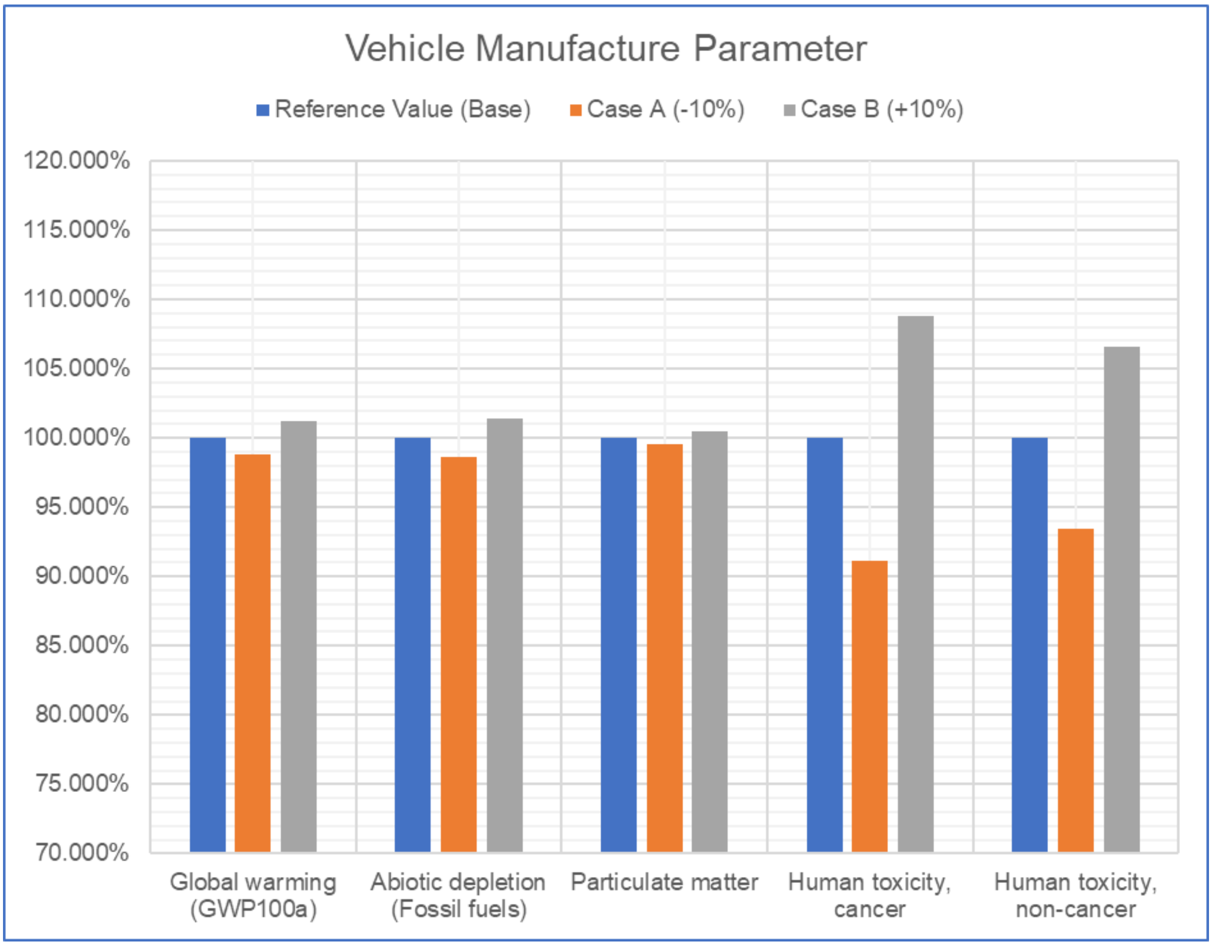


**Figure G.12: Sensitivity Analysis for LCA of LSDV (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.242239 | 0.242605 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 2.882091 | 3.003667 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000227 | 0.000227 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.55E-09 | 1.55E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 6.63E-09 | 6.64E-09 | 0 | 0 |

**Table G.13: Sensitivity Analysis for LCA of LSDV (Crude Oil Extraction Parameter)**

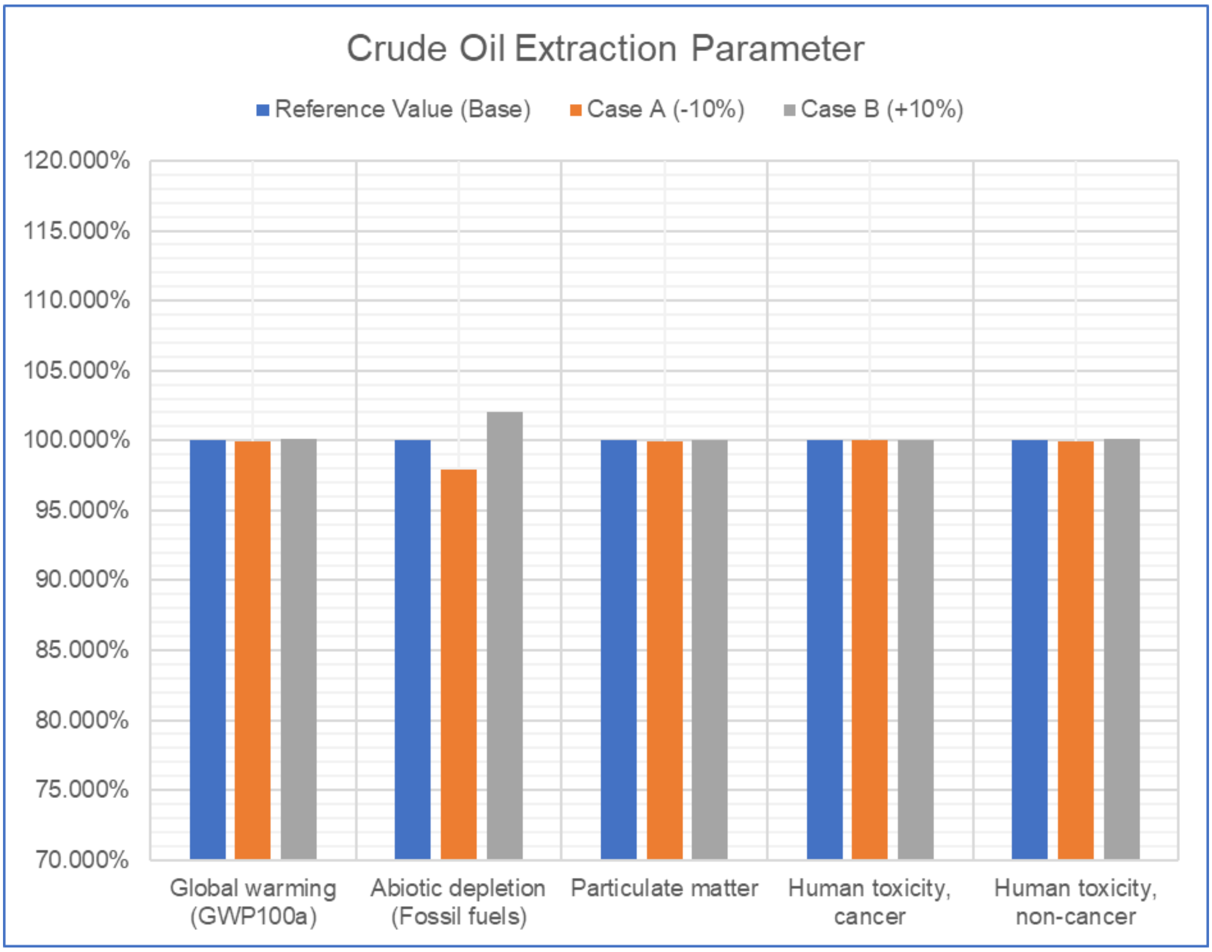


**Figure G.13: Sensitivity Analysis for LCA of LSDV (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.240959 | 0.243885 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 2.733726 | 3.152031 | -7 | 7 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000226 | 0.000228 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.54E-09 | 1.56E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 6.56E-09 | 6.70E-09 | -1 | 1 |

**Table G.14: Sensitivity Analysis for LCA of LSDV (Crude Oil Refining Parameter)**

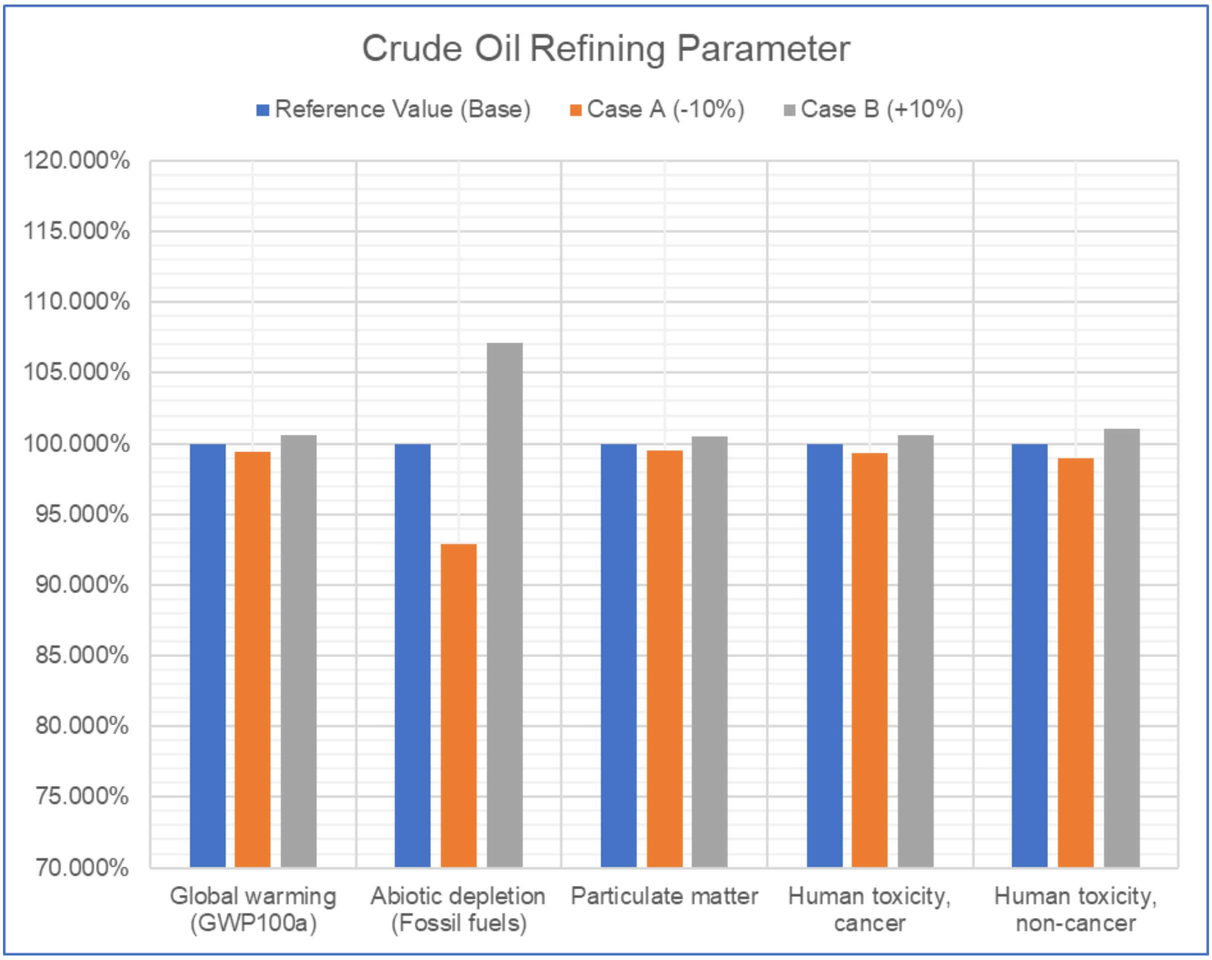


**Figure G.14: Sensitivity Analysis for LCA of LSDV (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.242422 | 0.24221 | 0.242634 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.942879 | 2.941708 | 2.94405 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 0.000227 | 0.000227 | 0.000227 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.55E-09 | 1.55E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.63E-09 | 6.57E-09 | 6.70E-09 | -1 | 1 |

**Table G.15: Sensitivity Analysis for LCA of LSDV (Vehicle Disposal Parameter)**

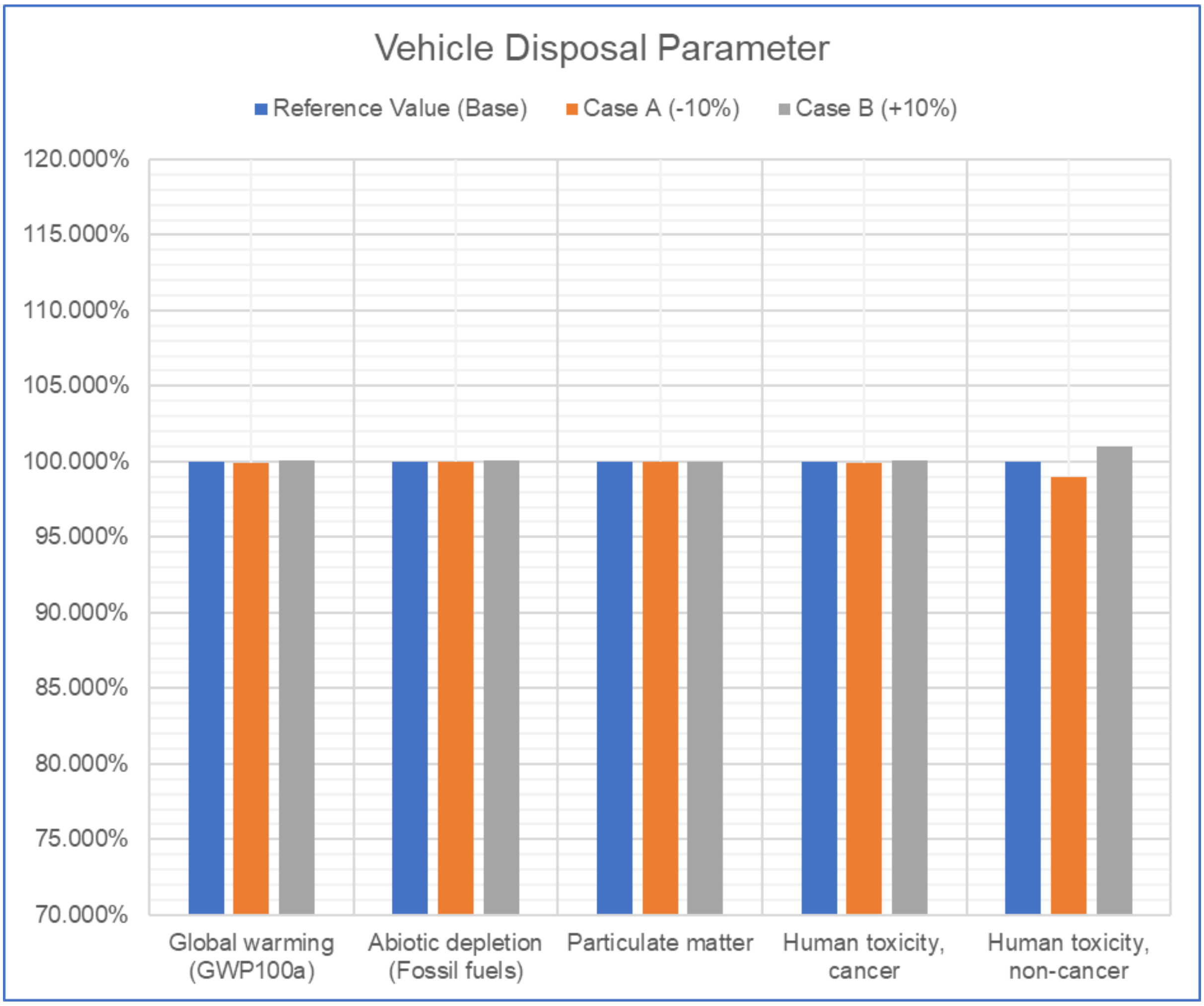


**Figure G.15: Sensitivity Analysis for LCA of LSDV (Vehicle Disposal Parameter)**

## Compressed Natural Gas vehicle (CNGV)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675 | 0.044084 | 0.036069 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.587817 | 0.65313 | 0.534379 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.49E-05 | 1.22E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.57E-09 | 1.29E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 6.11E-09 | 5.00E-09 | 11 | -9 |

**Table G.16: Sensitivity Analysis for LCA of CNGV (Occupancy Rate Parameter)**

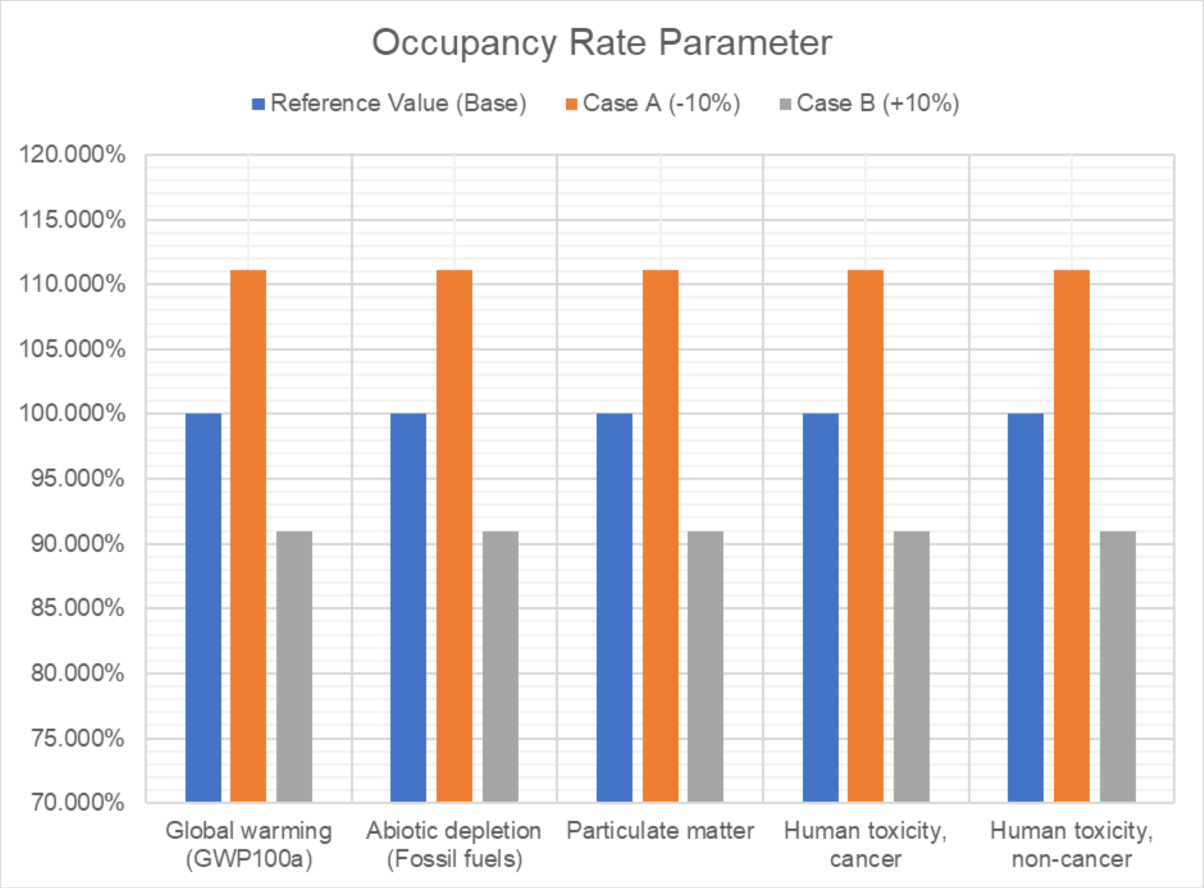


**Figure G.16: Sensitivity Analysis for LCA of CNGV (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675 | 0.036774 | 0.042576 | -7 | 7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.587817 | 0.547382 | 0.628253 | -7 | 7 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.24E-05 | 1.45E-05 | -7 | 8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.28E-09 | 1.55E-09 | -9 | 10 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 5.06E-09 | 5.94E-09 | -8 | 8 |

**Table G.17: Sensitivity Analysis for LCA of CNGV (Vehicle Manufacture Parameter)**

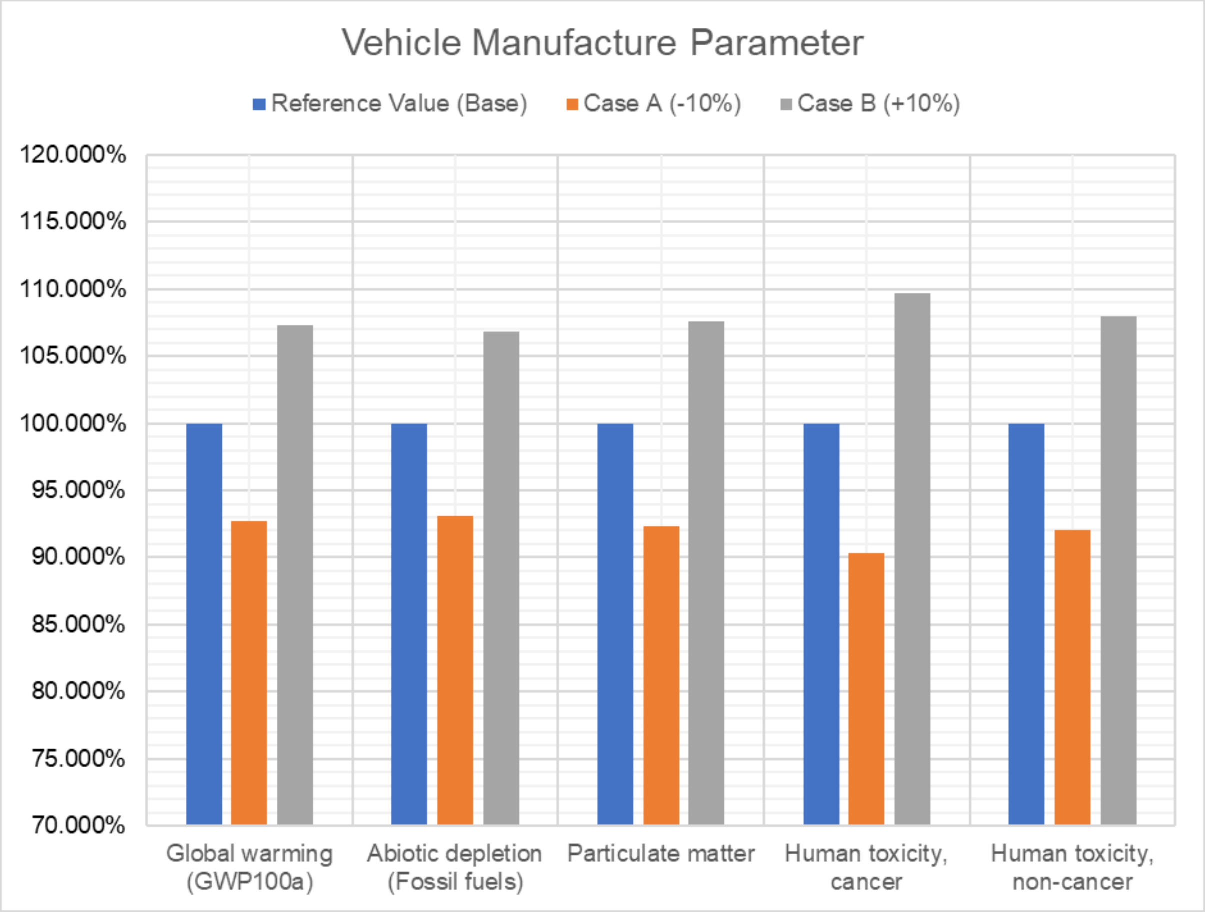


**Figure G.17: Sensitivity Analysis for LCA of CNGV (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675 | 0.039073 | 0.040278 | -2 | 2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.587817 | 0.576493 | 0.599141 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.33E-05 | 1.36E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.41E-09 | 1.42E-09 | 0 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 5.46E-09 | 5.54E-09 | -1 | 1 |

**Table G.18: Sensitivity Analysis for LCA of CNGV (Vehicle Maintenance Parameter)**

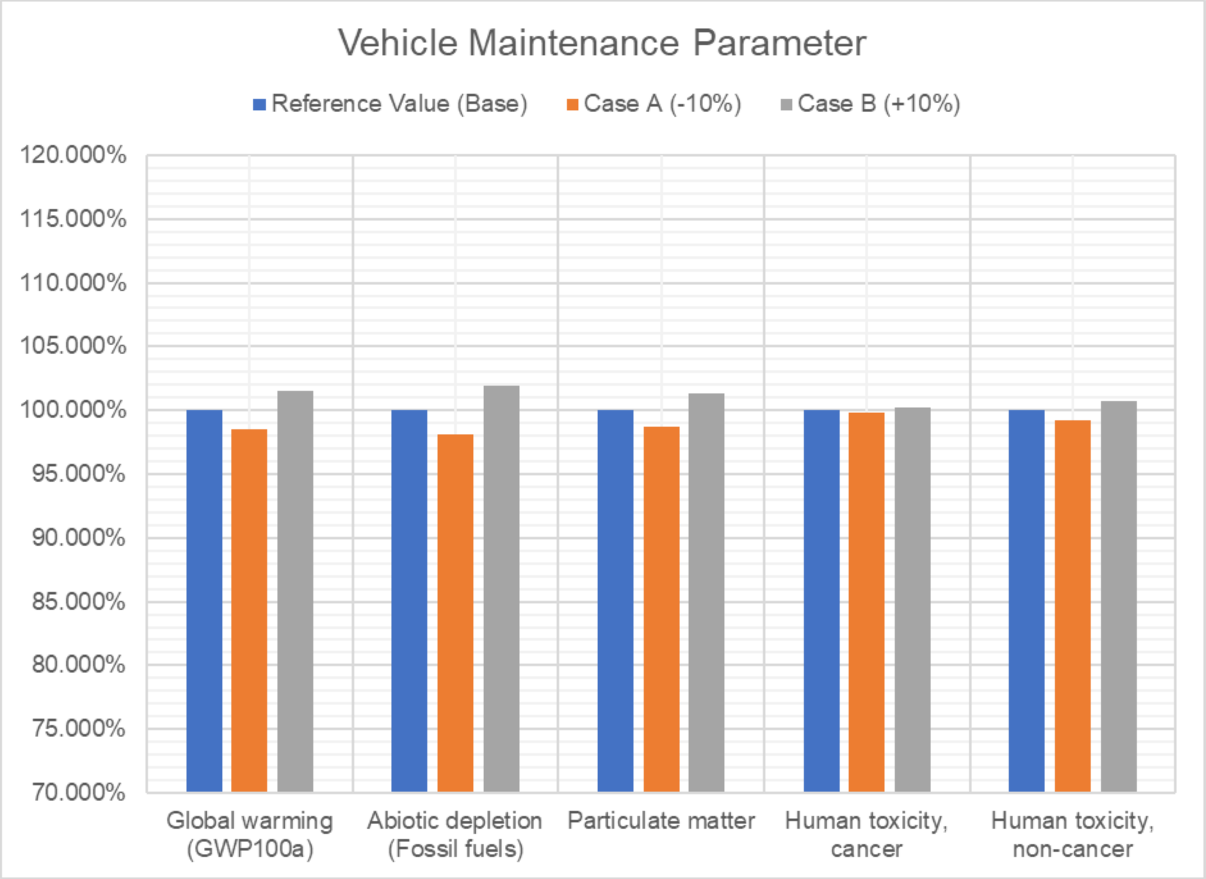


**Figure G.18: Sensitivity Analysis for LCA of CNGV (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675 | 0.039955 | 0.039446 | 1 | -1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.587817 | 0.594319 | 0.582498 | 1 | -1 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.36E-05 | 1.33E-05 | 1 | -1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.41E-09 | 1.41E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 5.51E-09 | 5.50E-09 | 0 | 0 |

**Table G.19: Sensitivity Analysis for LCA of CNGV (Kilometres Travelled Parameter)**

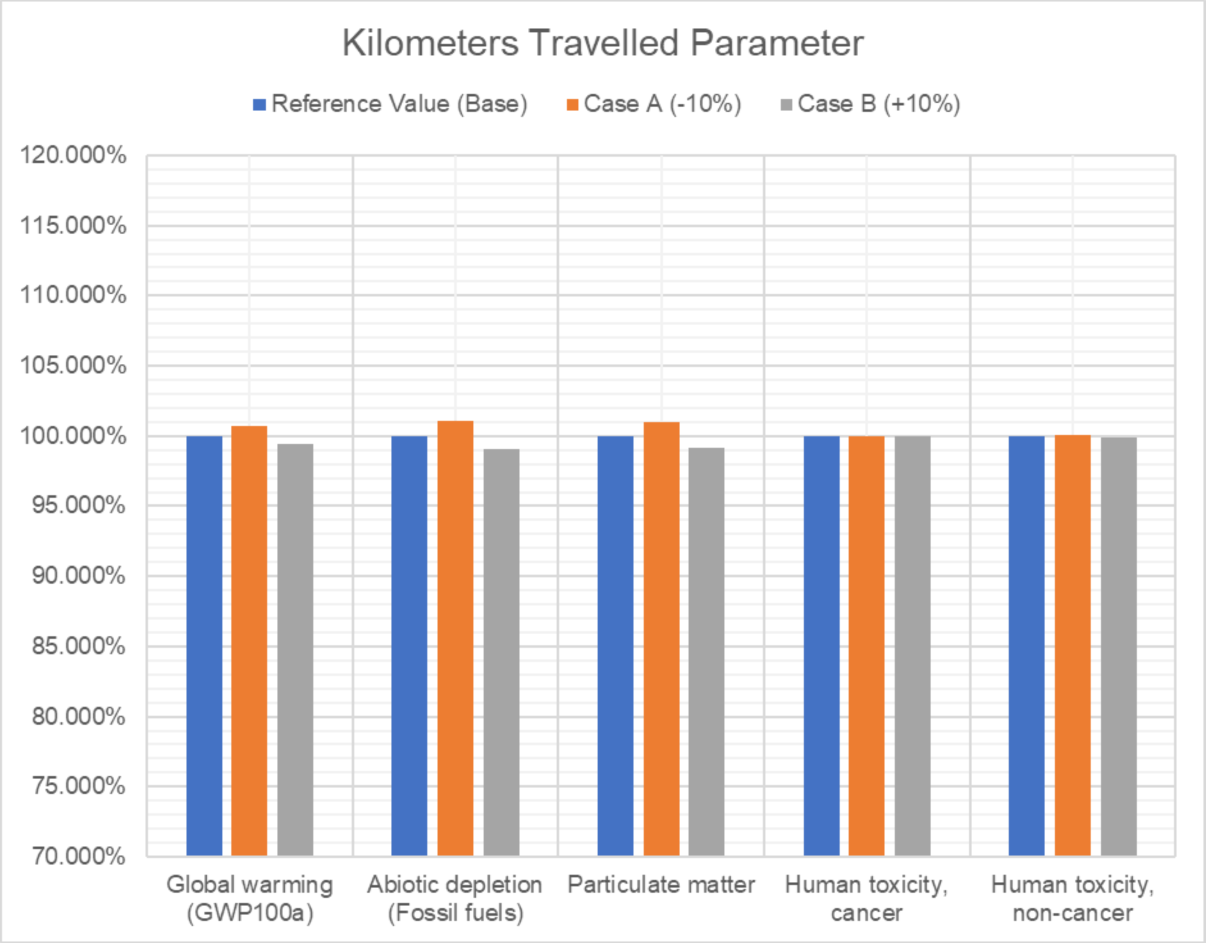


**Figure G.19: Sensitivity Analysis for LCA of CNGV (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675 | 0.039463 | 0.039888 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.587817 | 0.586646 | 0.588988 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.34E-05 | 1.35E-05 | 0 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.41E-09 | 1.41E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 5.43E-09 | 5.57E-09 | -1 | 1 |

**Table G.20: Sensitivity Analysis for LCA of CNGV (Vehicle Disposal Parameter)**

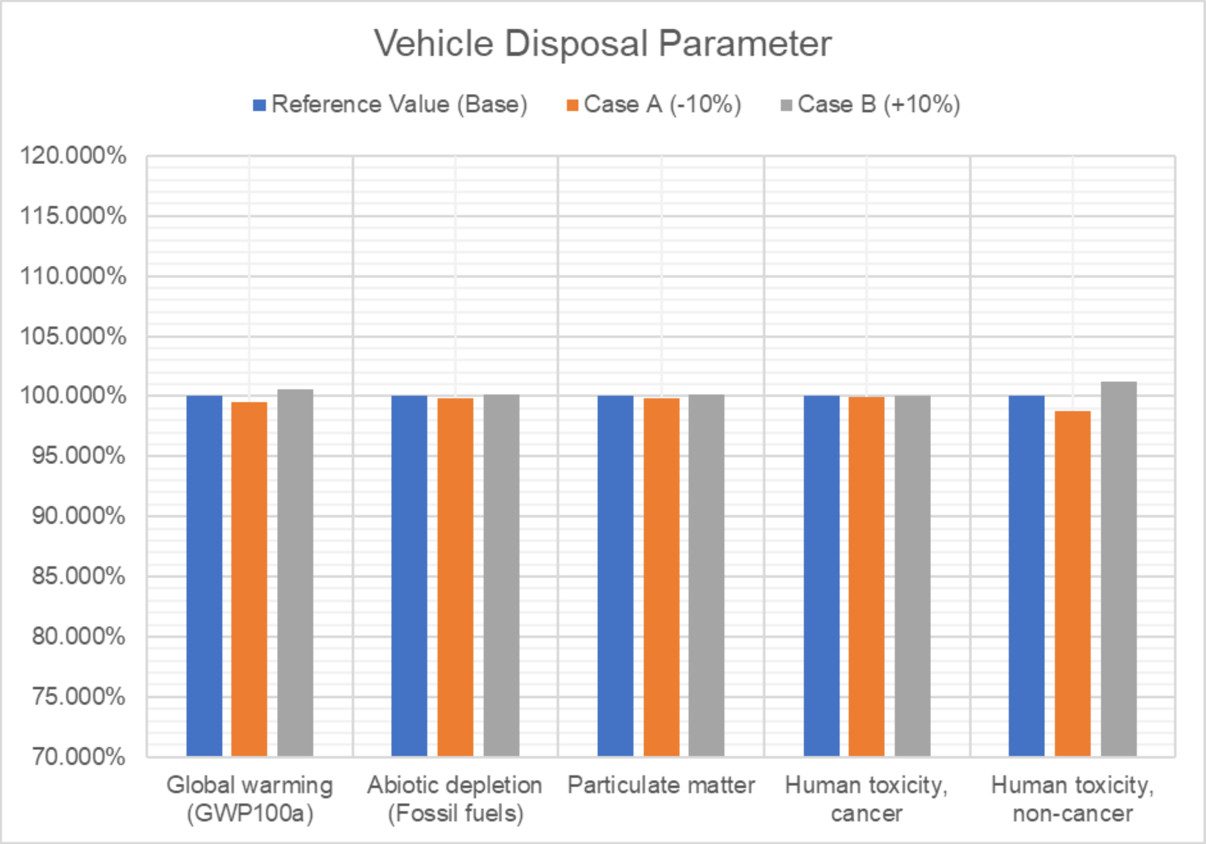


**Figure G.20: Sensitivity Analysis for LCA of CNGV (Vehicle Disposal Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675357 | 0.039675357 | 0.039675357 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.58781735 | 0.58781735 | 0.58781735 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.34E-05 | 1.34E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.41E-09 | 1.41E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 5.50E-09 | 5.50E-09 | 0 | 0 |

**Table G.21: Sensitivity Analysis for LCA of CNGV (Natural Gas Production Parameter)**

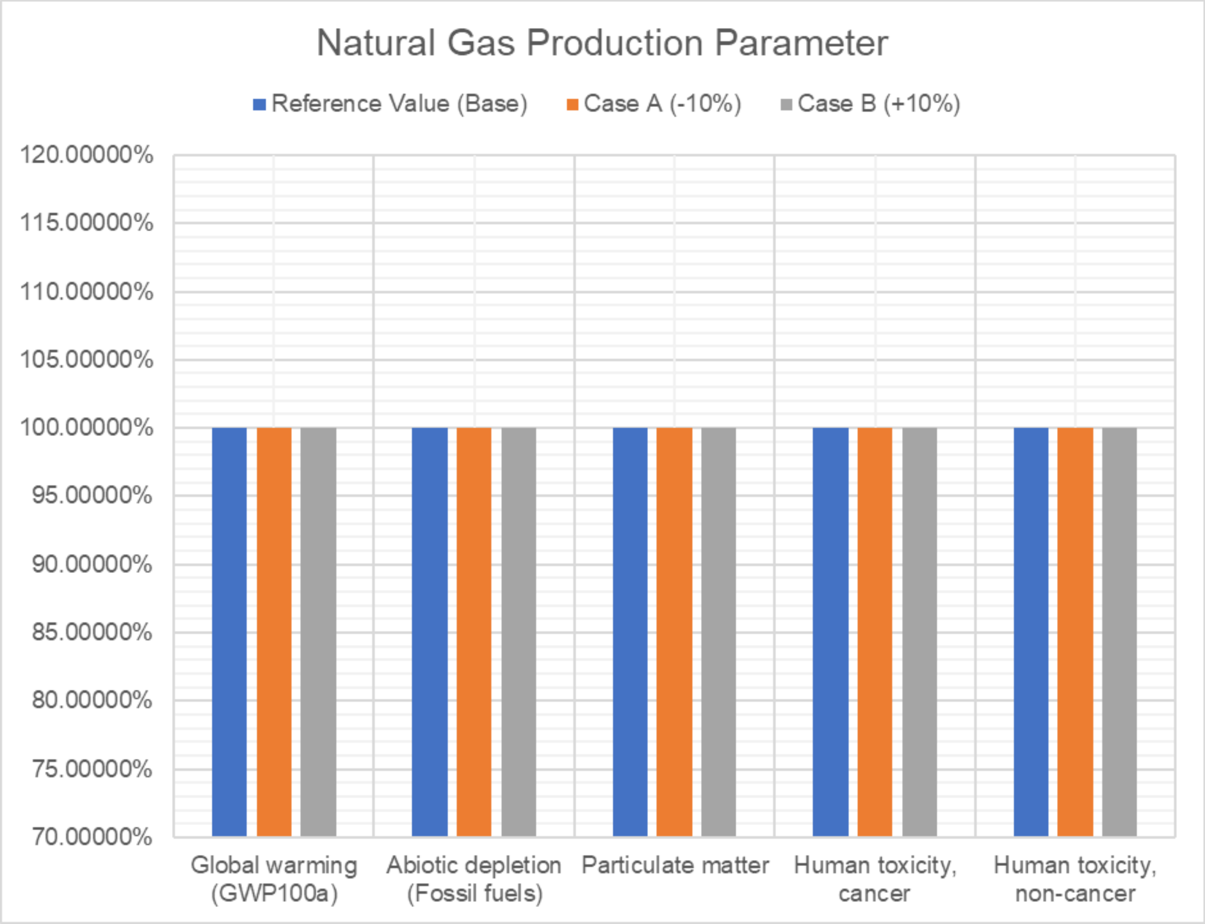


**Figure G.21: Sensitivity Analysis for LCA of CNGV (Natural Gas Production Parameter)**

| Impact Category | Reference value (base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.039675357 | 0.039672185 | 0.03967853 | -0.0080 | 0.0080 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.58781735 | 0.58777566 | 0.58785903 | -0.0071 | 0.00709 |
| **Particulate Matter (kg/pkm)** | 1.34E-05 | 1.34E-05 | 1.34E-05 | 0.0000 | 0.00000 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.41E-09 | 1.41E-09 | 1.41E-09 | 0.0000 | 0.0000 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 5.50E-09 | 5.50E-09 | 5.50E-09 | 0.00000 | 0.0000 |

**Table G.22: Sensitivity Analysis for LCA of CNGV (Natural Gas Processing Parameter)**

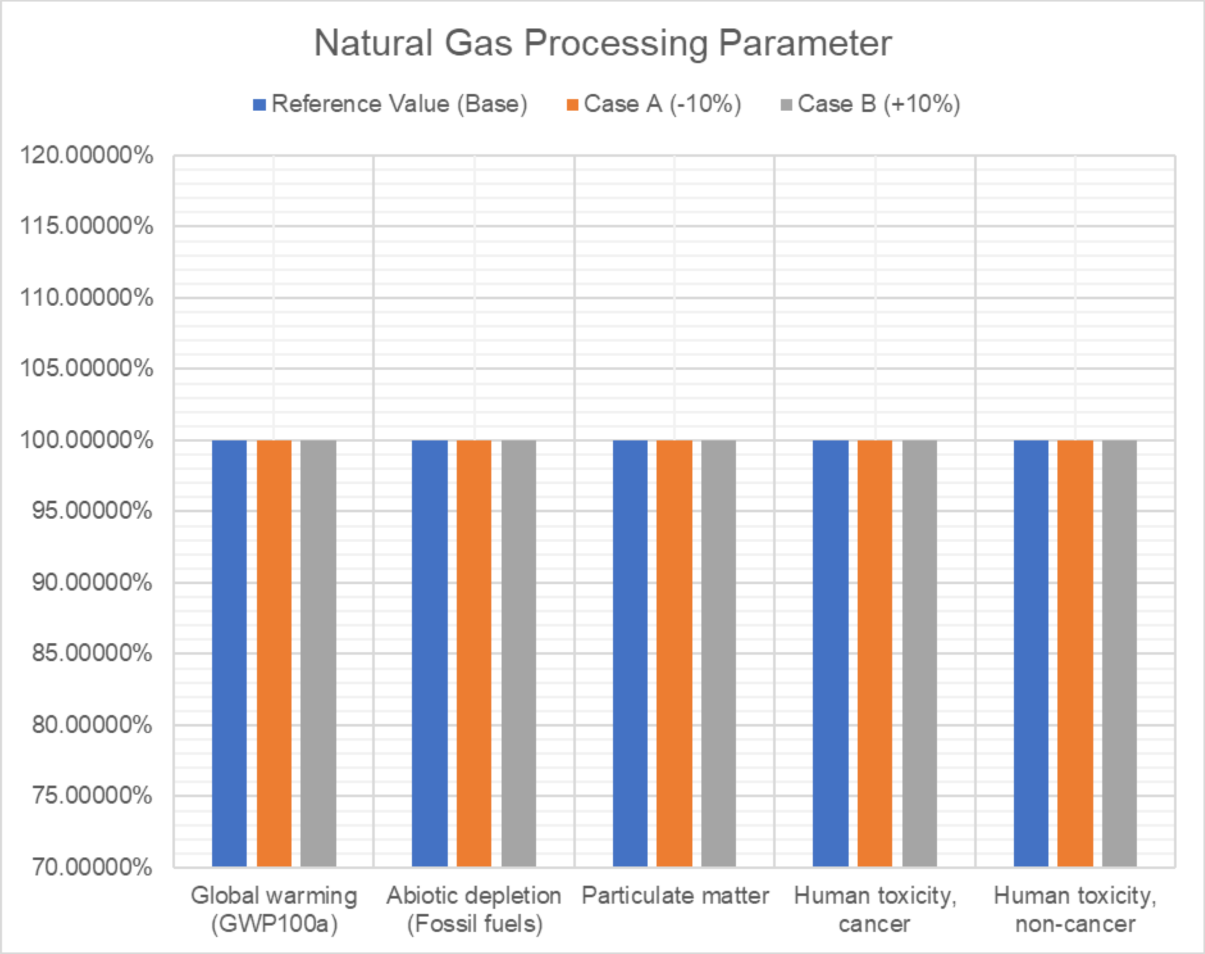


**Figure G.22: Sensitivity Analysis for LCA of CNGV (Natural Gas Processing Parameter)**

## Liquid Petroleum Gas vehicle (LPGV)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.201732 | 0.224147 | 0.183393 | 11.1 | -9.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.489779 | 2.766421 | 2.263436 | 11.1 | -9.09 |
| **Particulate Matter (kg/pkm)** | 2.49E-05 | 2.76E-05 | 2.26E-05 | 10.8 | -9.24 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.49E-09 | 1.65E-09 | 1.35E-09 | 10.7 | -9.4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.44E-09 | 7.16E-09 | 5.86E-09 | 11.18 | -9.0 |

**Table G.23: Sensitivity Analysis for LCA of LPGV (Occupancy Rate Parameter)**

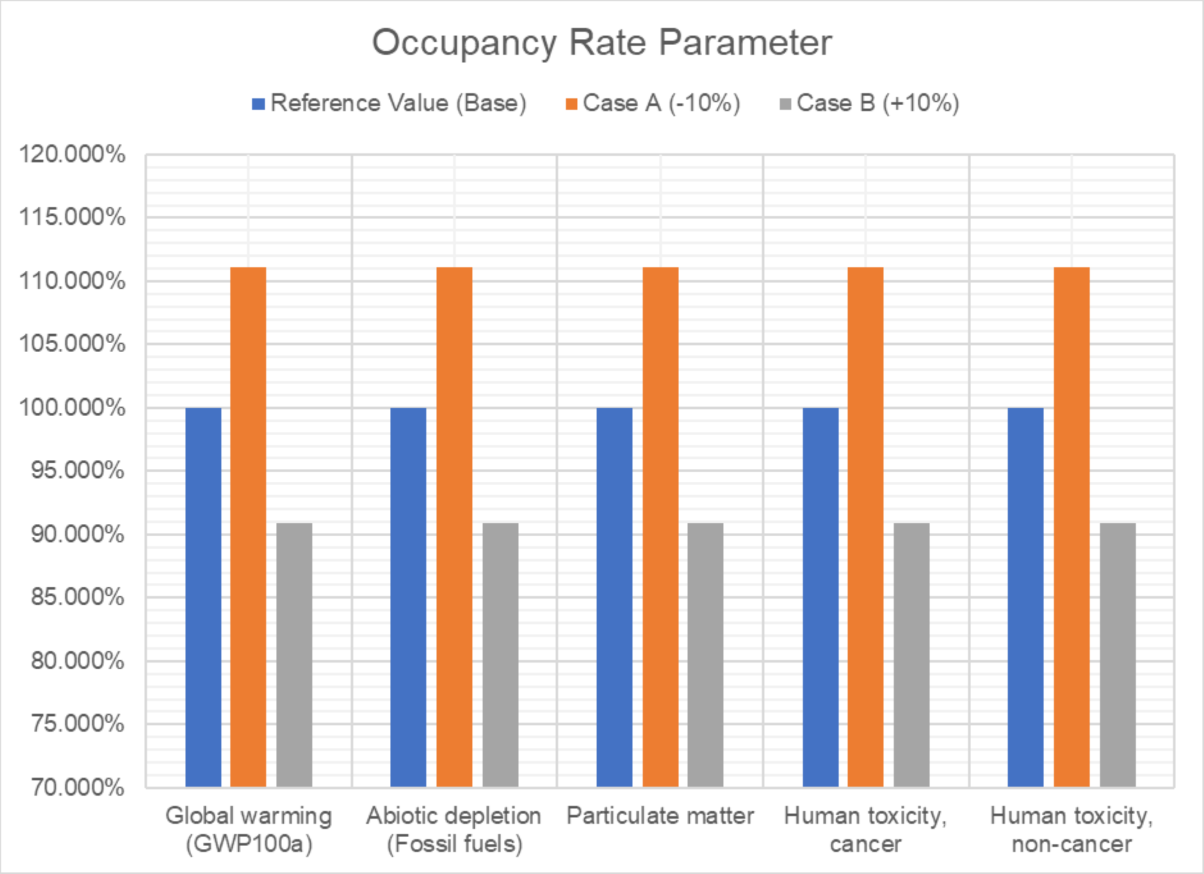


**Figure G.23: Sensitivity Analysis for LCA of LPGV (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.201732 | 0.220018 | 0.186771 | 9.1 | -7.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.489779 | 2.70761 | 2.311554 | 8.7 | -7.16 |
| **Particulate Matter (kg/pkm)** | 2.49E-05 | 2.63E-05 | 2.37E-05 | 5.6 | -4.82 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.49E-09 | 1.50E-09 | 1.48E-09 | 0.7 | -0.7 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.44E-09 | 6.55E-09 | 6.35E-09 | 1.71 | -1.4 |

**Table G.24: Sensitivity Analysis for LCA of LPGV (Kilometres Travelled Parameter)**

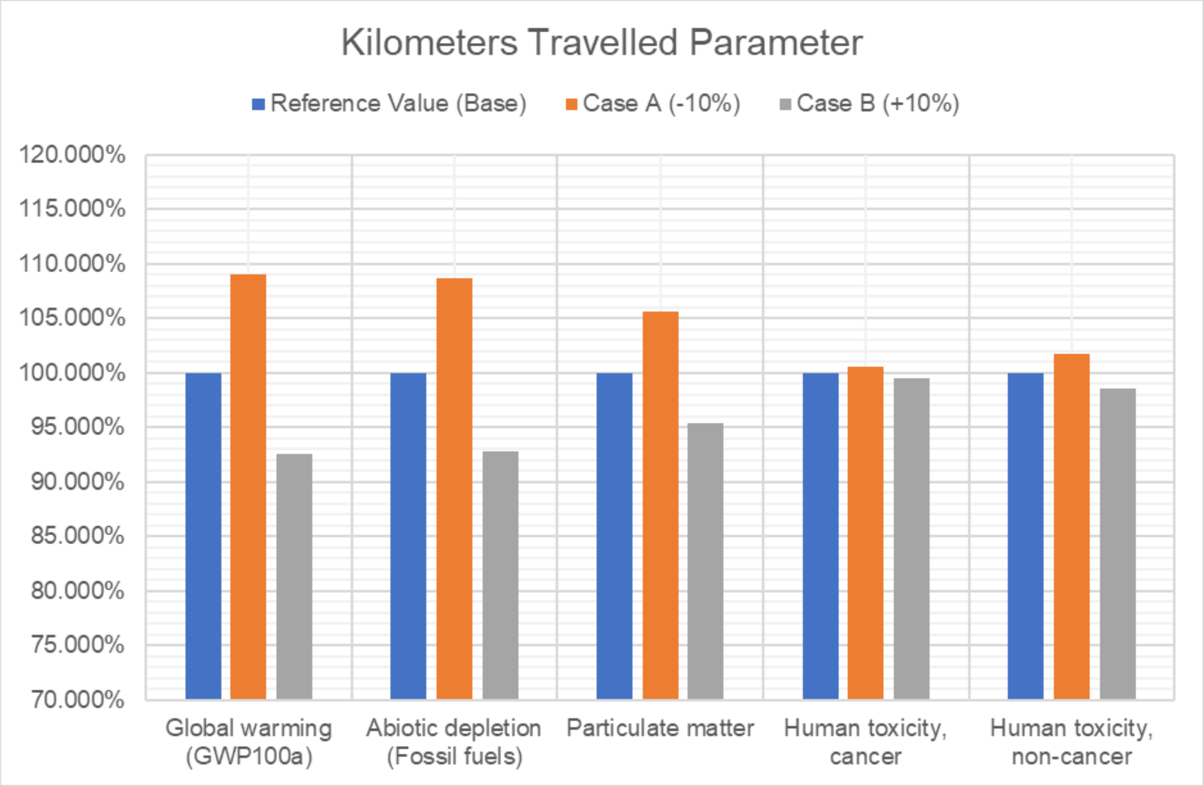


**Figure G.24: Sensitivity Analysis for LCA of LPGV (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.201732 | 0.185274 | 0.218189 | -8.2 | 8.2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.489779 | 2.293732 | 2.685827 | -7.9 | 7.87 |
| **Particulate Matter (kg/pkm)** | 2.49E-05 | 2.36E-05 | 2.61E-05 | -5.2 | 4.82 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.49E-09 | 1.48E-09 | 1.50E-09 | -0.7 | 0.7 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.44E-09 | 6.35E-09 | 6.54E-09 | -1.40 | 1.6 |

**Table G.25: Sensitivity Analysis for LCA of LPGV (Fuel Consumption Parameter)**

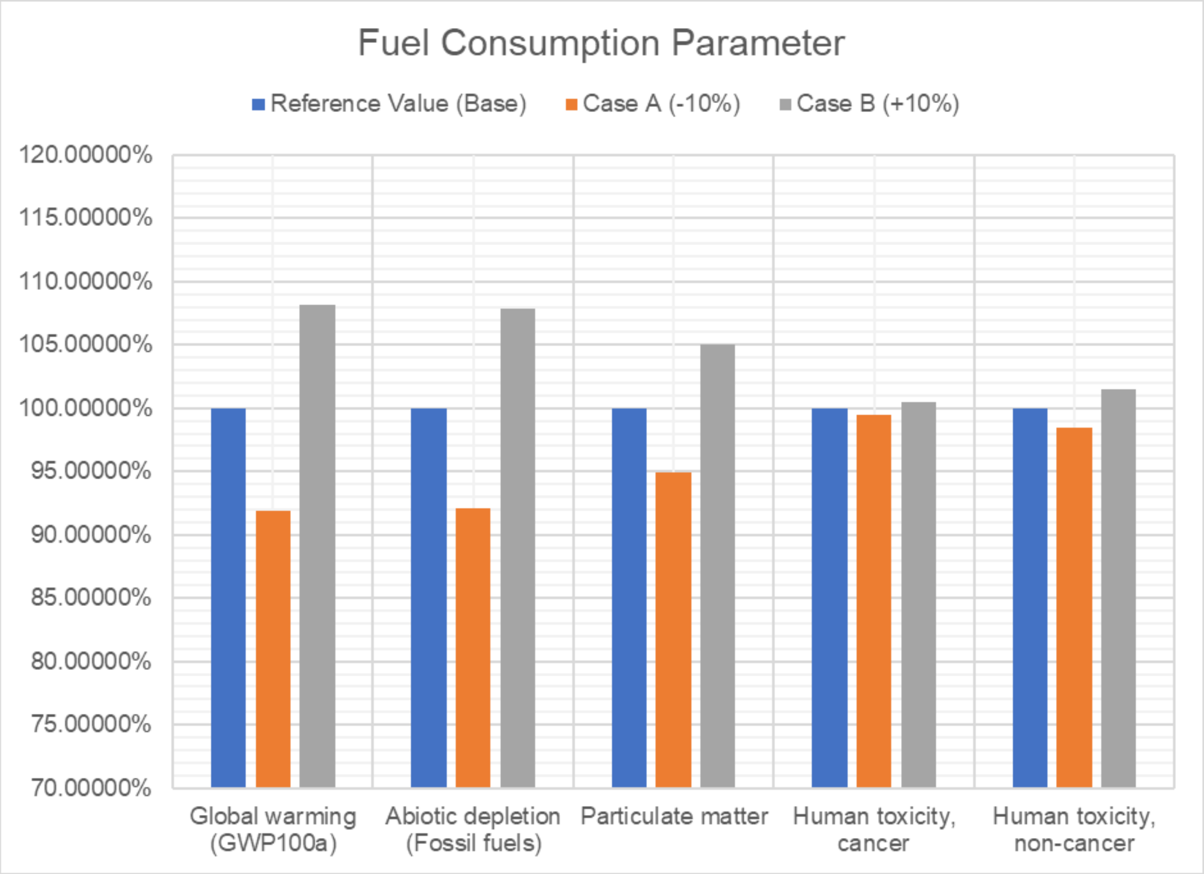


**Figure G.25: Sensitivity Analysis for LCA of LPGV (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.201732 | 0.201129 | 0.202334 | -0.3 | 0.3 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.489779 | 2.478455 | 2.501103 | -0.5 | 0.45 |
| **Particulate Matter (kg/pkm)** | 2.49E-05 | 2.47E-05 | 2.50E-05 | -0.8 | 0.40 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.49E-09 | 1.49E-09 | 1.49E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.44E-09 | 6.40E-09 | 6.49E-09 | -0.62 | 0.8 |

**Table G.26: Sensitivity Analysis for LCA of LPGV (Vehicle Maintenance Parameter)**

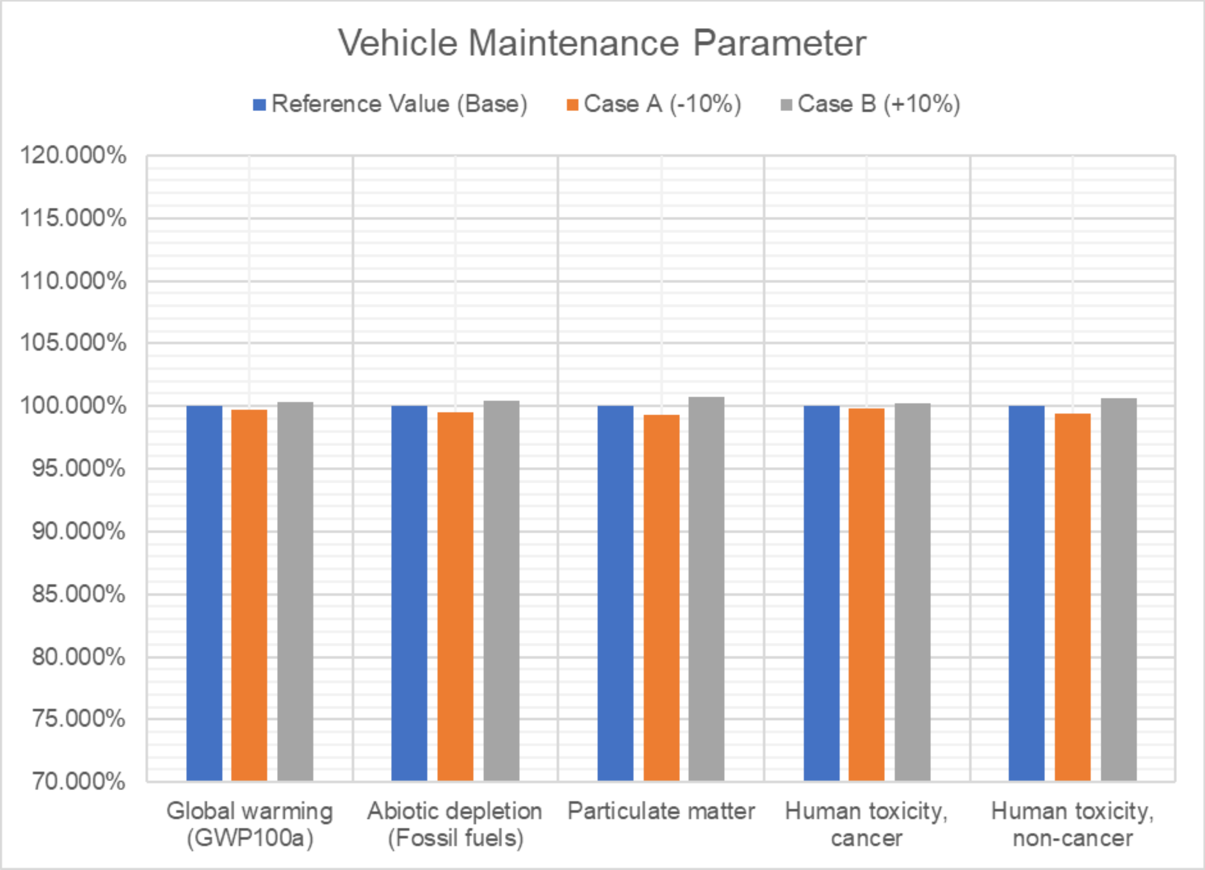


**Figure G.26: Sensitivity Analysis for LCA of LPGV (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.201732 | 0.20152 | 0.201944 | -0.1 | 0.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.489779 | 2.488608 | 2.49095 | 0.0 | 0.05 |
| **Particulate Matter (kg/pkm)** | 2.49E-05 | 2.48E-05 | 2.49E-05 | -0.4 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.49E-09 | 1.49E-09 | 1.49E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.44E-09 | 6.38E-09 | 6.51E-09 | -0.93 | 1.1 |

**Table G.27: Sensitivity Analysis for LCA of LPGV (Vehicle Disposal Parameter)**

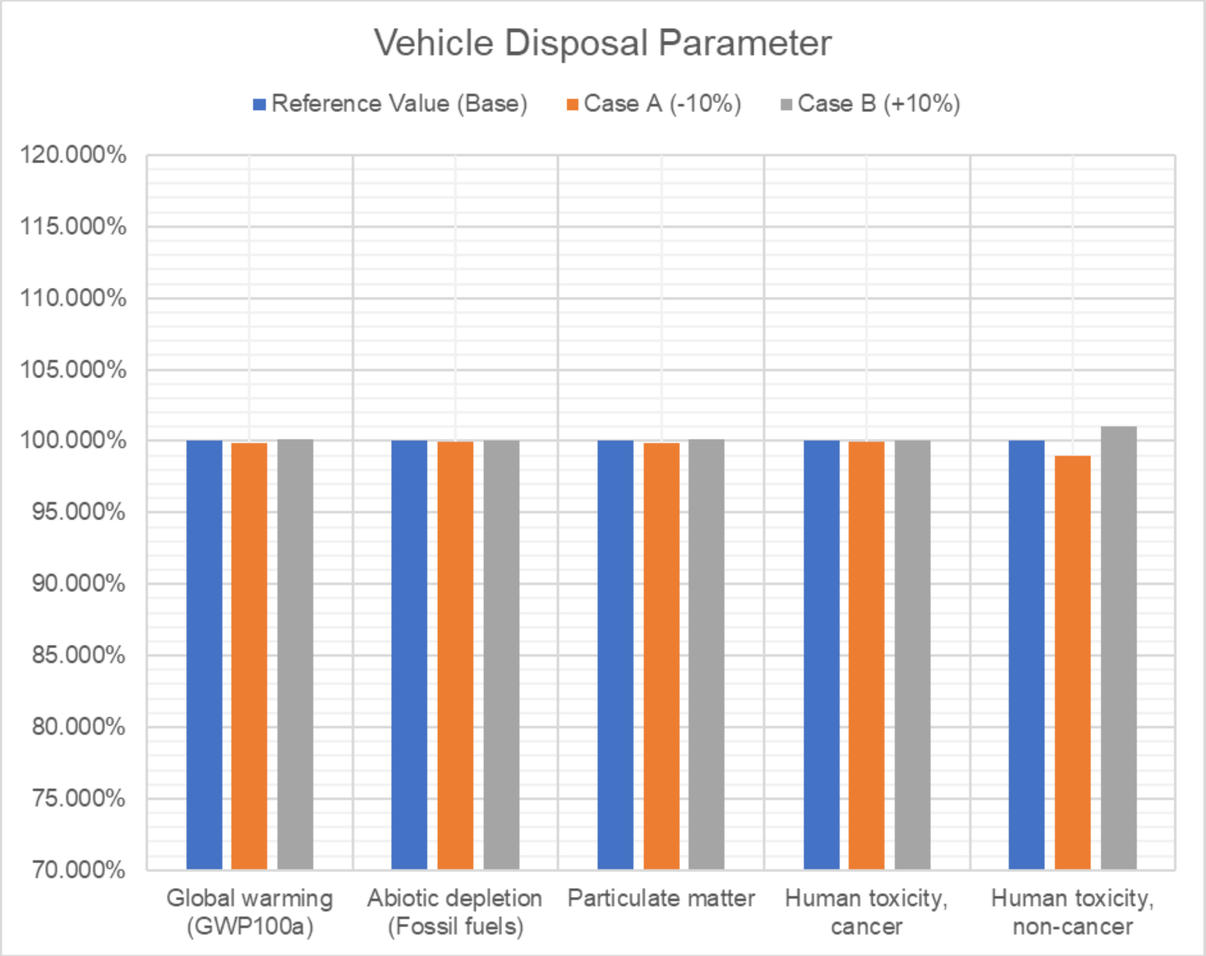


**Figure G.27: Sensitivity Analysis for LCA of LPGV (Vehicle Disposal Parameter)**

### Hybrid Electric Vehicles (HEV)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| Global Warming (GWP100a) | 0.129583 | 0.143981 | 0.117803 | 11.1 | -9.1 |
| Abiotic Depletion (Fossil Fuels) (MJ/pkm) | 0.755051 | 0.838946 | 0.68641 | 11.1 | -9.09 |
| Particulate Matter (kg/pkm) | 4.88E-05 | 5.42E-05 | 4.44E-05 | 11.1 | -9.02 |
| Human Toxicity, Cancer (kg/pkm) | 1.58E-09 | 1.76E-09 | 1.44E-09 | 11.4 | -8.9 |
| Human Toxicity, Non-Cancer (kg/pkm) | 7.83E-09 | 8.70E-09 | 7.12E-09 | 11.11 | -9.1 |

**Table G.28: Sensitivity Analysis for LCA of HEV (Occupancy Rate Parameter)**

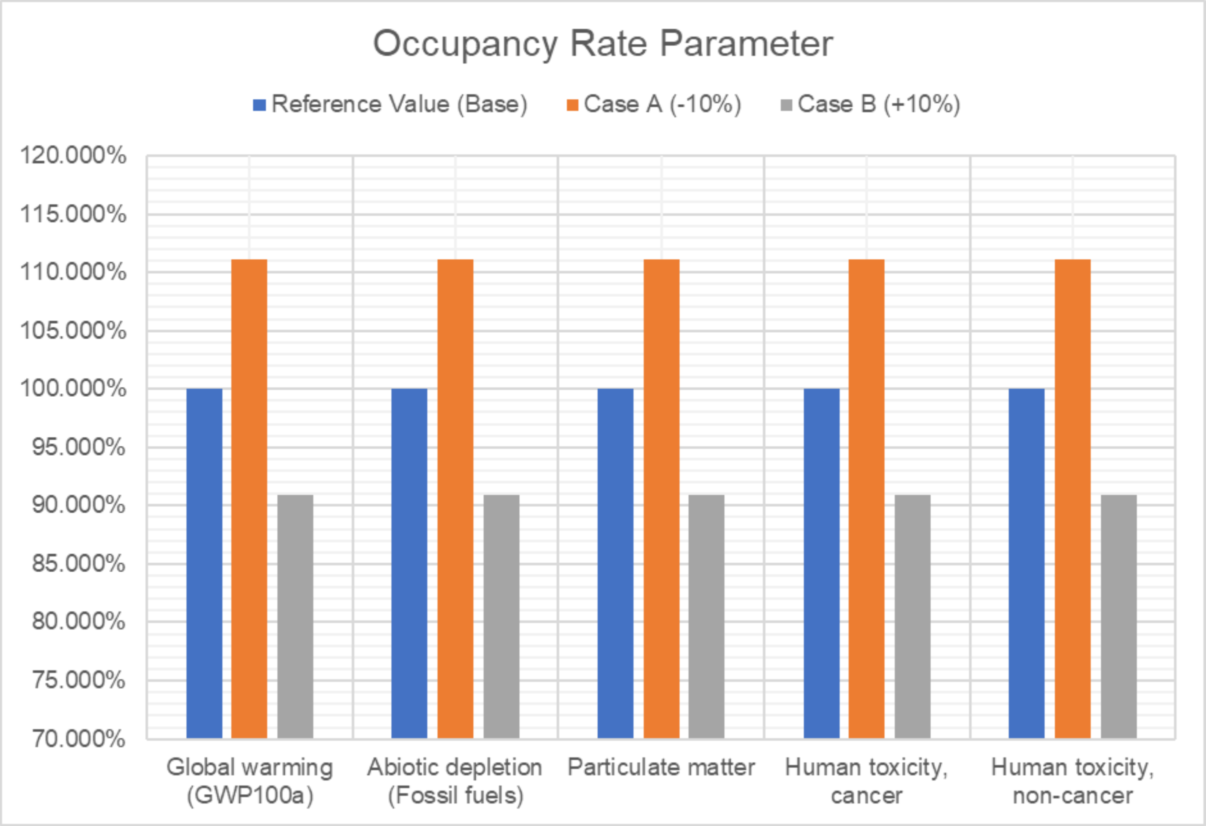


**Figure G.28: Sensitivity Analysis for LCA of HEV (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.129583 | 0.139721 | 0.121289 | 7.8 | -6.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.755051 | 0.778351 | 0.735987 | 3.1 | -2.52 |
| **Particulate Matter (kg/pkm)** | 4.88E-05 | 5.26E-05 | 4.57E-05 | 7.8 | -6.35 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.59E-09 | 1.57E-09 | 0.6 | -0.6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.83E-09 | 7.92E-09 | 7.76E-09 | 1.15 | -0.9 |

**Table G.29: Sensitivity Analysis for LCA of HEV (Kilometres Travelled Parameter)**

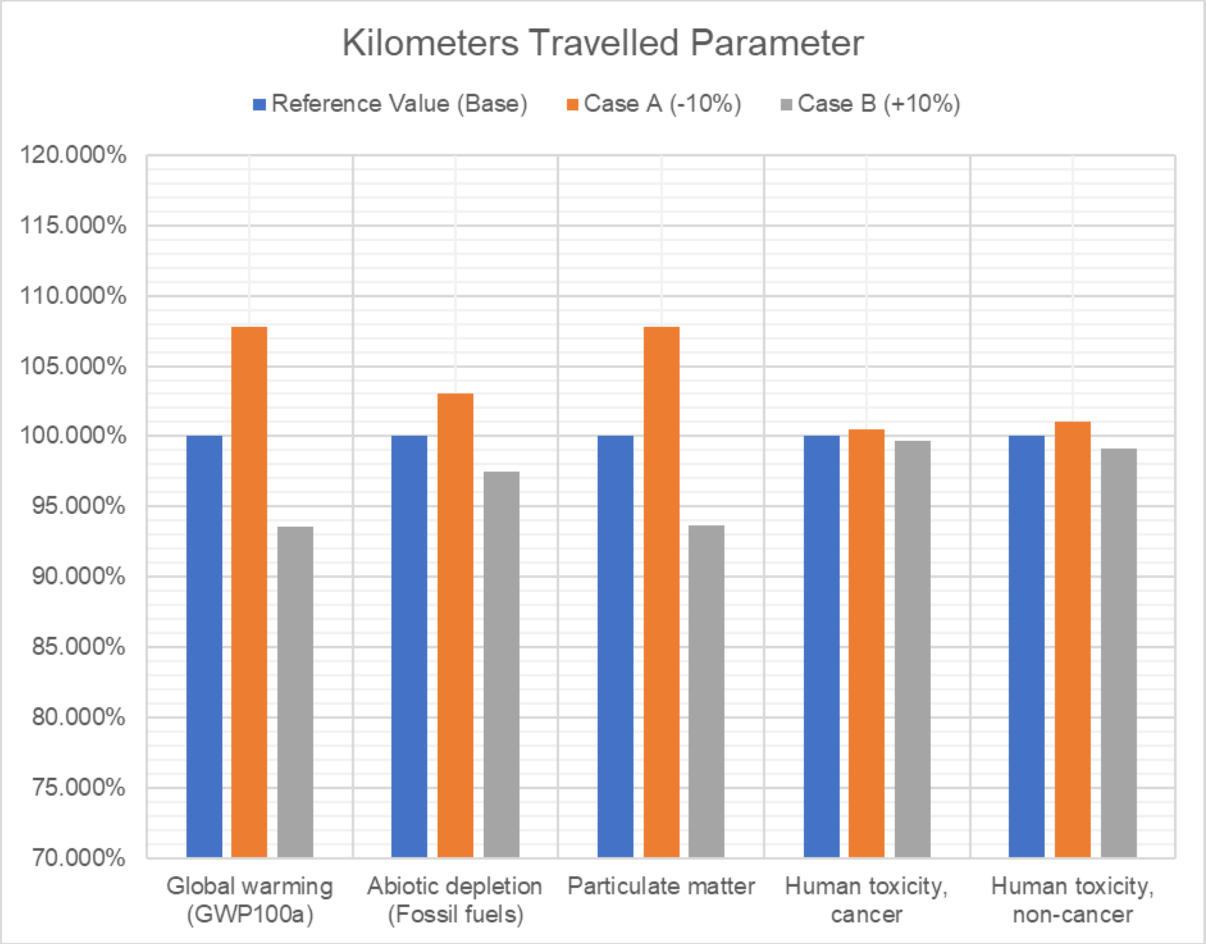


**Figure G.29: Sensitivity Analysis for LCA of HEV (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.129583 | 0.120459 | 0.138707 | -7.0 | 7.0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.755051 | 0.734081 | 0.776021 | -2.8 | 2.78 |
| **Particulate Matter (kg/pkm)** | 4.88E-05 | 4.54E-05 | 5.22E-05 | -7.0 | 6.97 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.57E-09 | 1.59E-09 | -0.6 | 0.6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.83E-09 | 7.76E-09 | 7.91E-09 | -0.89 | 1.0 |

**Table G.30: Sensitivity Analysis for LCA of HEV (Fuel Consumption Parameter)**

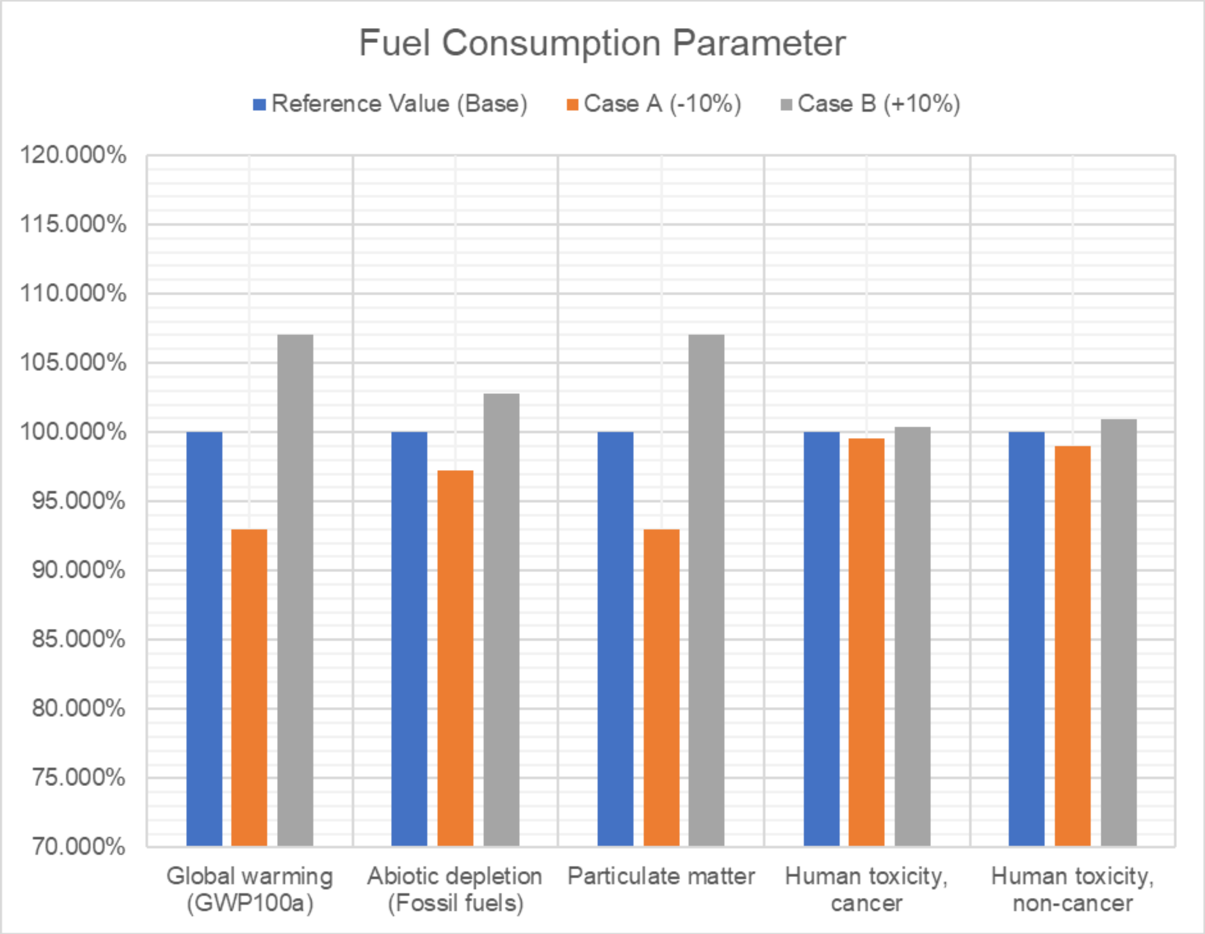


**Figure G.30: Sensitivity Analysis for LCA of HEV (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.12958319 | 0.12659822 | 0.13256815 | -2.3 | 2.3 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75505103 | 0.71355839 | 0.79654366 | -5.5 | 5.50 |
| **Particulate Matter (kg/pkm)** | 4.88E-05 | 4.76E-05 | 5.00E-05 | -2.5 | 2.46 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.44E-09 | 1.72E-09 | -8.9 | 8.9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.83E-09 | 7.30E-09 | 8.37E-09 | -6.77 | 6.9 |

**Table G.31: Sensitivity Analysis for LCA of HEV (Vehicle Manufacture Parameter)**

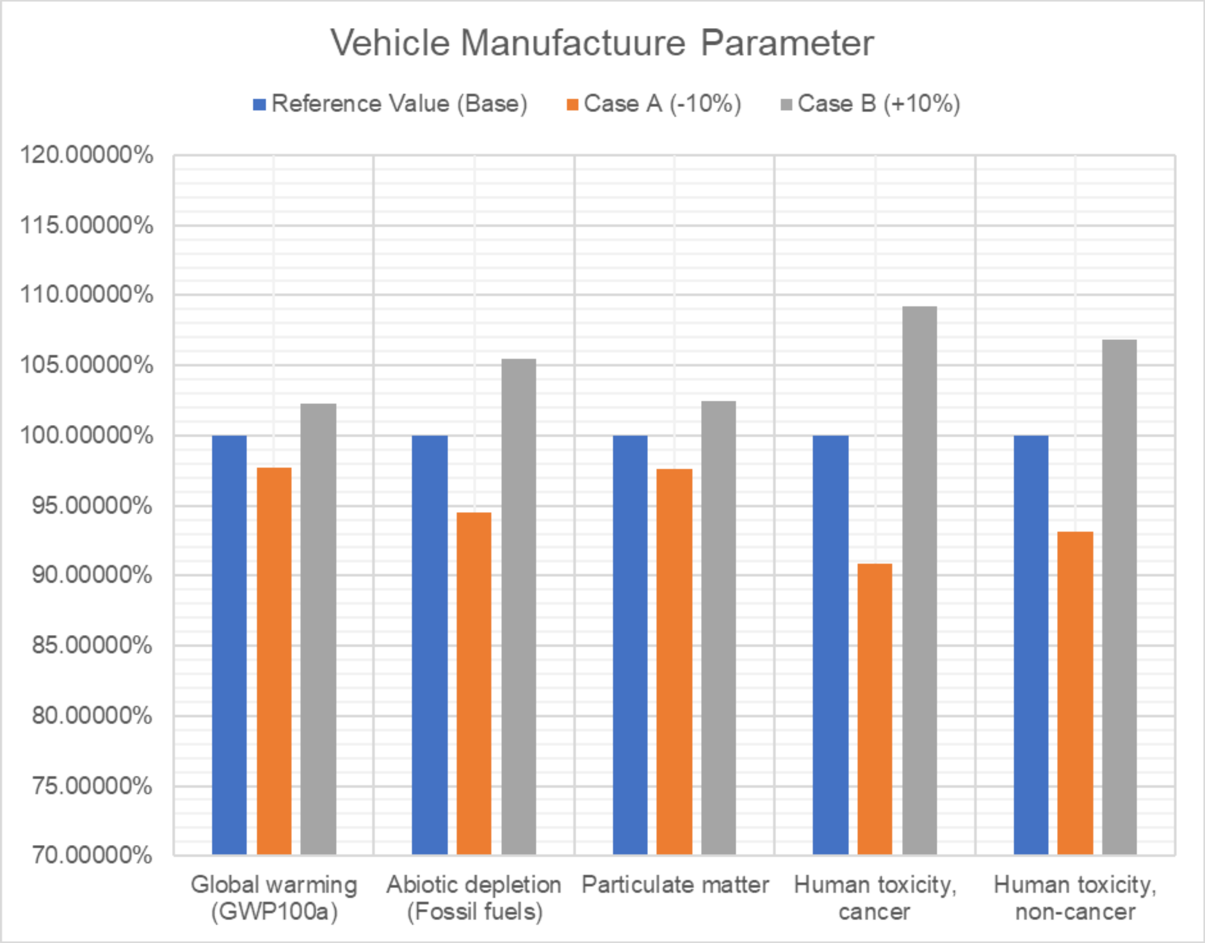


**Figure G.31: Sensitivity Analysis for LCA of HEV (Vehicle Manufacture Parameter)**

| Impact category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg /pkm)** | 0.129583 | 0.128958 | 0.130208 | -0.5 | 0.5 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.755051 | 0.743287 | 0.766815 | -1.6 | 1.56 |
| **Particulate matter (kg/pkm)** | 4.88E-05 | 4.86E-05 | 4.91E-05 | -0.4 | 0.61 |
| **Human toxicity, cancer (kg/pkm)** | 1.58E-09 | 1.57E-09 | 1.59E-09 | -0.6 | 0.6 |
| **Human toxicity, non-cancer (kg/pkm)** | 7.83E-09 | 7.73E-09 | 7.94E-09 | -1.28 | 1.4 |

**Table G.32: Sensitivity Analysis for LCA of HEV (Vehicle Maintenance Parameter)**

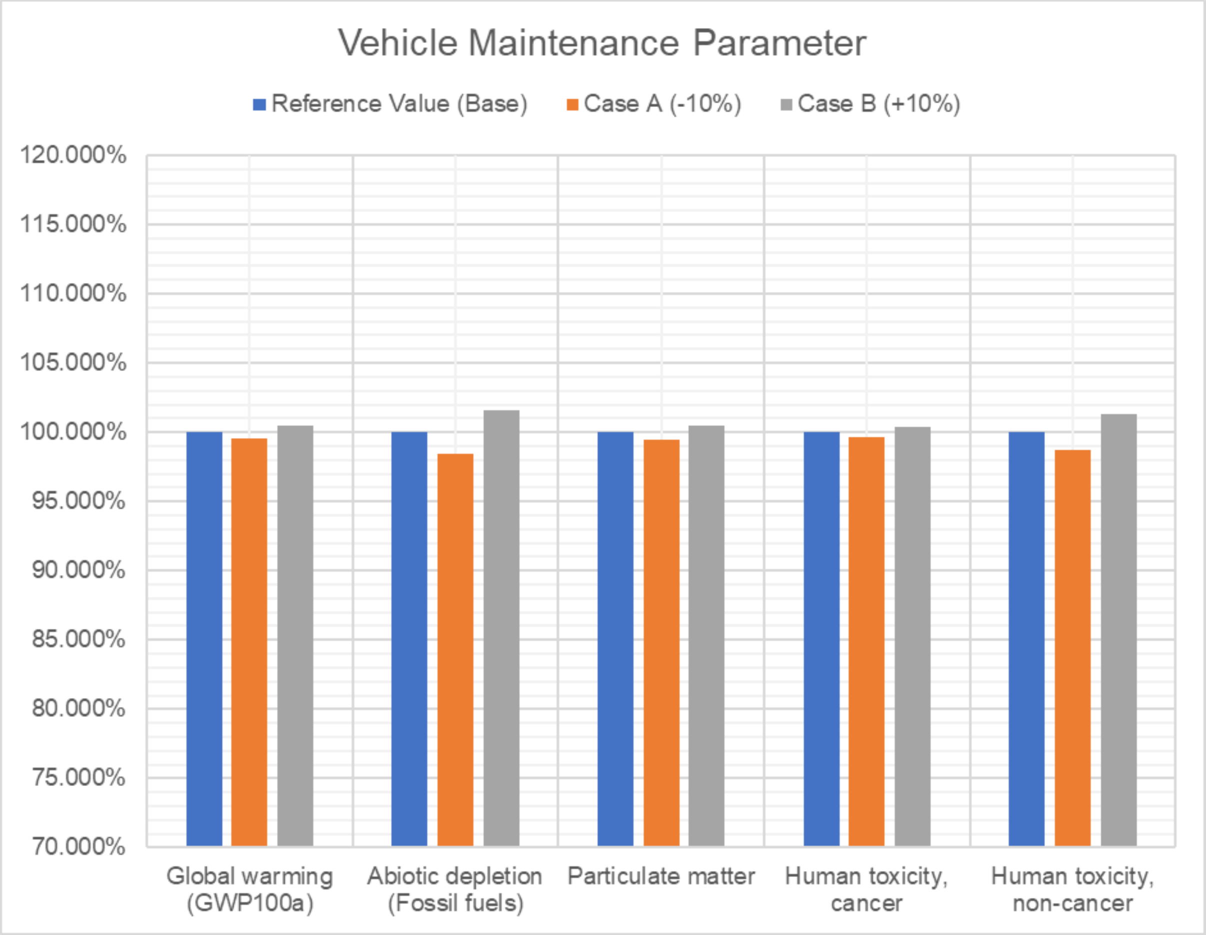


**Figure G.32: Sensitivity Analysis for LCA of HEV (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.129583 | 0.129332 | 0.129834 | -0.2 | 0.2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.755051 | 0.752685 | 0.757417 | -0.3 | 0.31 |
| **Particulate Matter (kg/pkm)** | 4.88E-05 | 4.88E-05 | 4.88E-05 | 0.0 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.83E-09 | 7.82E-09 | 7.85E-09 | -0.13 | 0.3 |

**Table G.33: Sensitivity Analysis for LCA of HEV (Crude Oil Refining Parameter)**

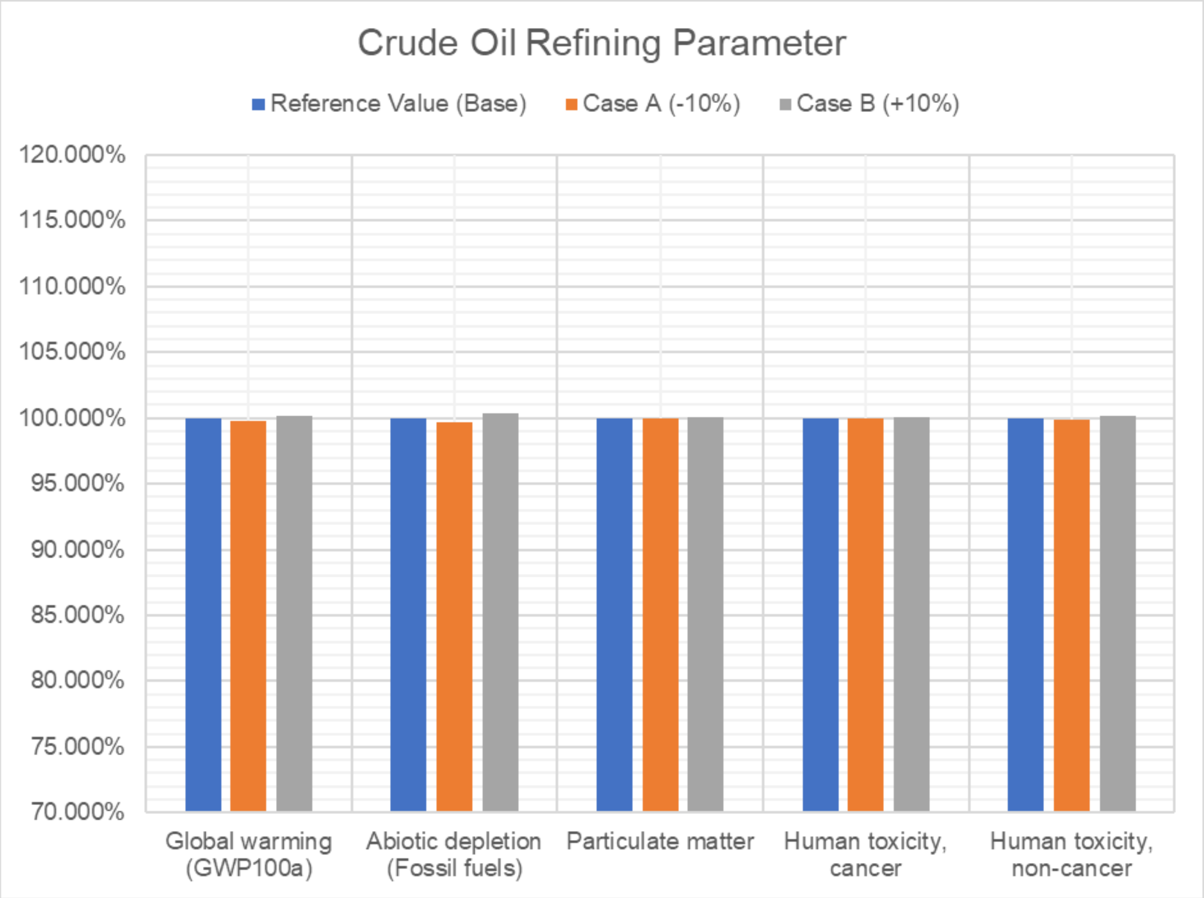


**Figure G.33: Sensitivity Analysis for LCA of HEV (Crude Oil Refining Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.129583 | 0.129358 | 0.129808 | -0.2 | 0.2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.755051 | 0.753773 | 0.756329 | -0.2 | 0.17 |
| **Particulate Matter (kg/pkm)** | 4.88E-05 | 4.88E-05 | 4.88E-05 | 0.0 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.83E-09 | 7.76E-09 | 7.90E-09 | -0.89 | 0.9 |

Table G.34: Sensitivity Analysis for LCA of HEV (Vehicle Disposal Parameter)

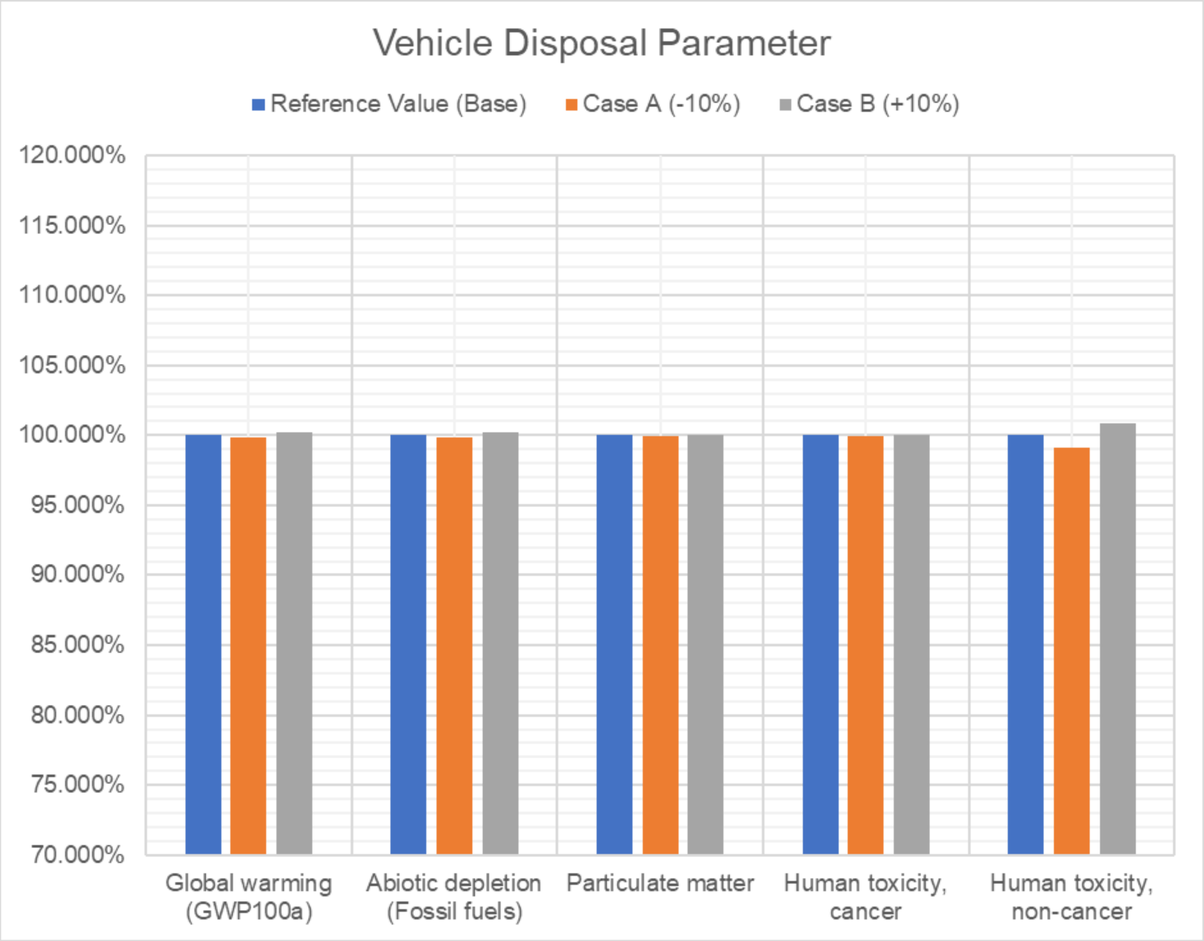


Figure G.34: Sensitivity Analysis for LCA of HEV (Vehicle Disposal Parameter)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.129583 | 0.129375 | 0.129792 | -0.2 | 0.2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.755051 | 0.753194 | 0.756908 | -0.2 | 0.25 |
| **Particulate Matter (kg/pkm)** | 4.88E-05 | 4.88E-05 | 4.88E-05 | 0.0 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.83E-09 | 7.82E-09 | 7.84E-09 | -0.13 | 0.1 |

**Table G.35: Sensitivity Analysis for LCA of HEV (Crude Oil Extraction Parameter)**

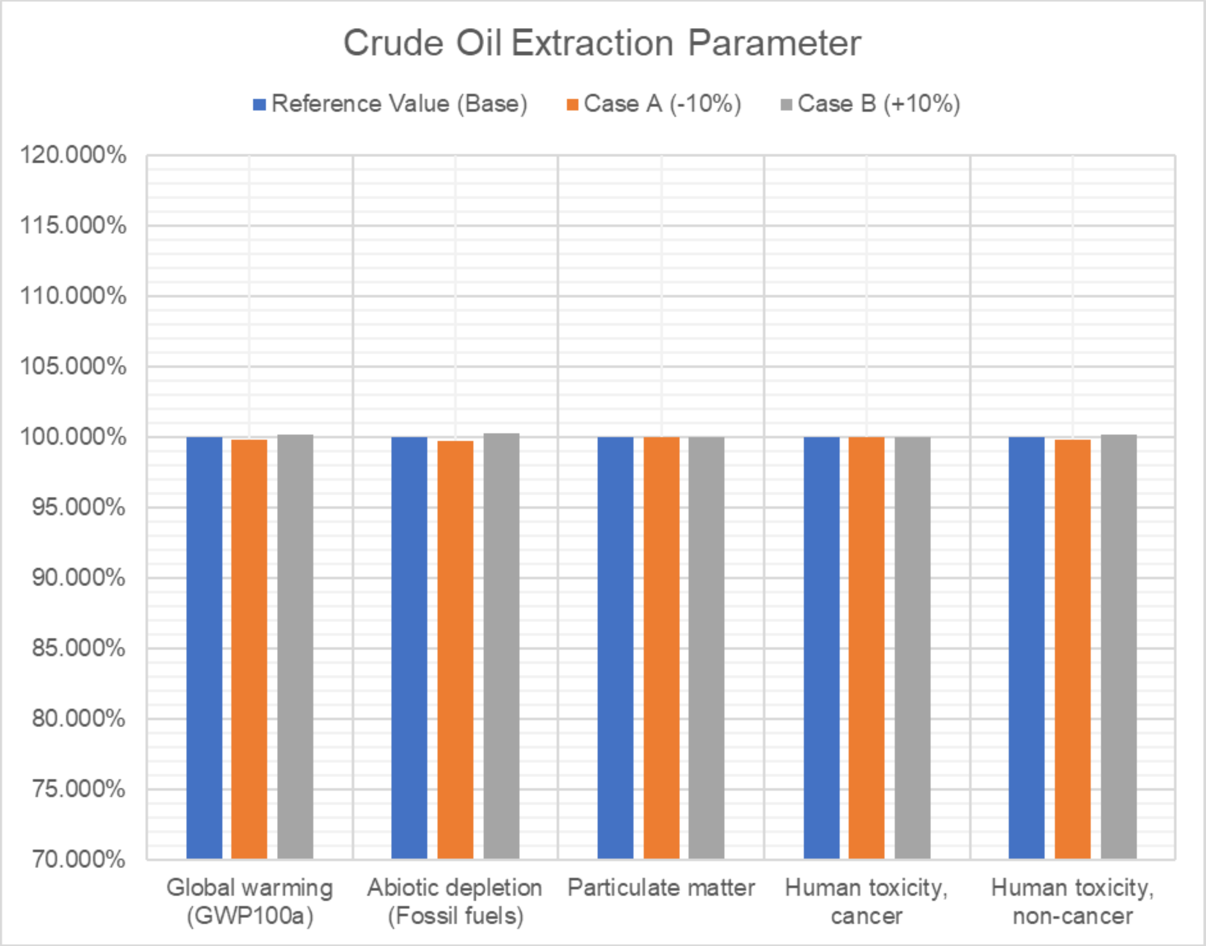


**Figure G.35: Sensitivity Analysis for LCA of HEV (Crude Oil Extraction Parameter)**

### Plug in Hybrid Vehicles (PHEV)

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.161683 | 0.179648 | 0.146985 | 11.1 | -9.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.593524 | 1.770582 | 1.448658 | 11.1 | -9.09 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 6.30E-05 | 5.16E-05 | 11.1 | -8.99 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.59E-09 | 2.12E-09 | 11.2 | -9.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.90E-08 | 2.37E-08 | 11.11 | -9.2 |

**Table G.36: Sensitivity Analysis for LCA of PHEV (Occupancy Rate Parameter)**

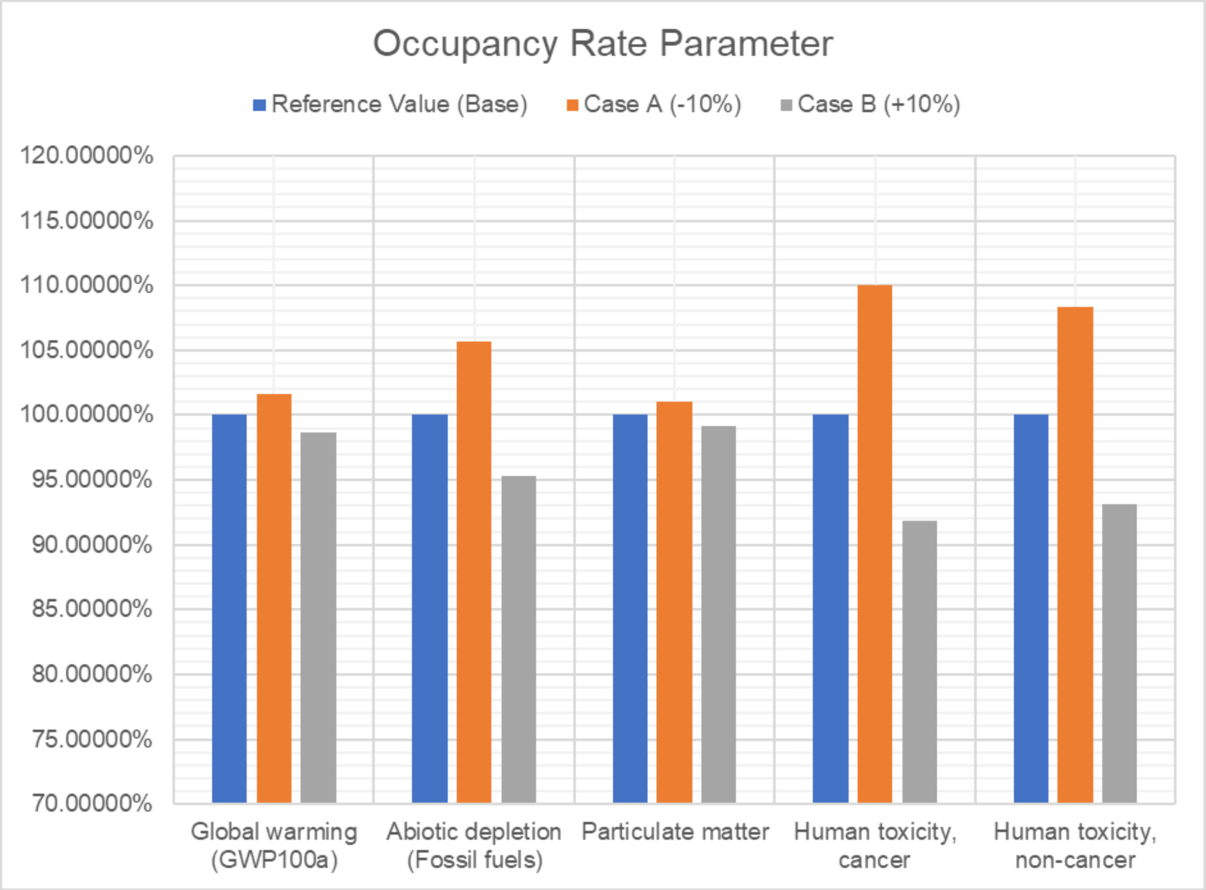


**Figure G.36: Sensitivity Analysis for LCA of PHEV (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.161683 | 0.174568 | 0.151141 | 8.0 | -6.5 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.593524 | 1.696098 | 1.5096 | 6.4 | -5.27 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.94E-05 | 5.46E-05 | 4.8 | -3.70 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.35E-09 | 2.32E-09 | 0.9 | -0.4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.64E-08 | 2.58E-08 | 1.15 | -1.1 |

**Table G.37: Sensitivity Analysis for LCA of PHEV (Kilometre Travelled Parameter)**

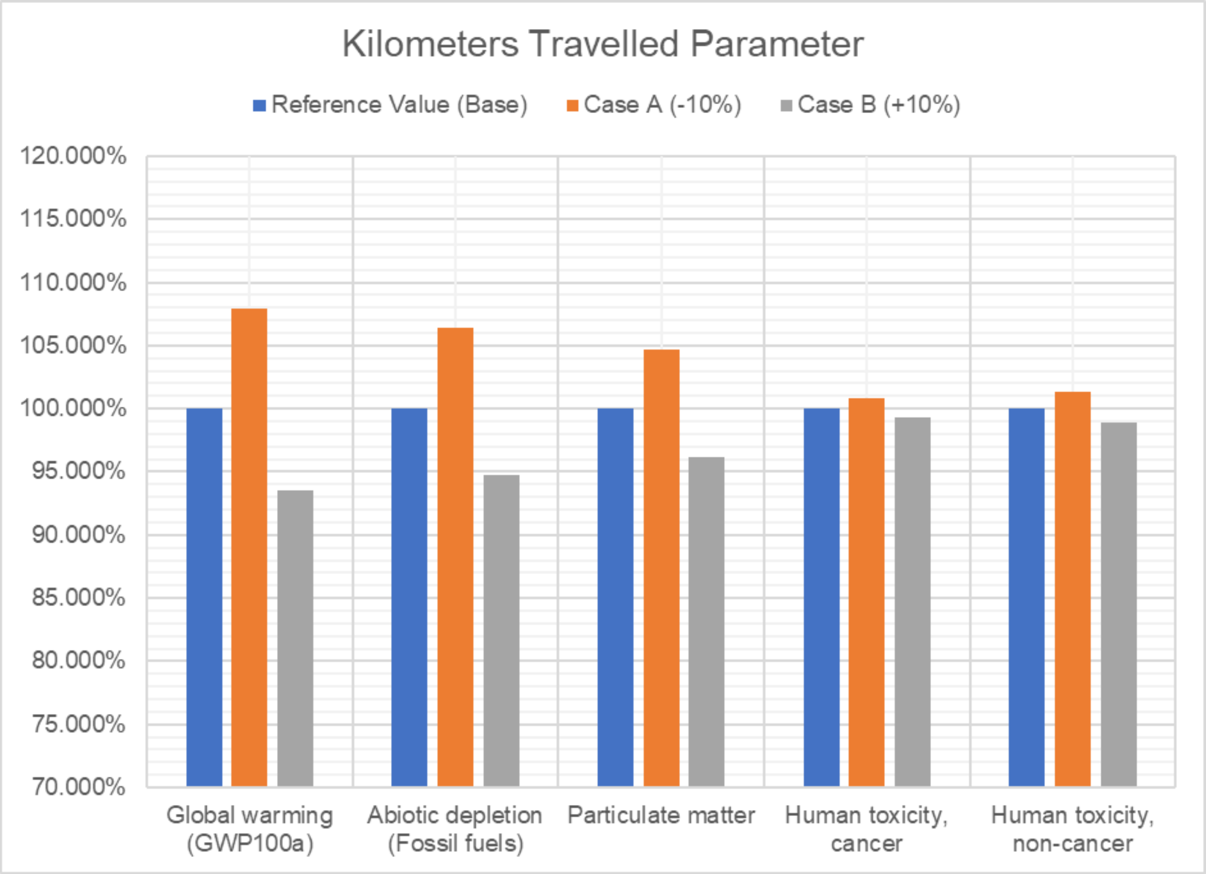


**Figure G.37: Sensitivity Analysis for LCA of PHEV (Kilometre Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.161683 | 0.154455 | 0.168911 | -4.5 | 4.5 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.593524 | 1.511216 | 1.675832 | -5.2 | 5.17 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.60E-05 | 5.75E-05 | -1.2 | 1.41 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.32E-09 | 2.35E-09 | -0.4 | 0.9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.58E-08 | 2.64E-08 | -1.15 | 1.1 |

**Figure G.38: Sensitivity Analysis for LCA of PHEV (Electricity Grid Consumption Parameter)**

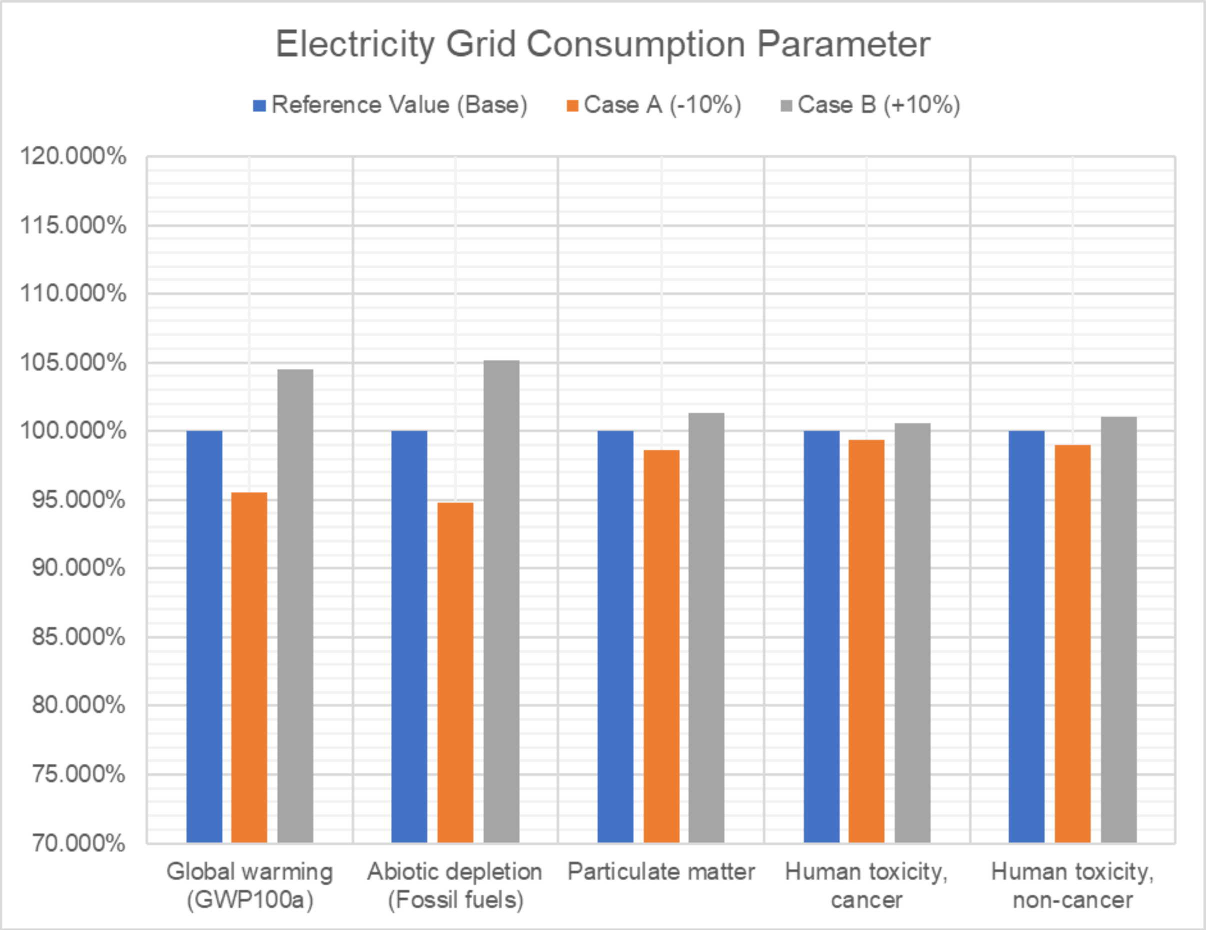


**Figure G.38: Sensitivity Analysis for LCA of PHEV (Electricity Grid Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.16168219 | 0.15450212 | 0.16886227 | -4.4 | 4.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.5935286 | 1.5116413 | 1.6754159 | -5.1 | 5.14 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.60E-05 | 5.74E-05 | -1.2 | 1.23 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.33E-09 | 2.34E-09 | 0.0 | 0.4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.59E-08 | 2.63E-08 | -0.77 | 0.8 |

**Figure G.39: Sensitivity Analysis for LCA of PHEV (Electricity Mix Production Parameter)**

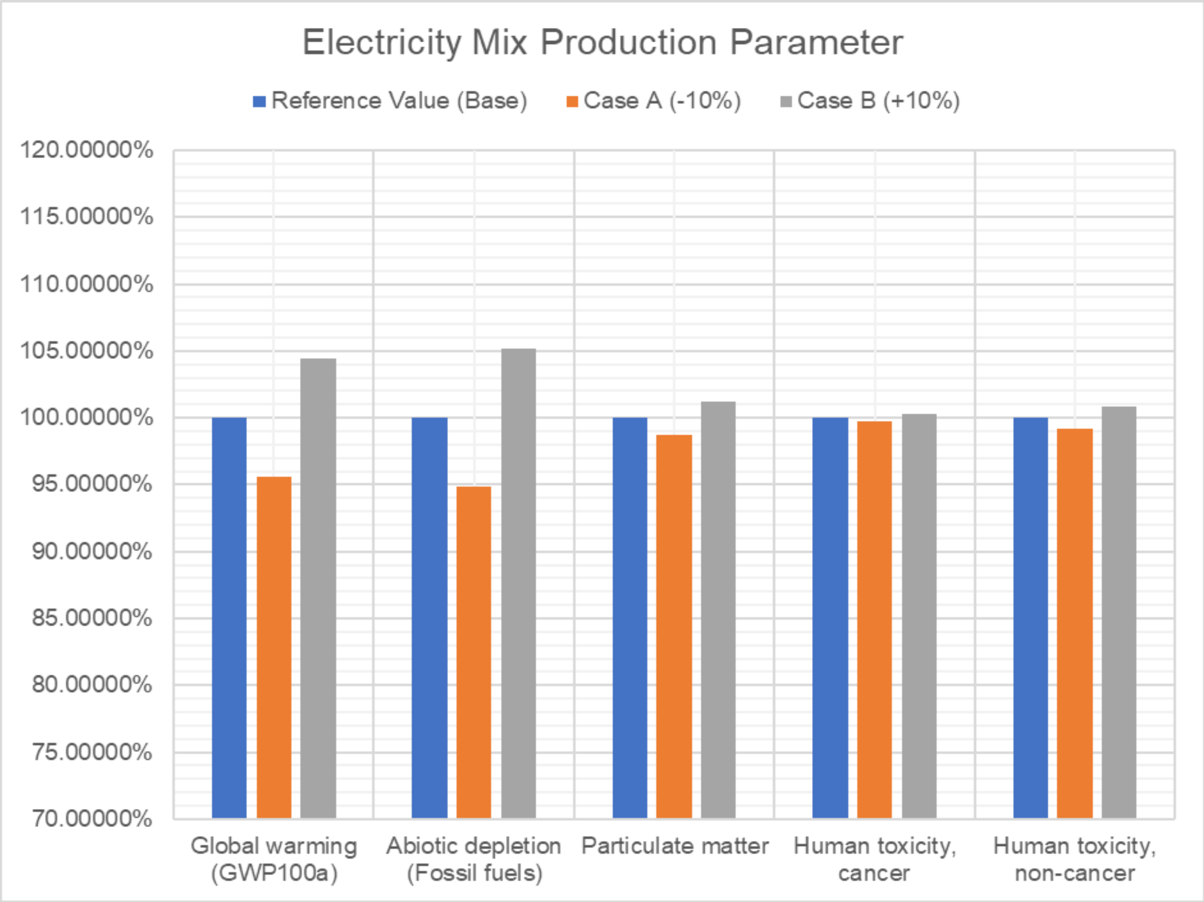


**Figure G.39: Sensitivity Analysis for LCA of PHEV (Electricity Mix Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.161683 | 0.157315 | 0.166052 | -2.7 | 2.7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.593524 | 1.583515 | 1.603532 | -0.6 | 0.63 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.51E-05 | 5.84E-05 | -2.8 | 3.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.33E-09 | 2.34E-09 | 0.0 | 0.4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.61E-08 | 2.61E-08 | 0.00 | 0.0 |

**Table G.40: Sensitivity Analysis for LCA of PHEV (Fuel Consumption Parameter)**

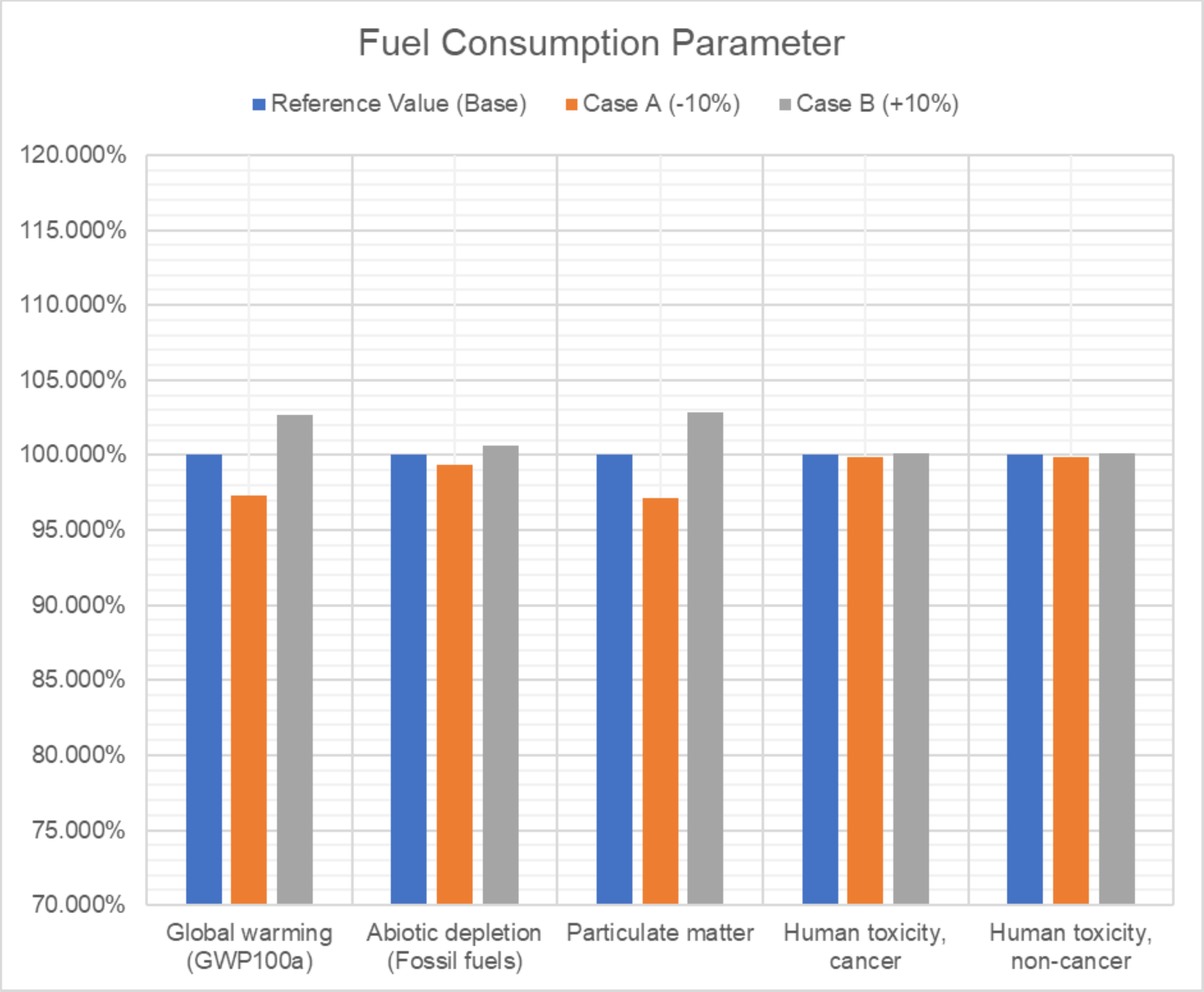


**Figure G.40: Sensitivity Analysis for LCA of PHEV (Fuel Consumption Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+105)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.16168219 | 0.1583951 | 0.16496929 | -2 | 2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.5935286 | 1.5463762 | 1.640681 | -3 | 3 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.47E-05 | 5.88E-05 | -4 | 4 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.16E-09 | 2.51E-09 | -8 | 8 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.48E-08 | 2.74E-08 | -5 | 5 |

**Table G.41: Sensitivity Analysis for LCA of PHEV (Vehicle Manufacture Parameter)**

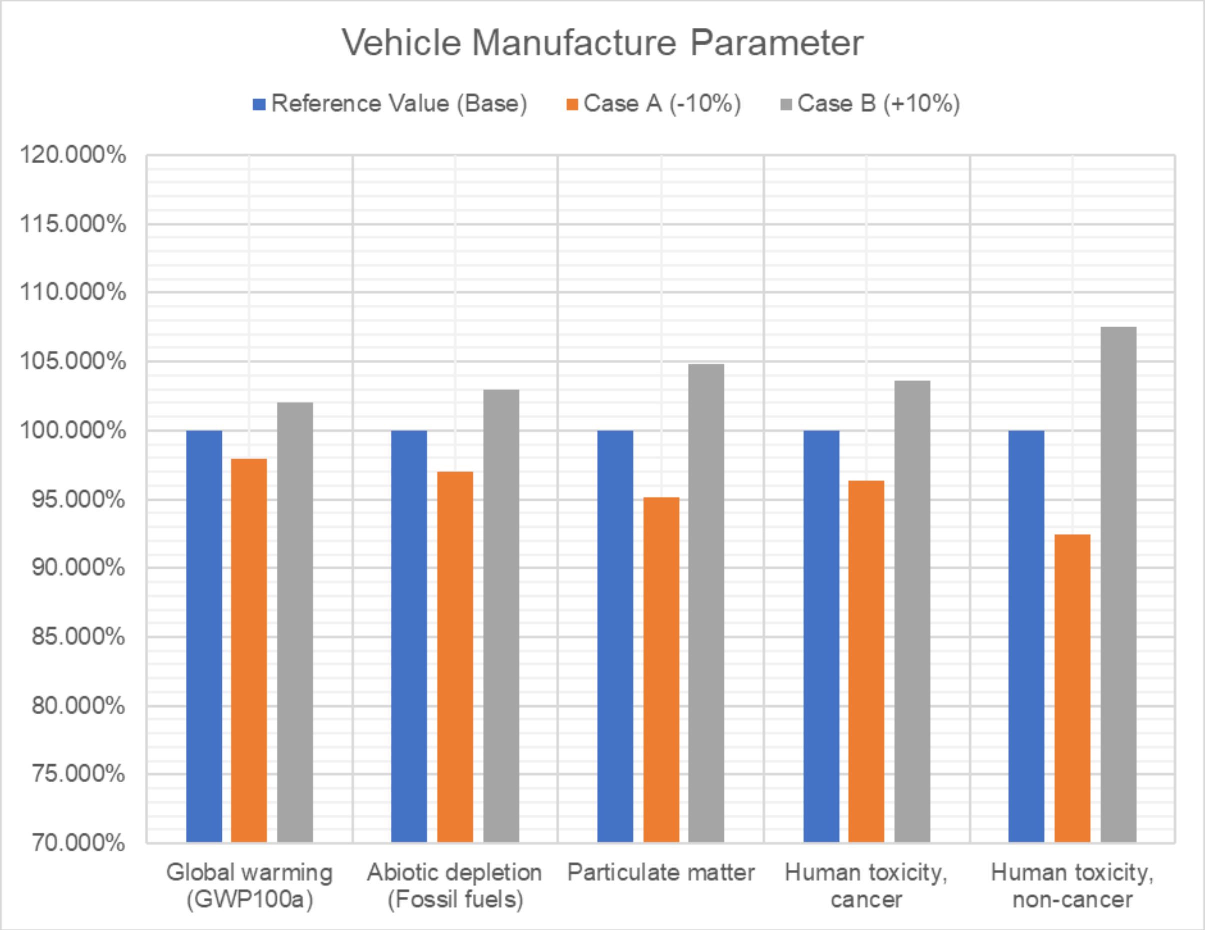


**Figure G.41: Sensitivity Analysis for LCA of PHEV (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.16168219 | 0.16077643 | 0.16258795 | -0.6 | 0.6 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.5935286 | 1.576259 | 1.6107982 | -1.1 | 1.08 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.56E-05 | 5.78E-05 | -1.9 | 1.94 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.30E-09 | 2.37E-09 | -1.3 | 1.7 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.52E-08 | 2.70E-08 | -3.45 | 3.4 |

**Table G.42: Sensitivity Analysis for LCA of PHEV (Vehicle Maintenance Parameter)**

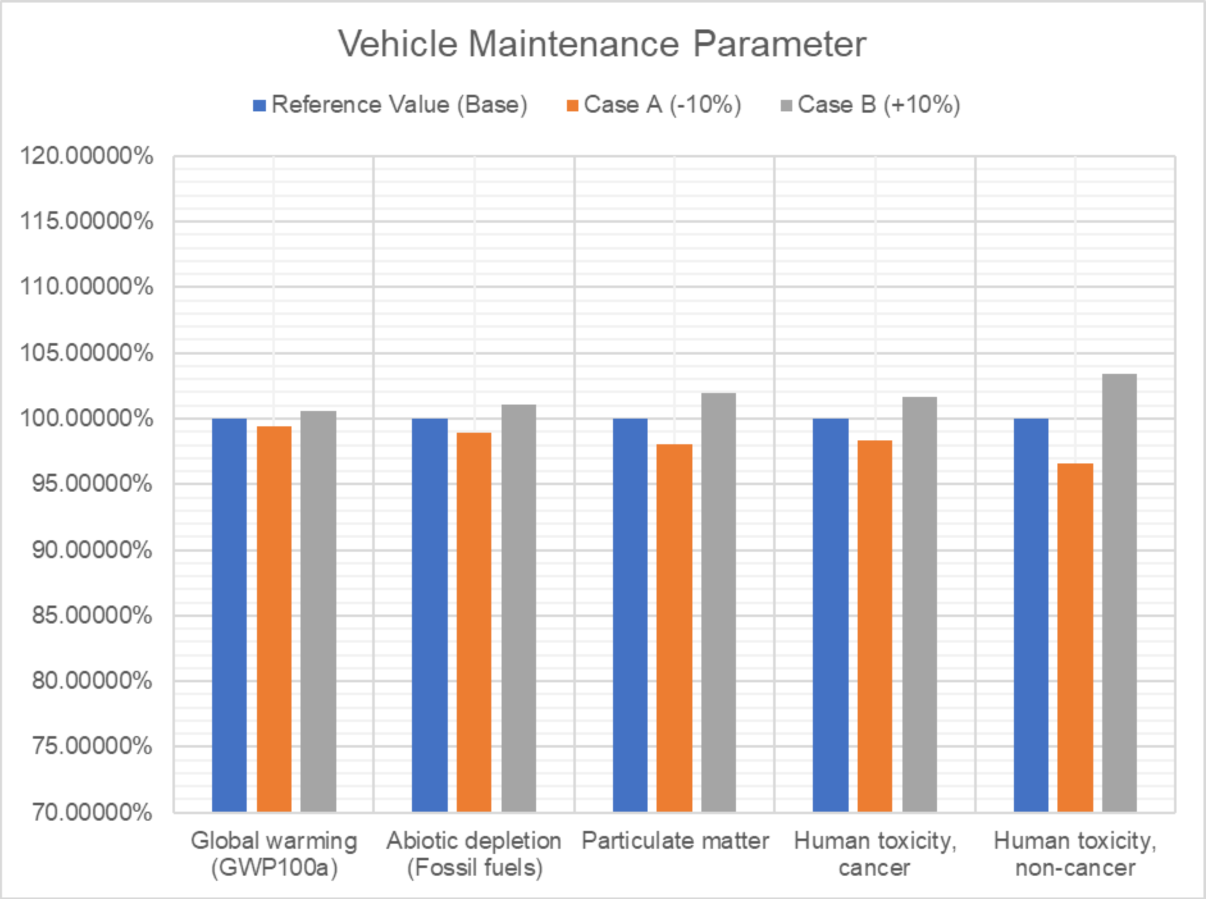


**Figure G.42: Sensitivity Analysis for LCA of PHEV (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.161683 | 0.161794 | 0.161593 | 0.1 | -0.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.593524 | 1.594509 | 1.592718 | 0.1 | -0.05 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.67E-05 | 5.67E-05 | 0.0 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.33E-09 | 2.33E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.61E-08 | 2.61E-08 | 0.00 | 0.0 |

**Table G.43: Sensitivity Analysis for LCA of PHEV (Crude Oil Refining Parameter)**

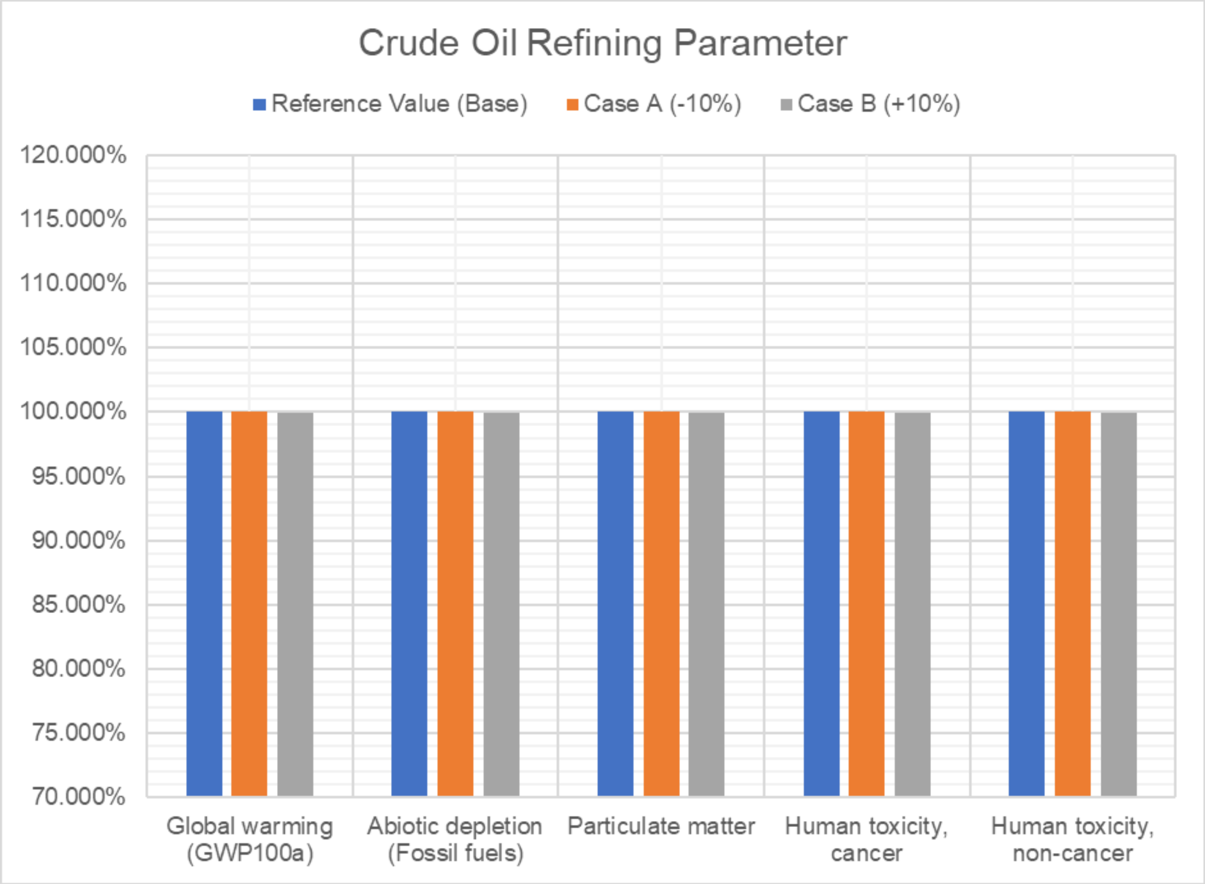


**Figure G.43: Sensitivity Analysis for LCA of PHEV (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a)** | 0.161683 | 0.161583 | 0.161783 | -0.1 | 0.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.593524 | 1.592637 | 1.59441 | -0.1 | 0.06 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.67E-05 | 5.67E-05 | 0.0 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.33E-09 | 2.33E-09 | 2.33E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.61E-08 | 2.61E-08 | 2.61E-08 | 0.00 | 0.0 |

**Table G.44: Sensitivity Analysis for LCA of PHEV (Crude Oil Extraction Parameter)**

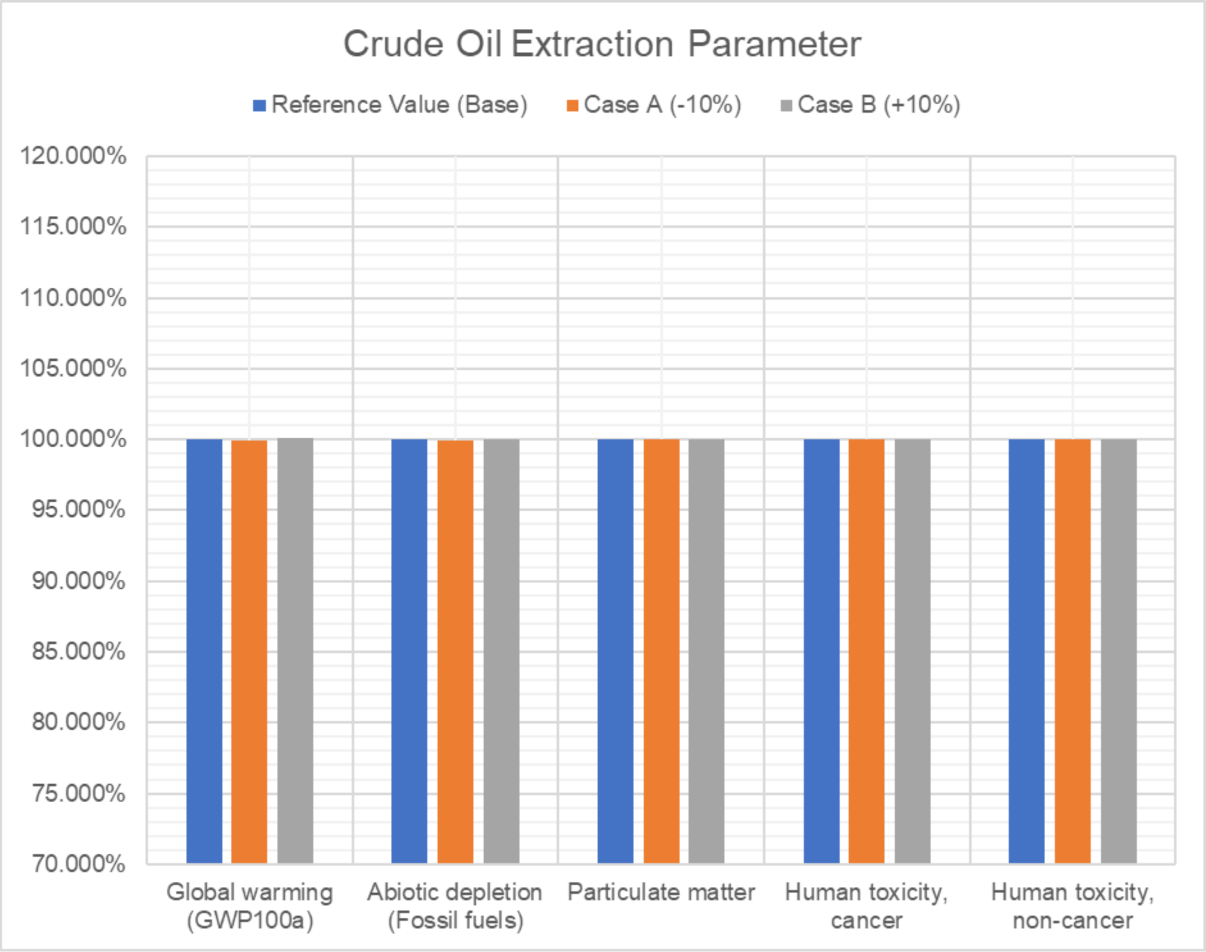


**Figure G.44: Sensitivity Analysis for LCA of PHEV (Crude Oil Extraction Parameter)**

## Fuel Cell Vehicles (FCV)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913 | 0.053237 | 0.043557 | 11.1 | -9.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.651518 | 0.723909 | 0.592289 | 11.1 | -9.09 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.60E-05 | 1.31E-05 | 11.1 | -9.03 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.73E-09 | 1.42E-09 | 10.9 | -9.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 8.92E-09 | 7.30E-09 | 11.08 | -9.1 |

**Figure G.45: Sensitivity Analysis for LCA of FCV (Occupancy Rate Parameter)**

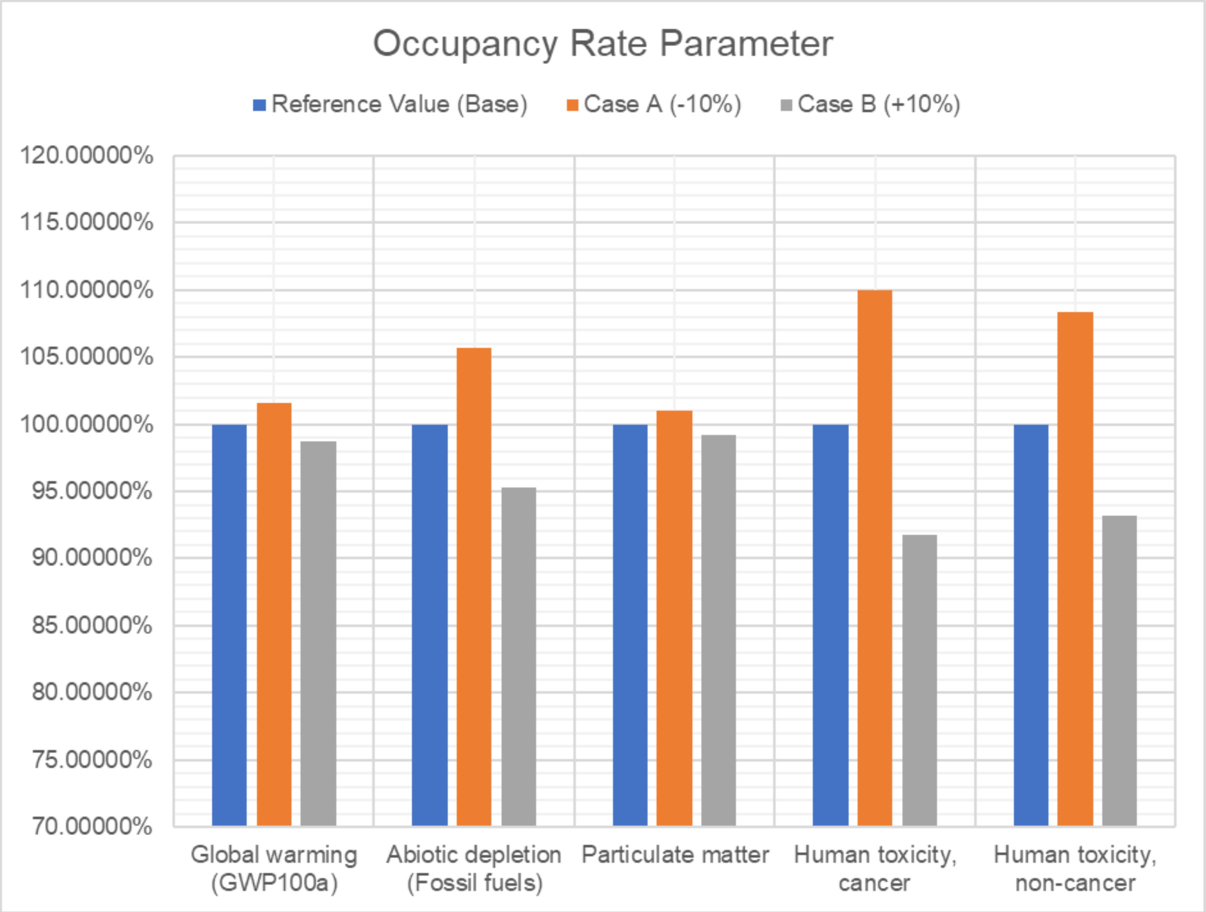


**Figure G.45: Sensitivity Analysis for LCA of FCV (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913068 | 0.044851168 | 0.050974969 | -6.4 | 6.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.65151828 | 0.60926993 | 0.69376663 | -6.5 | 6.48 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.33E-05 | 1.55E-05 | -7.6 | 7.64 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.41E-09 | 1.70E-09 | -9.6 | 9.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 7.53E-09 | 8.53E-09 | -6.23 | 6.2 |

**Table G.46: Sensitivity Analysis for LCA of FCV (Vehicle Manufacture Parameter)**

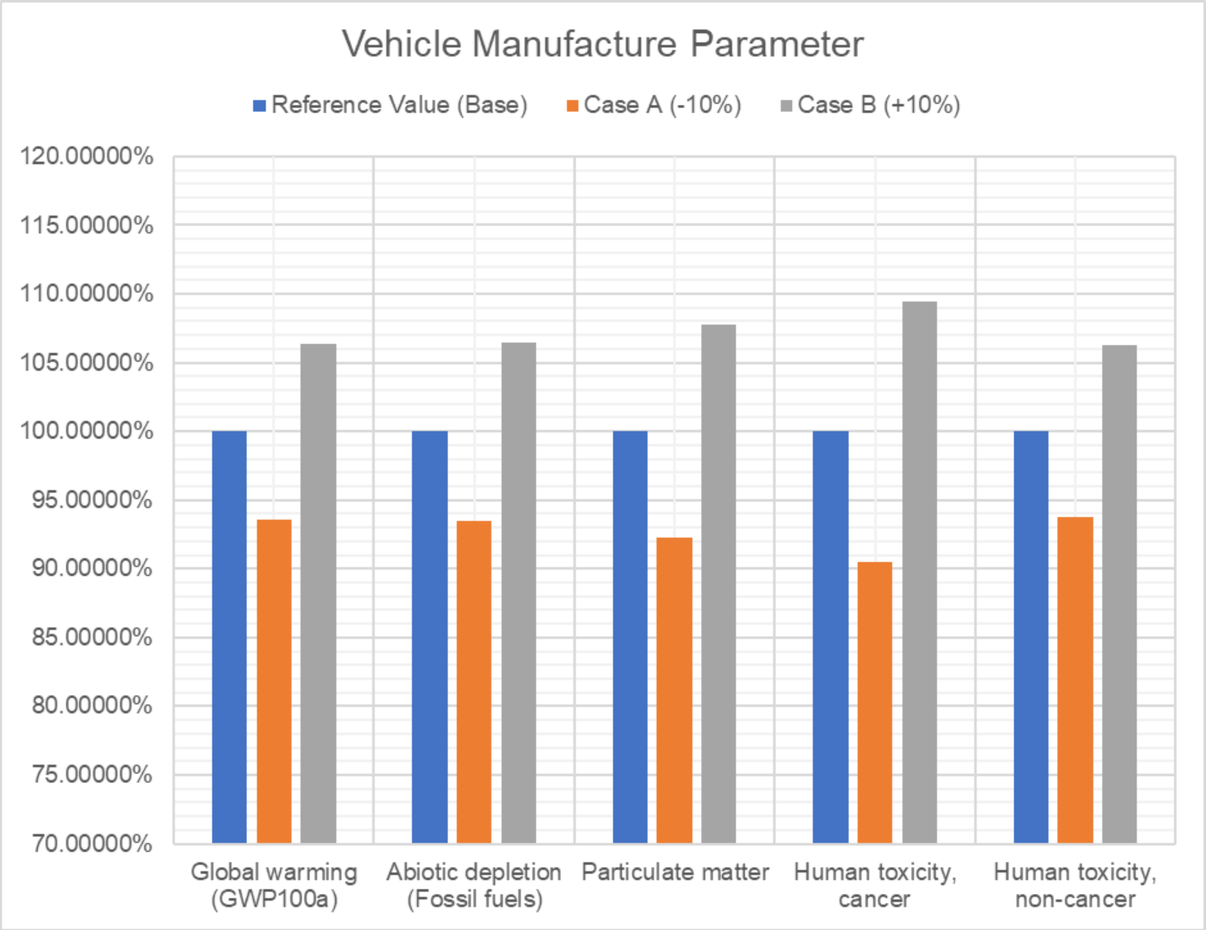


**Figure G.46: Sensitivity Analysis for LCA of FCV (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913 | 0.046998 | 0.048828 | -1.9 | 1.9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.651518 | 0.64111 | 0.661927 | -1.6 | 1.60 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.43E-05 | 1.45E-05 | -0.7 | 0.69 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.55E-09 | 1.56E-09 | -0.6 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 7.84E-09 | 8.23E-09 | -2.37 | 2.5 |

**Figure G.47: Sensitivity Analysis for LCA of FCV (Fuel Consumption Parameter)**

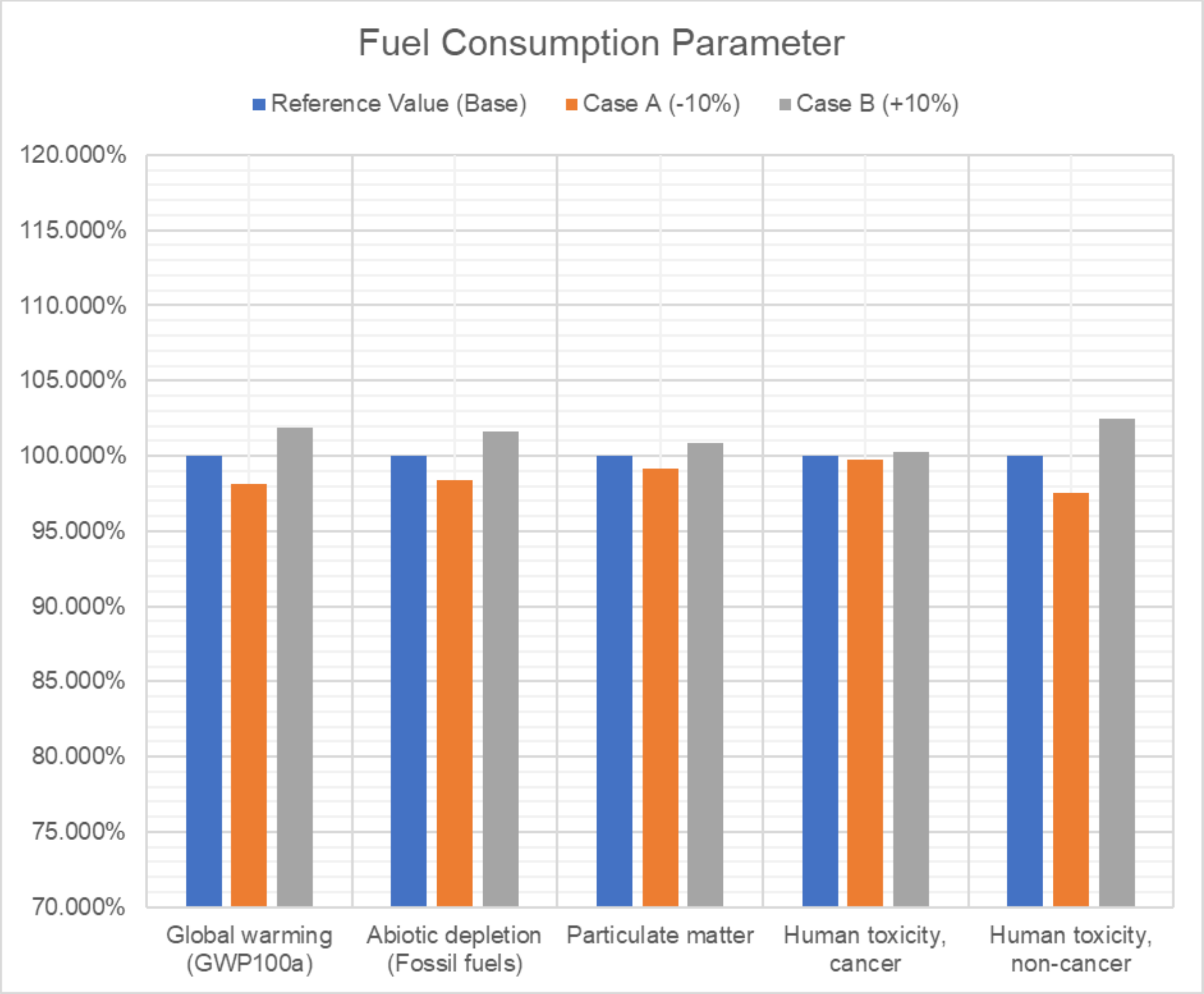


**Figure G.47: Sensitivity Analysis for LCA of FCV (Fuel Consumption Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913068 | 0.047310638 | 0.048515499 | -1.3 | 1.3 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.65151828 | 0.6401943 | 0.66284226 | -1.7 | 1.74 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.42E-05 | 1.46E-05 | -1.4 | 1.39 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.55E-09 | 1.56E-09 | -0.6 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 7.99E-09 | 8.07E-09 | -0.50 | 0.5 |

**Figure G.48: Sensitivity Analysis for LCA of FCV (Vehicle Maintenance Parameter)**

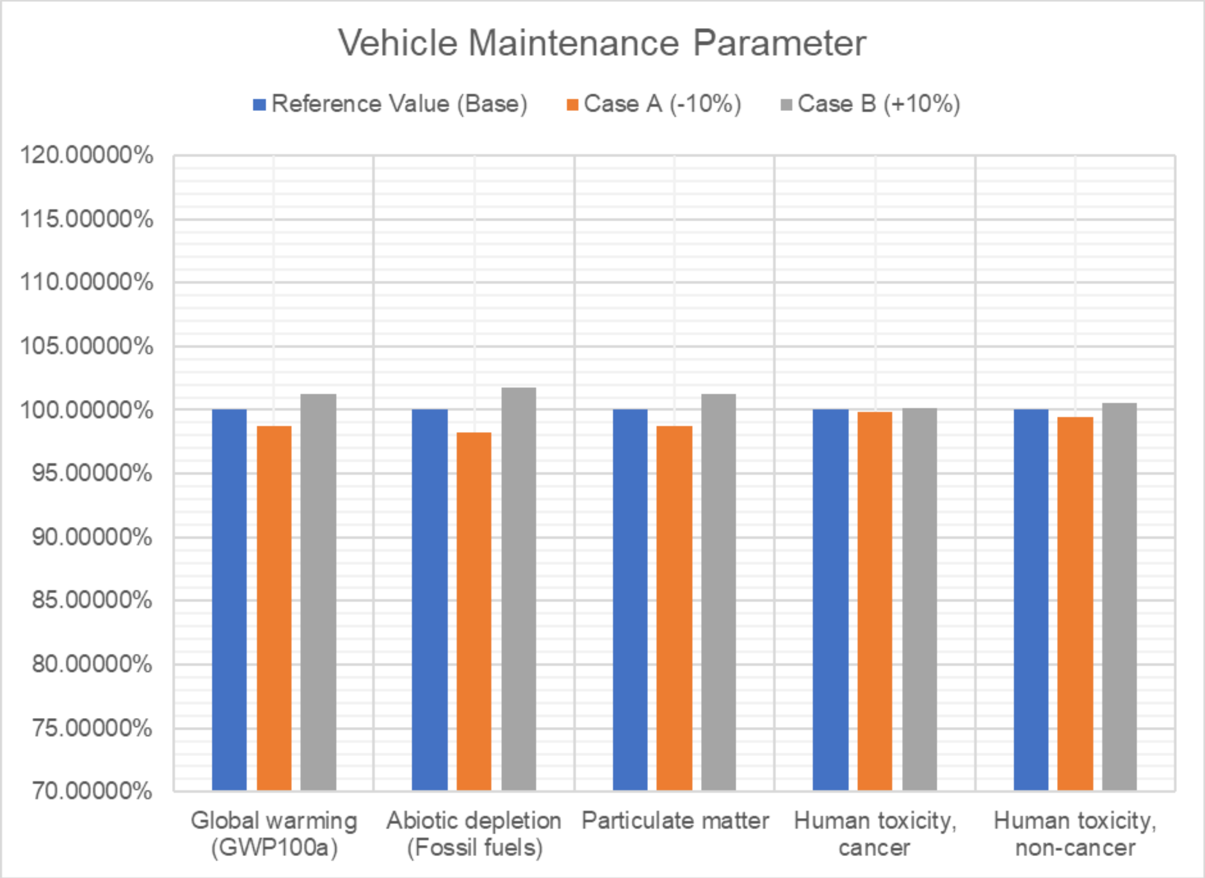


**Figure G.48: Sensitivity Analysis for LCA of FCV (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913 | 0.046998 | 0.048828 | -1.9 | 1.9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.651518 | 0.64111 | 0.661927 | -1.6 | 1.60 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.43E-05 | 1.45E-05 | -0.7 | 0.69 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.55E-09 | 1.56E-09 | -0.6 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 7.84E-09 | 8.23E-09 | -2.37 | 2.5 |

**Table G.49: Sensitivity Analysis for LCA of FCV (Hydrogen Production Parameter)**

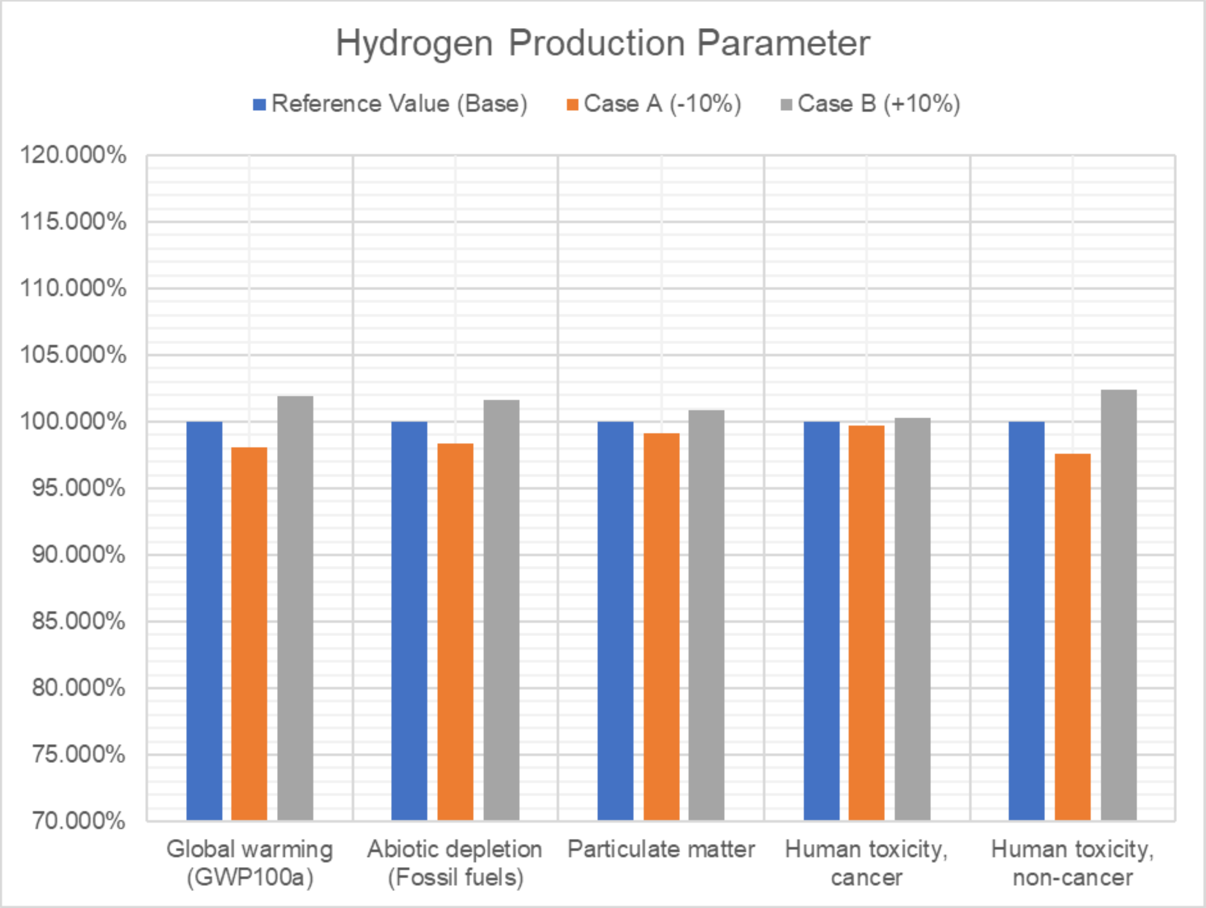


**Figure G.49: Sensitivity Analysis for LCA of FCV (Hydrogen Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913 | 0.047701 | 0.048125 | -0.4 | 0.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.651518 | 0.650347 | 0.652689 | -0.2 | 0.18 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.44E-05 | 1.44E-05 | 0.0 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.56E-09 | 1.56E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 7.96E-09 | 8.10E-09 | -0.87 | 0.9 |

**Table G.50: Sensitivity Analysis for LCA of FCV (Vehicle Disposal Parameter)**

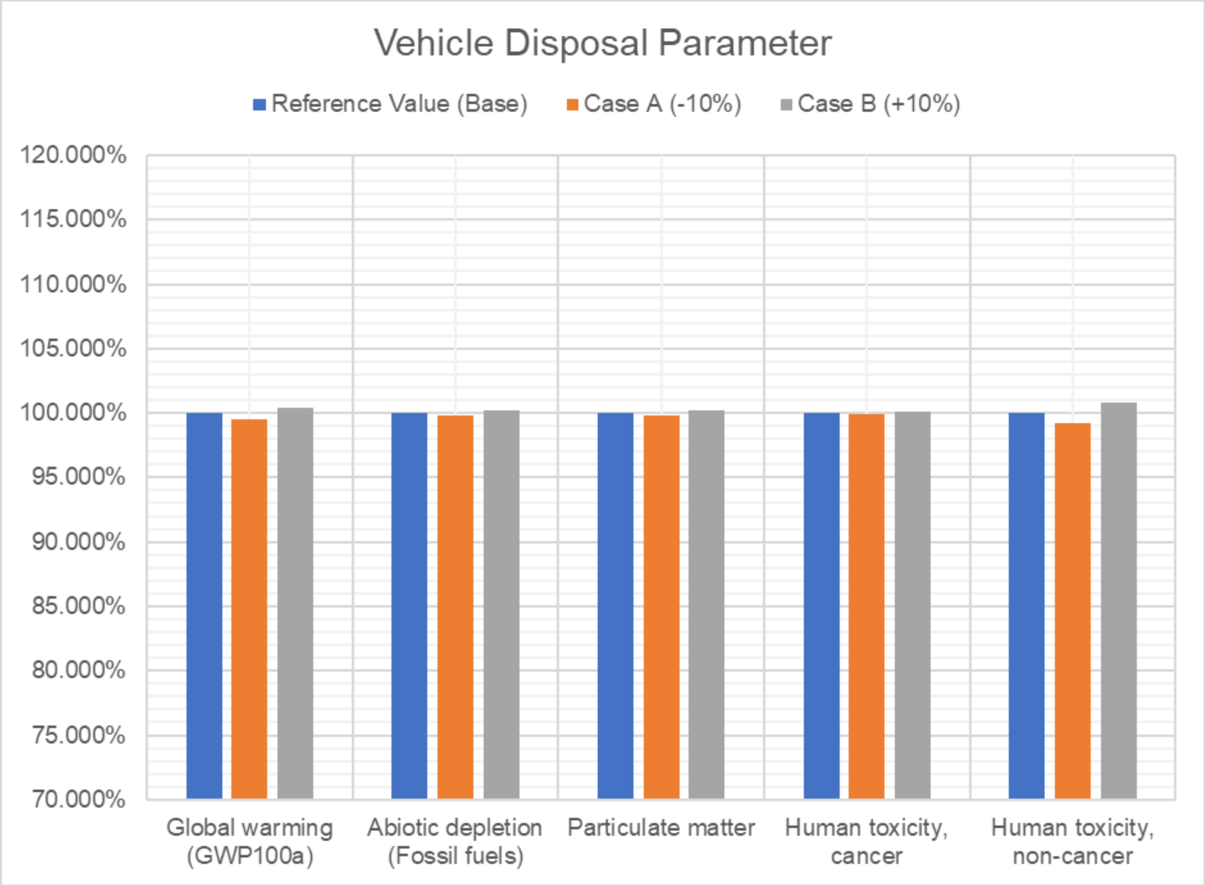


**Figure G.50: Sensitivity Analysis for LCA of FCV (Vehicle Disposal Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.047913068 | 0.047913056 | 0.04791308 | -0.00003 | 0.00003 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.65151828 | 0.65151814 | 0.65151842 | -0.000021 | 0.000021 |
| **Particulate Matter (kg/pkm)** | 1.44E-05 | 1.44E-05 | 1.44E-05 | 0.00000 | 0.000000 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.56E-09 | 1.56E-09 | 1.56E-09 | 0.0000 | 0.00000 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.03E-09 | 8.03E-09 | 8.03E-09 | 0.00000 | 0.00000 |

**Table G.51: Sensitivity analysis for LCA of FCV (Hydrogen Processing Parameter)**

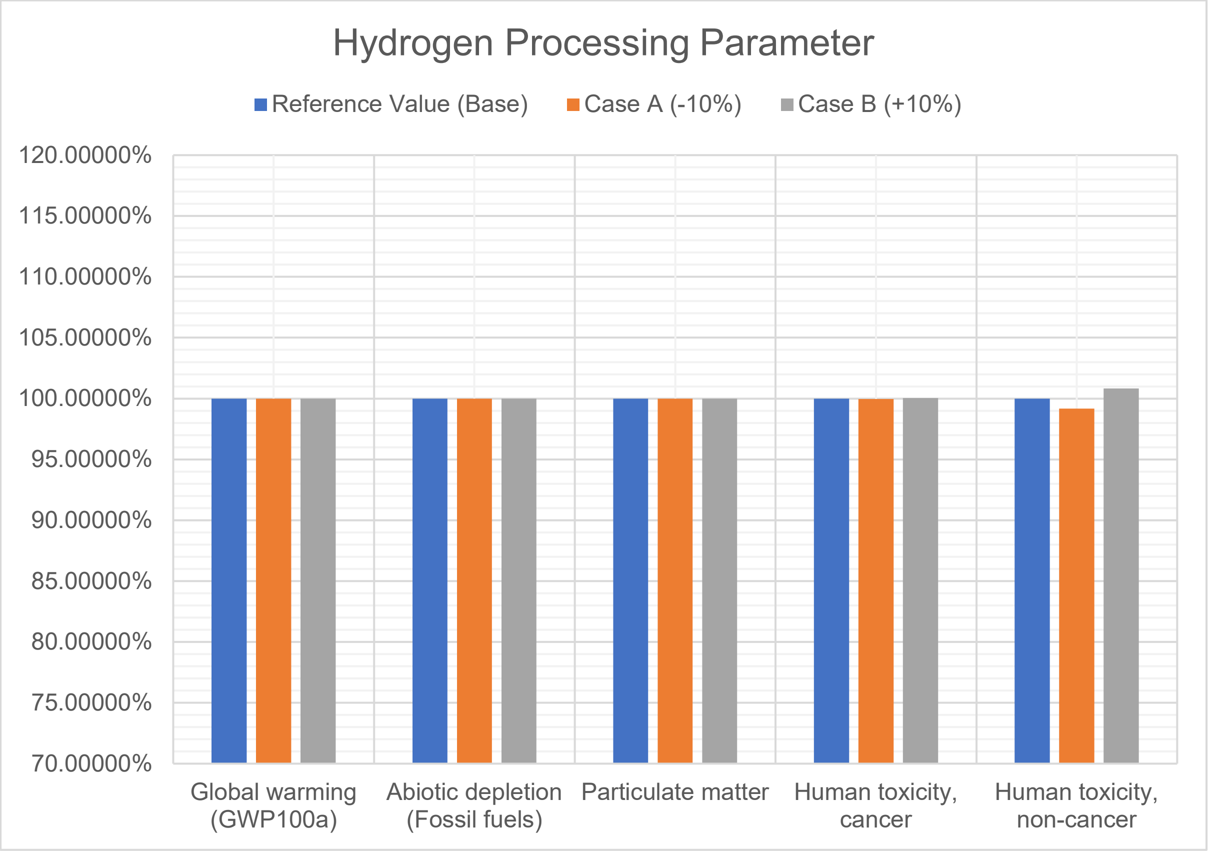


**Figure G.51: Sensitivity Analysis for LCA of FCV (Hydrogen Processing Parameter)**

## Battery Electric Vehicles (BEV)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.158228 | 0.175808 | 0.143843 | 11.1 | -9.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.933596 | 2.14844 | 1.757814 | 11.1 | -9.09 |
| **Particulate Matter (kg/pkm)** | 3.65E-05 | 4.05E-05 | 3.32E-05 | 11.0 | -9.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.45E-09 | 2.00E-09 | 11.4 | -9.1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.89E-08 | 2.10E-08 | 1.72E-08 | 11.11 | -9.0 |

Table G.52: Sensitivity Analysis for LCA of BEV (Occupancy Rate Parameter)

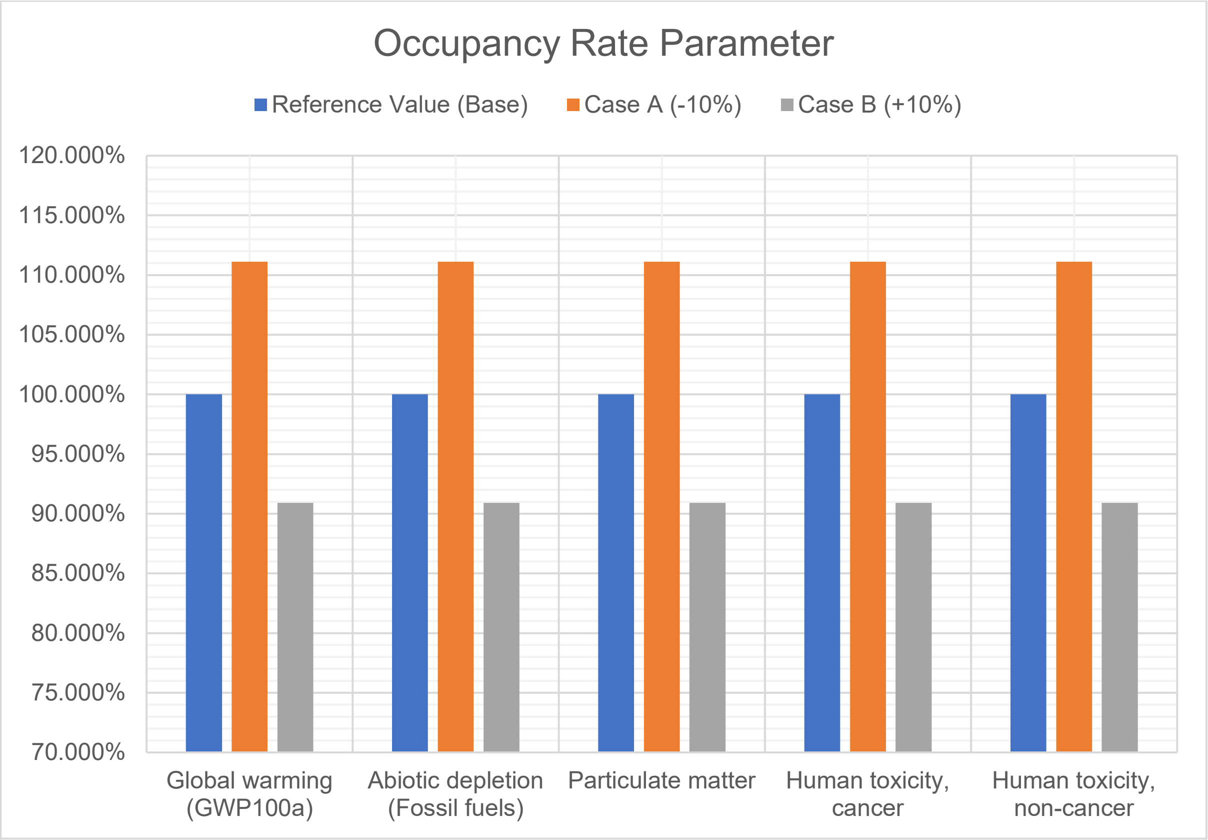


Figure G.52: Sensitivity Analysis for LCA of BEV (Occupancy Rate Parameter)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.158228 | 0.169038 | 0.149382 | 6.8 | -5.6 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.933596 | 2.056707 | 1.832869 | 6.4 | -5.21 |
| **Particulate Matter (kg/pkm)** | 3.65E-05 | 3.76E-05 | 3.55E-05 | 3.0 | -2.74 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.22E-09 | 2.18E-09 | 0.9 | -0.9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.89E-08 | 1.93E-08 | 1.86E-08 | 2.12 | -1.6 |

**Figure G.53: Sensitivity Analysis for LCA of BEV (Kilometre Travelled Parameter)**

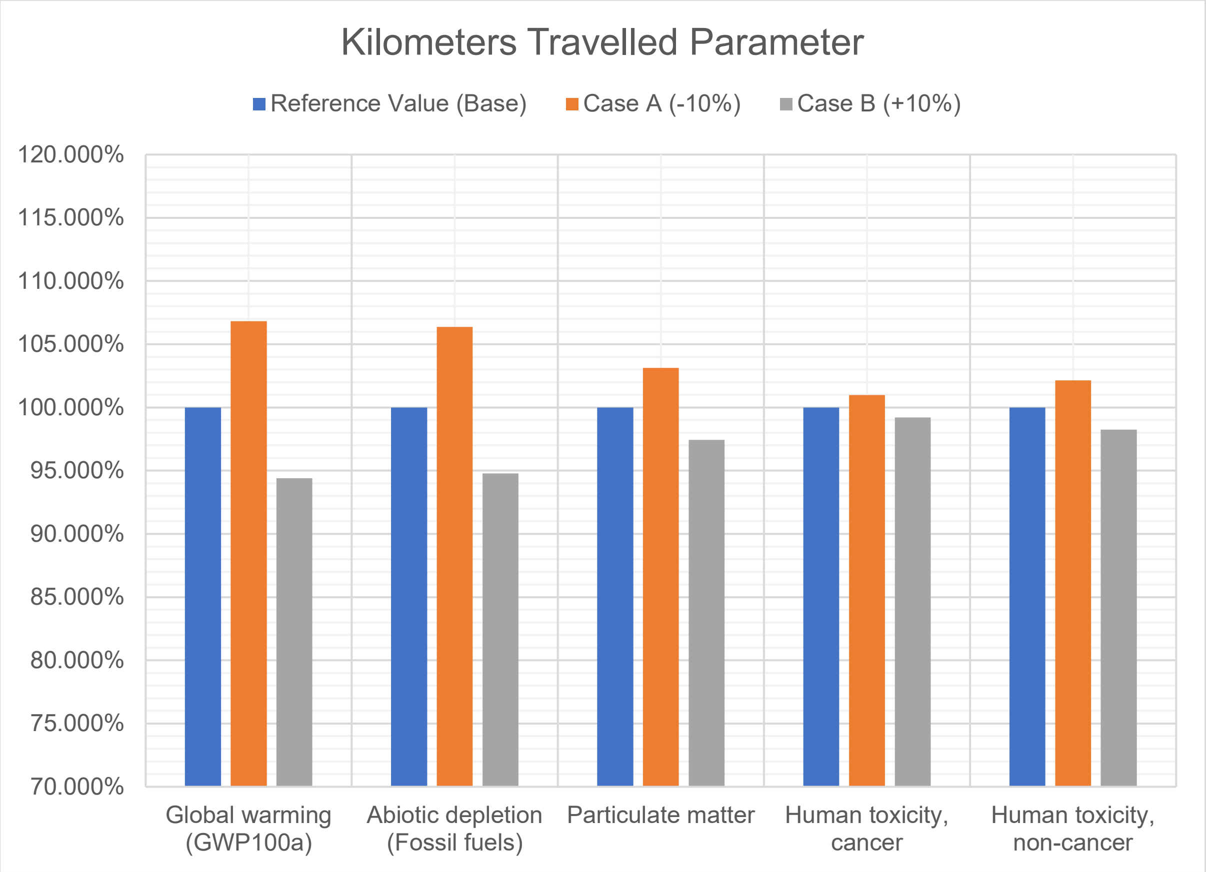


**Figure G.53: Sensitivity analysis for LCA of BEV (Kilometre Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.158228 | 0.148498 | 0.167957 | -6.1 | 6.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.933596 | 1.822796 | 2.044395 | -5.7 | 5.73 |
| **Particulate Matter (kg/pkm)** | 3.65E-05 | 3.54E-05 | 3.75E-05 | -3.0 | 2.74 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.18E-09 | 2.22E-09 | -0.9 | 0.9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.89E-08 | 1.85E-08 | 1.93E-08 | -2.12 | 2.1 |

**Table G.54: Sensitivity Analysis for LCA of BEV (Vehicle Manufacture Parameter)**

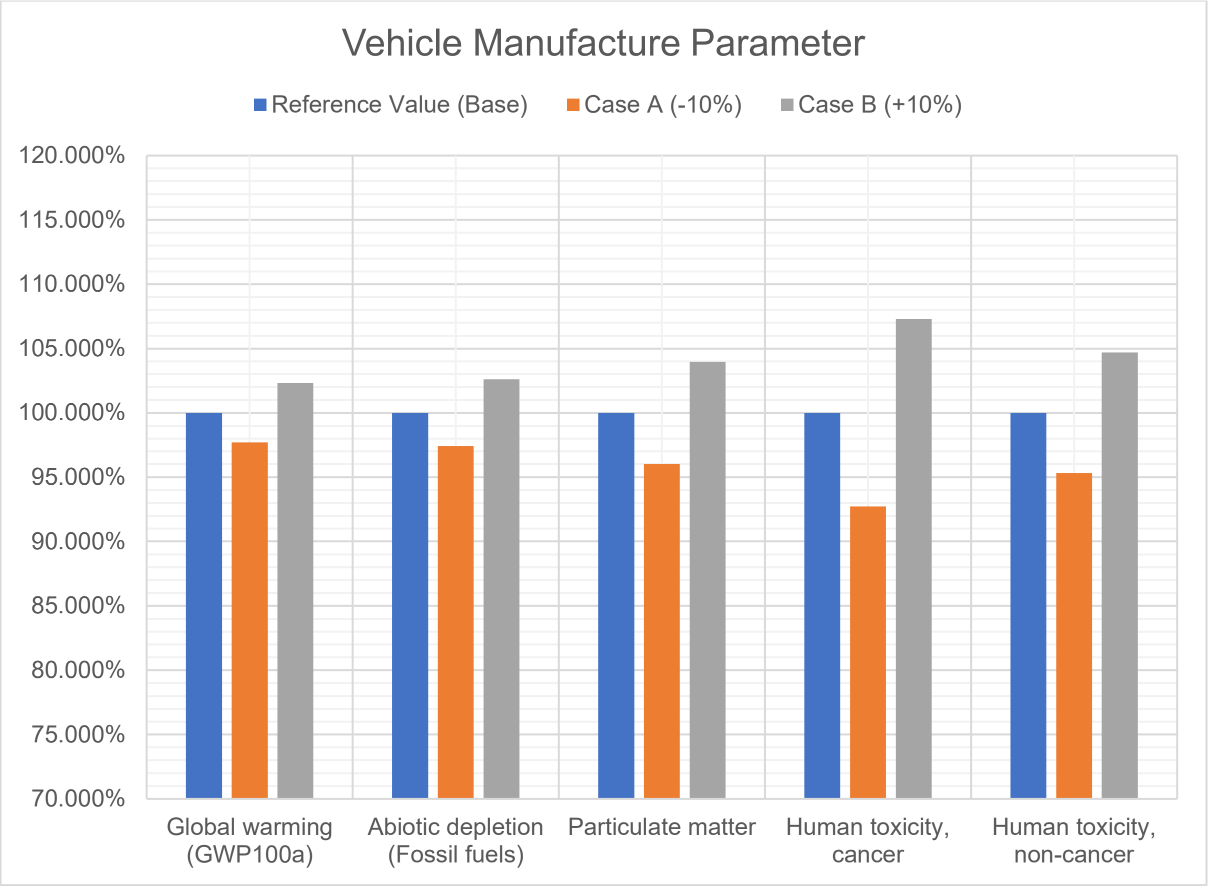


**Figure G.54: Sensitivity Analysis for LCA of BEV (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.158228 | 0.156191 | 0.160264 | -1.3 | 1.3 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.933596 | 1.904379 | 1.962812 | -1.5 | 1.51 |
| **Particulate Matter (kg/pkm)** | 3.65E-05 | 3.54E-05 | 3.75E-05 | -3.0 | 2.74 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.16E-09 | 2.24E-09 | -1.8 | 1.8 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.89E-08 | 1.84E-08 | 1.95E-08 | -2.65 | 3.2 |

**Figure G.55: Sensitivity Analysis for LCA of BEV (Vehicle Maintenance Parameter)**

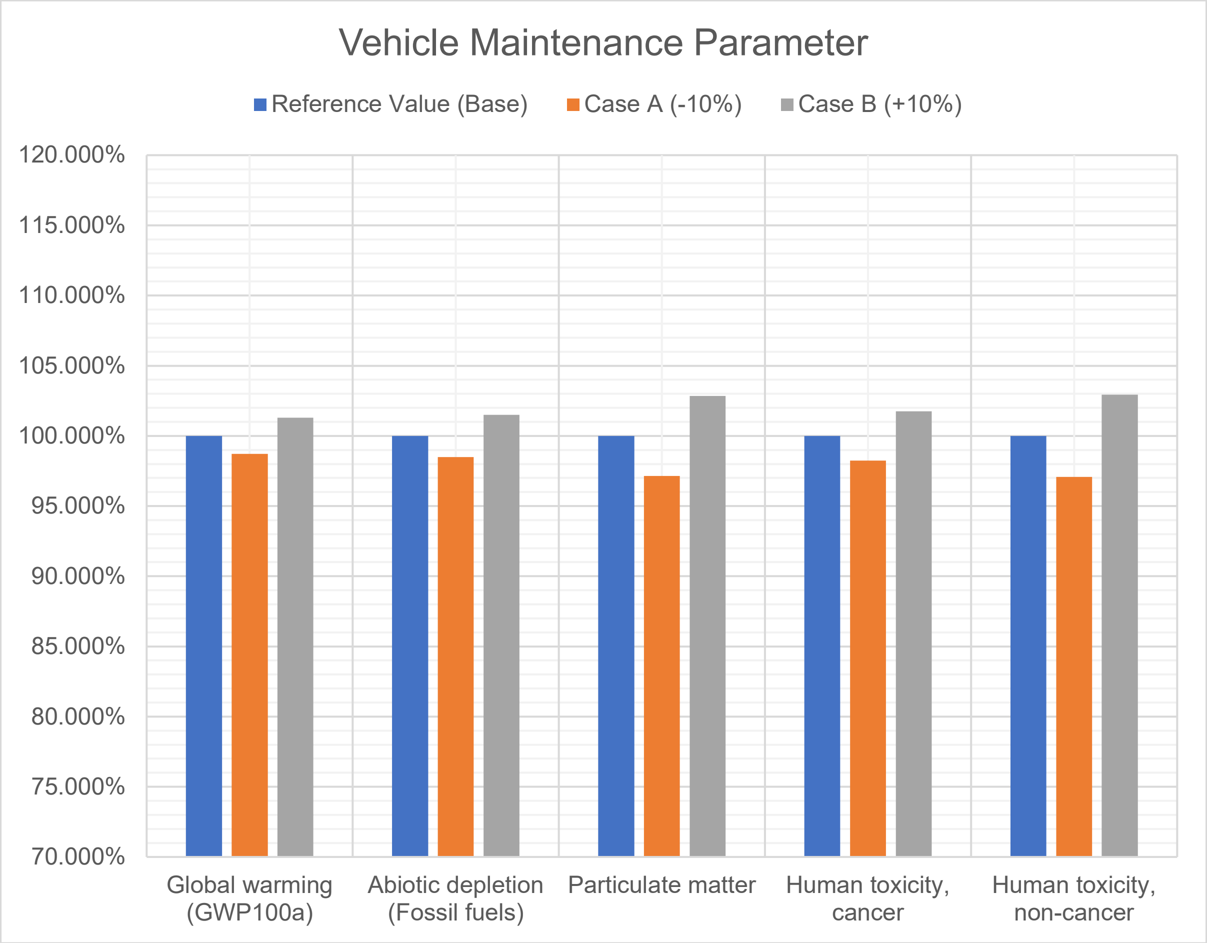


**Figure G.55: Sensitivity Analysis for LCA of BEV (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.158228 | 0.157801 | 0.158654 | -0.3 | 0.3 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.933596 | 1.930572 | 1.936619 | -0.2 | 0.16 |
| **Particulate Matter (kg/pkm)** | 3.65E-05 | 3.63E-05 | 3.66E-05 | -0.5 | 0.27 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.20E-09 | 2.20E-09 | 0.0 | 0.0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.89E-08 | 1.88E-08 | 1.90E-08 | -0.53 | 0.5 |

**Table G.56: Sensitivity Analysis for LCA of BEV (Vehicle Disposal Parameter)**

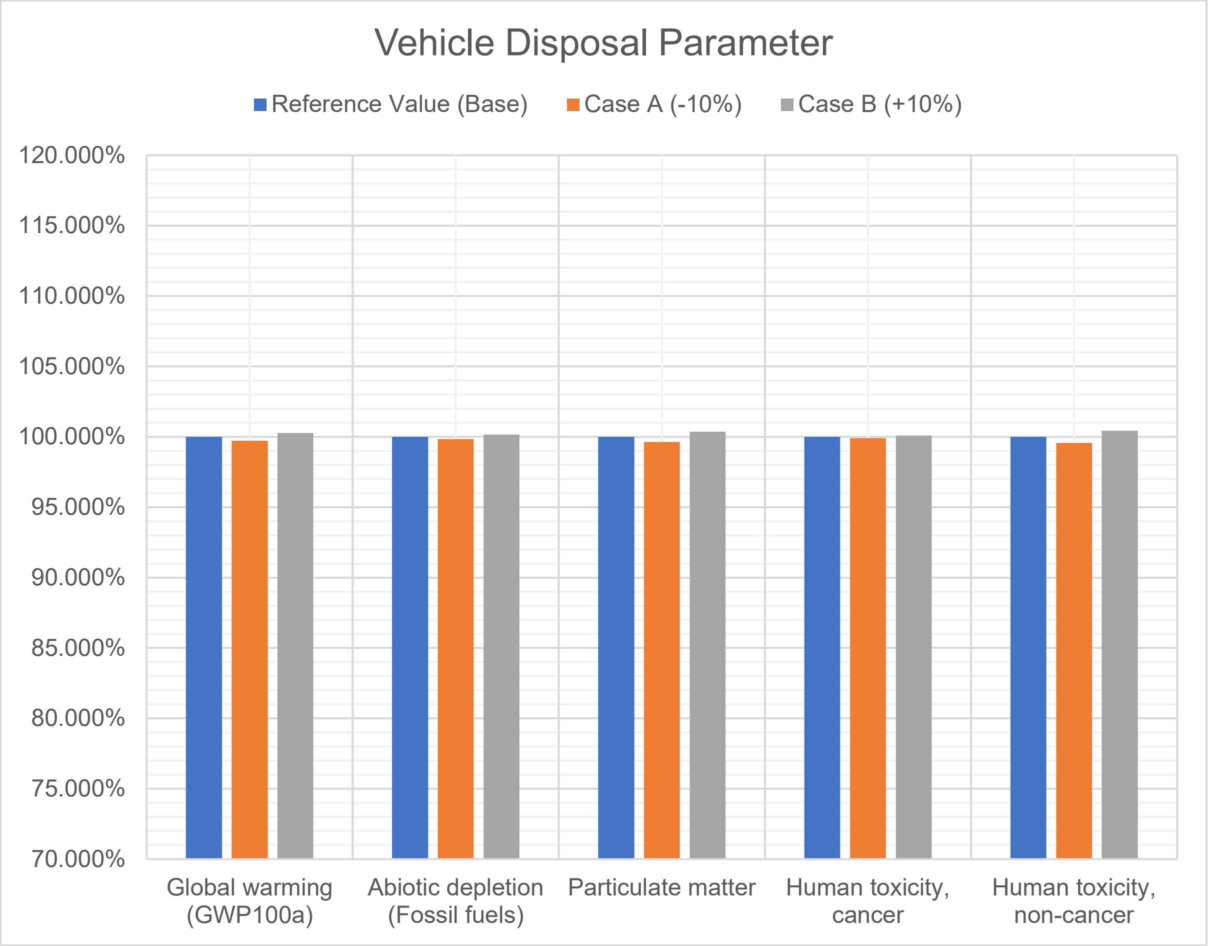


**Figure G.56: Sensitivity Analysis for LCA of BEV (Vehicle Disposal Parameter)**

### Low Sulphur Diesel Buses (LSD)

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.073333086 | 0.064064432 | 7 | -6 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.87248478 | 0.76326443 | 7 | -6 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.88E-05 | 4.90E-05 | 10 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.44E-10 | 4.38E-10 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.29E-09 | 2.24E-09 | 1 | -1 |

**Table G.57: Sensitivity Analysis of LCA of LSD Buses (Kilometre Travelled Parameter)**

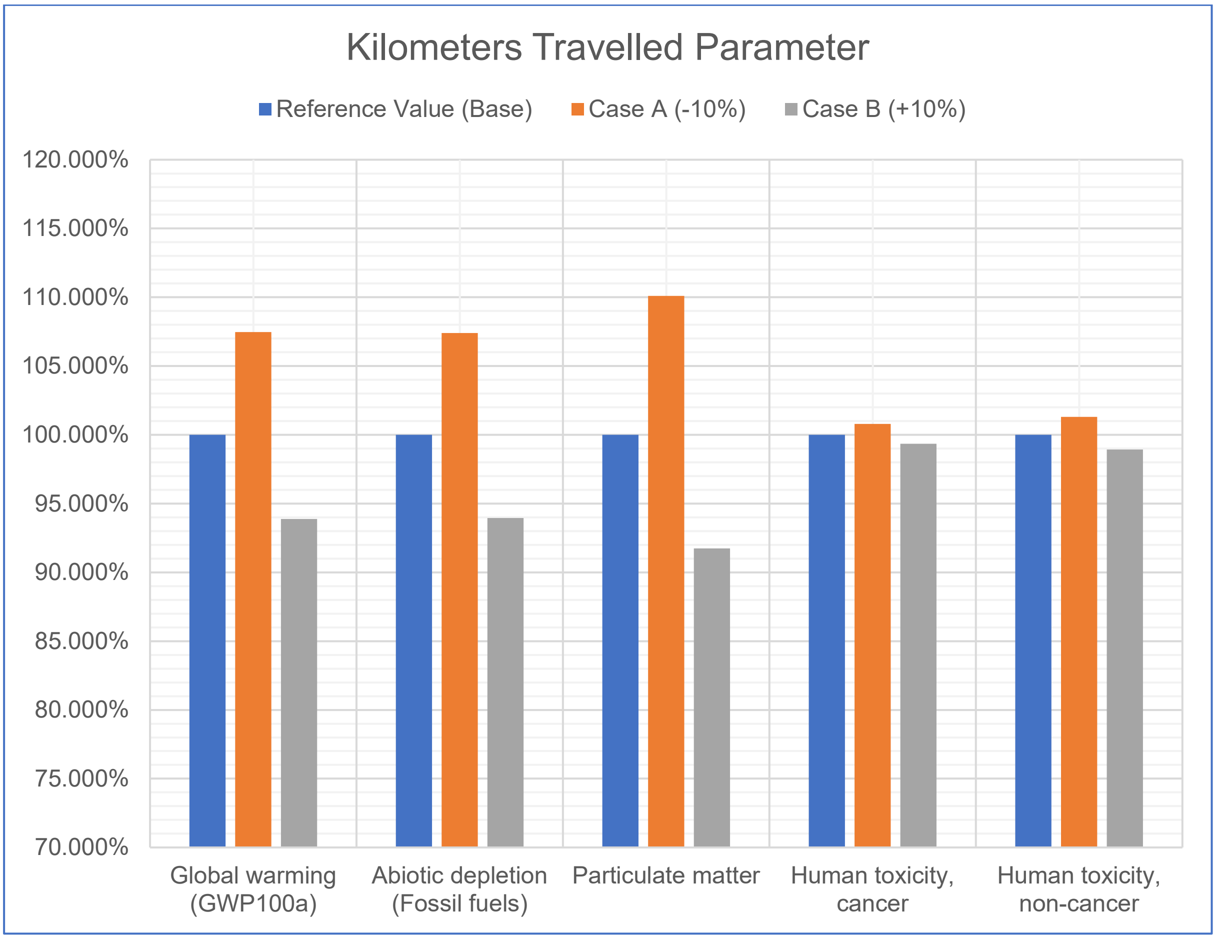


**Figure G.57: Sensitivity Analysis of LCA of LSD Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.063647343 | 0.07282331 | -7 | 7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.75834951 | 0.86647767 | -7 | 7 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 4.85E-05 | 5.82E-05 | -9 | 9 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.38E-10 | 4.44E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.24E-09 | 2.29E-09 | -1 | 1 |

**Table G.58: Sensitivity Analysis for LCA of LSD Buses (Fuel Consumption Parameter)**

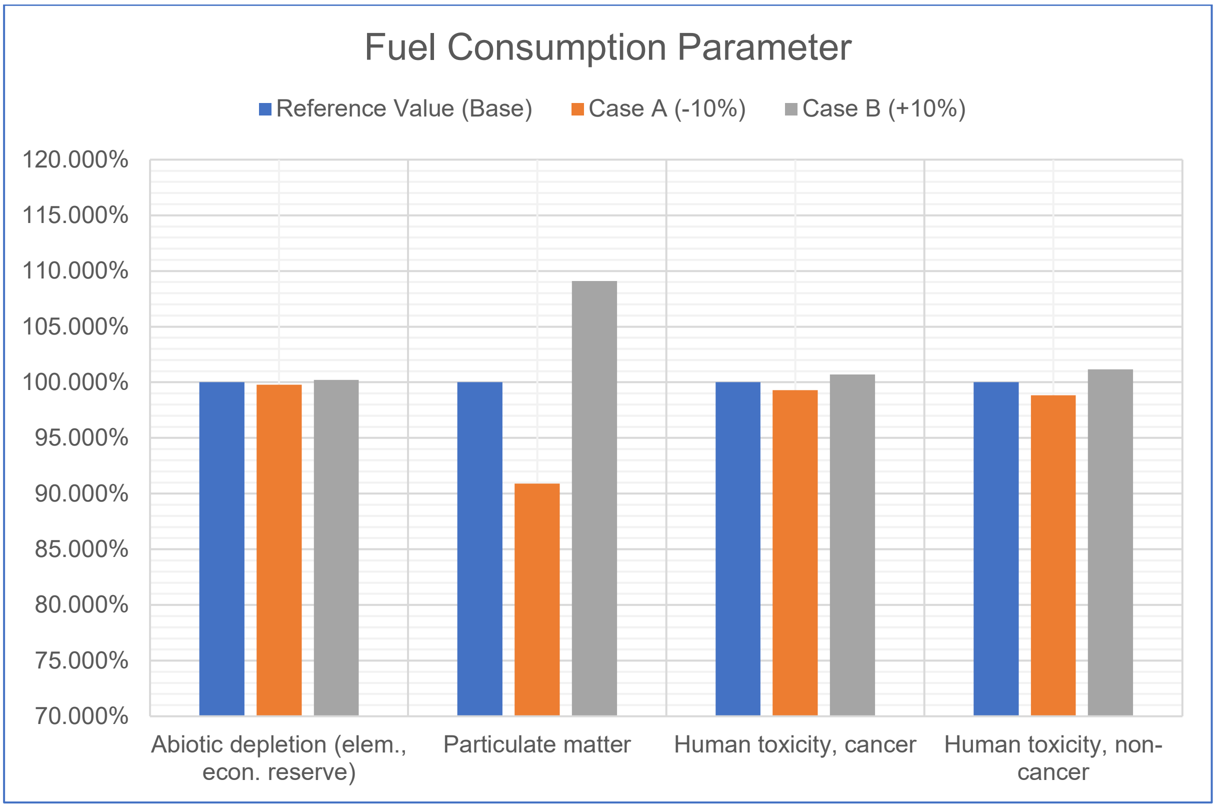


**Figure G.58: Sensitivity Analysis for LCA of LSD Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.075817029 | 0.062032115 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.90268177 | 0.73855781 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.93E-05 | 4.85E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.90E-10 | 4.01E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.52E-09 | 2.06E-09 | 11 | -9 |

**Table G.59: Sensitivity Analysis for LCA of LSD Buses (Occupancy Rate Parameter)**

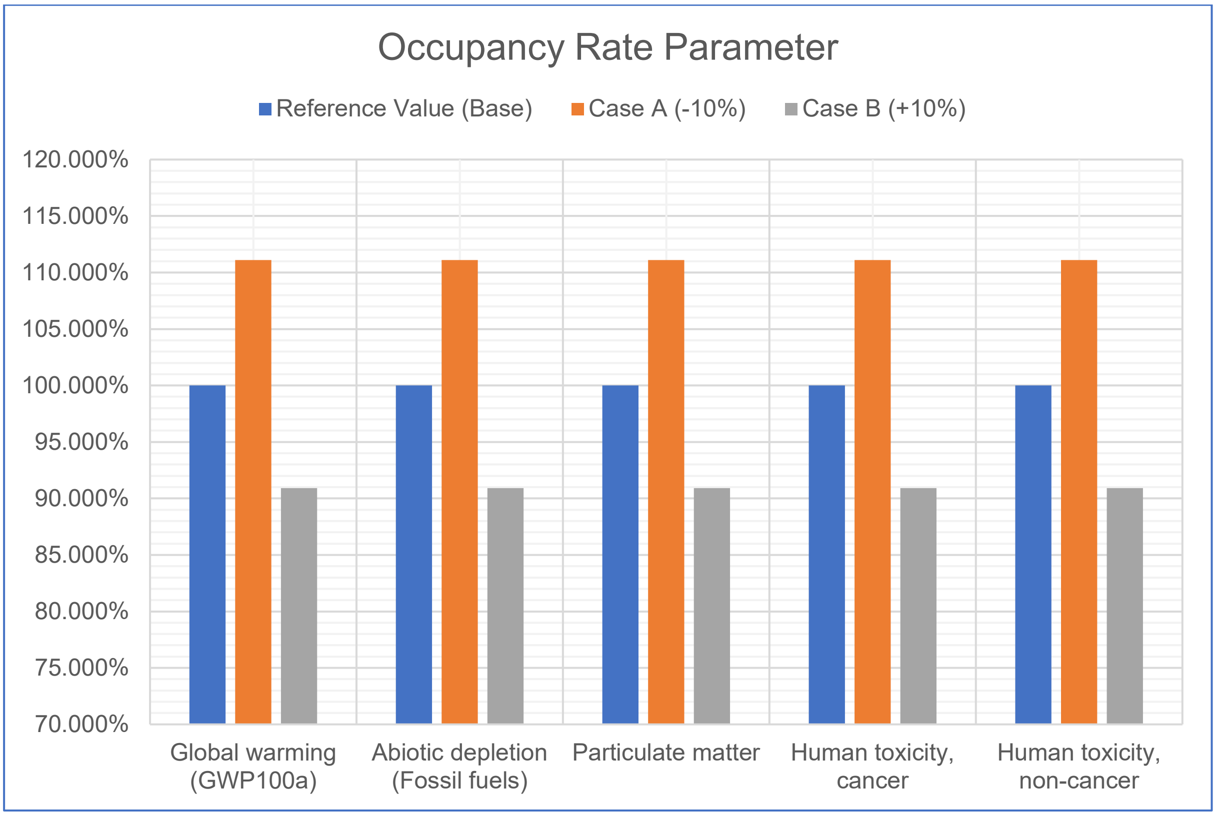


**Figure G.59: Sensitivity Analysis for LCA of LSD Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.067350757 | 0.069119895 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.80124753 | 0.82357965 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.31E-05 | 5.37E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.03E-10 | 4.79E-10 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.14E-09 | 2.39E-09 | -6 | 6 |

**Table G.60: Sensitivity Analysis for LCA of LSD Buses (Vehicle Manufacture Parameter)**

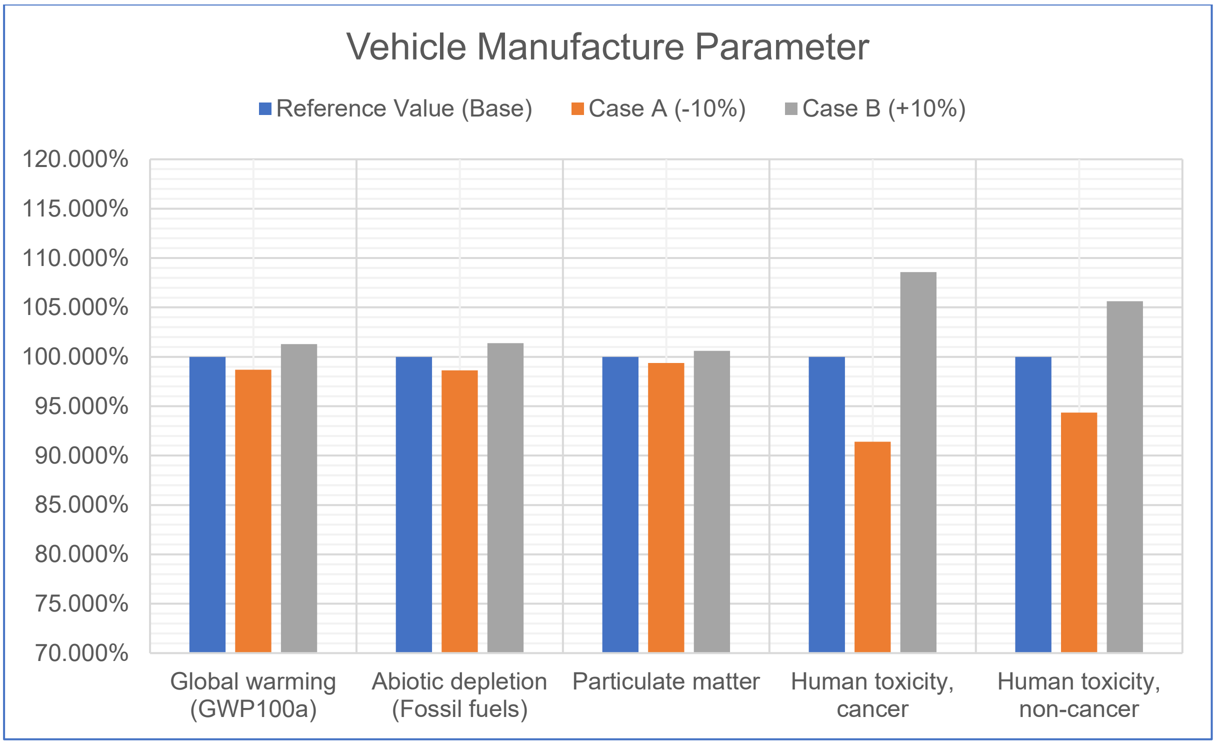


**Figure G.60: Sensitivity Analysis for LCA of LSD Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.068194307 | 0.068276345 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.79879704 | 0.82603014 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.34E-05 | 5.34E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.41E-10 | 4.41E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.26E-09 | 2.27E-09 | 0 | 0 |

**Table G.61: Sensitivity Analysis for LCA of LSD Buses (Crude Oil Extraction Parameter)**

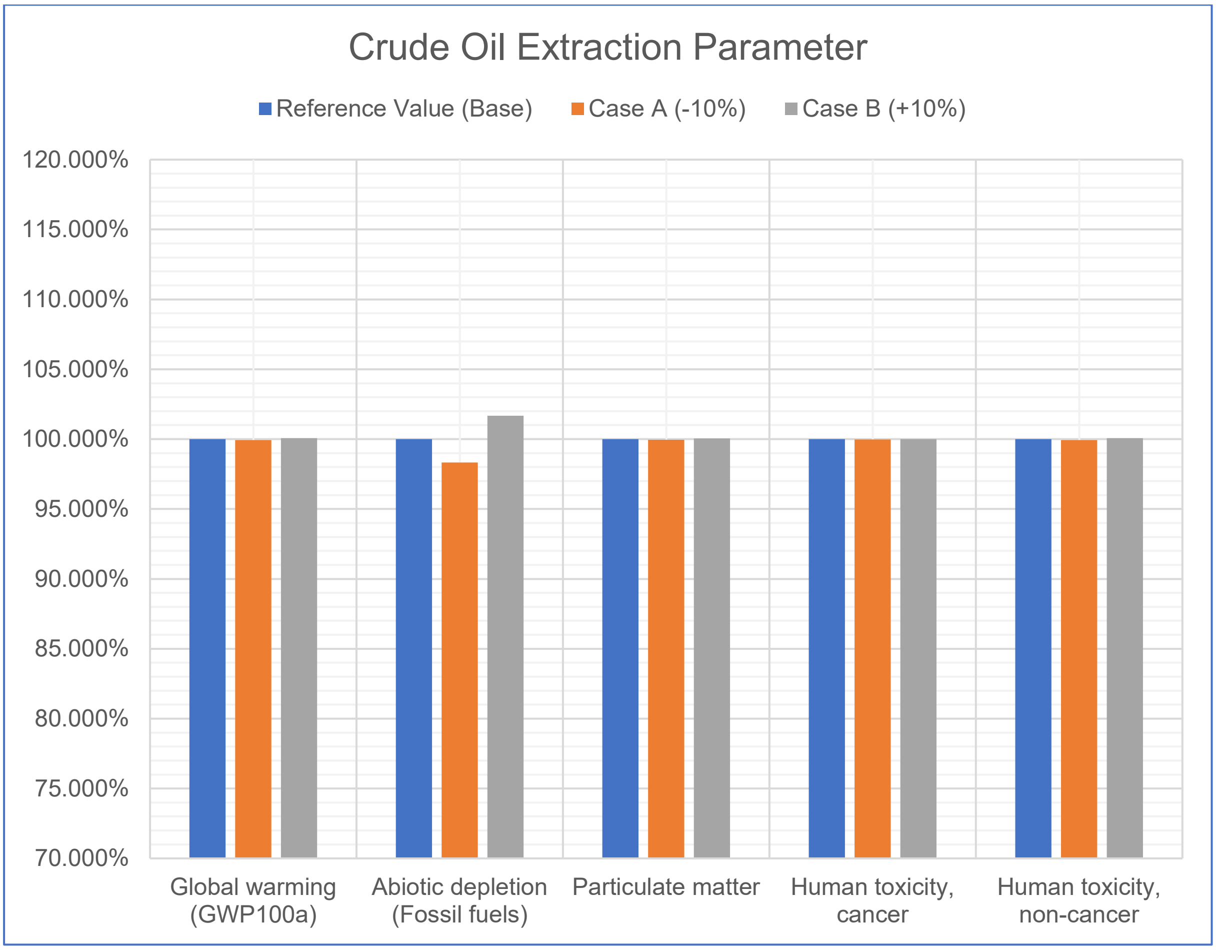


**Figure G.61: Sensitivity Analysis for LCA of LSD Buses (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.067907528 | 0.068563124 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.76556345 | 0.85926373 | -6 | 6 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.31E-05 | 5.37E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.39E-10 | 4.43E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.25E-09 | 2.28E-09 | -1 | 1 |

**Table G.62: Sensitivity Analysis for LCA of LSD Buses (Crude Oil Refining Parameter)**

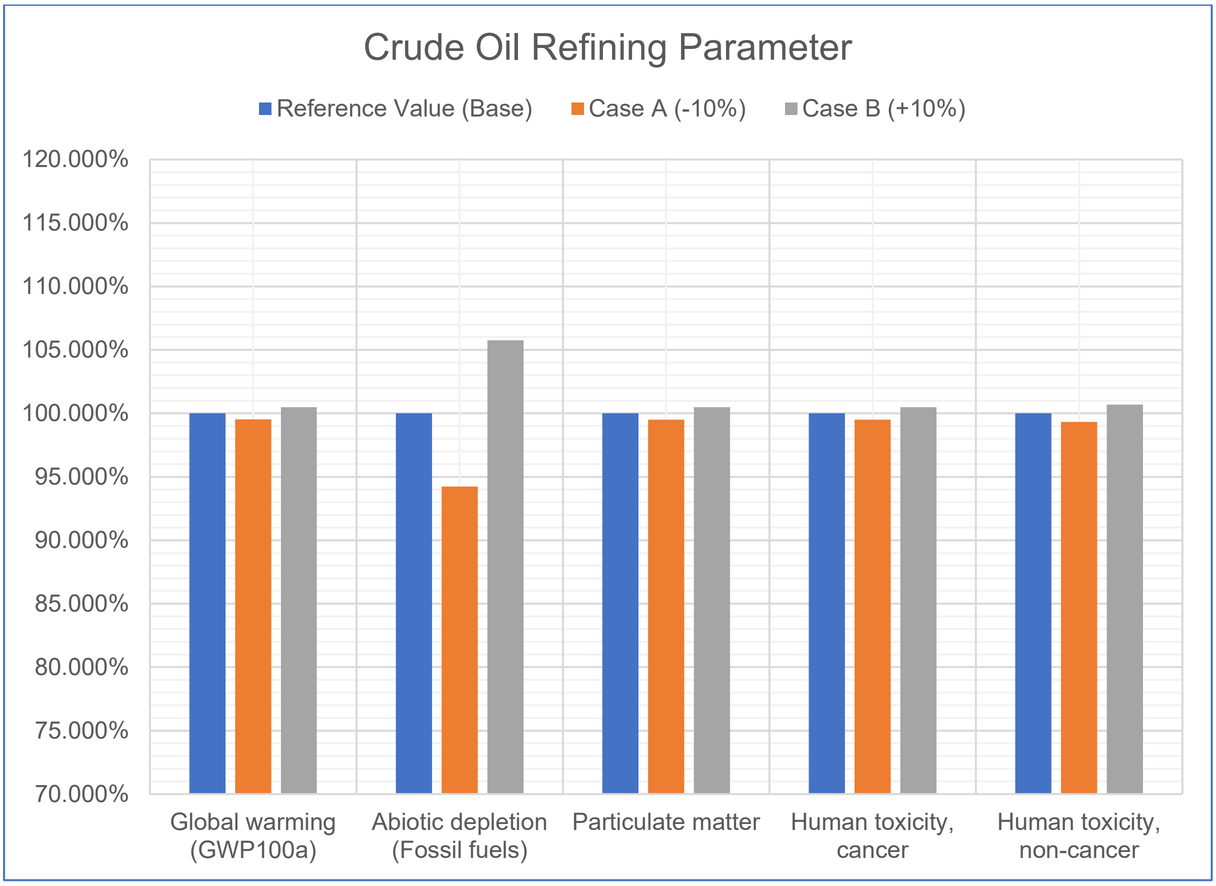


**Figure G.62: Sensitivity Analysis for LCA of LSD Buses (Crude Oil Refining Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.066907686 | 0.069562967 | -2 | 2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.79641098 | 0.8284162 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.32E-05 | 5.35E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.38E-10 | 4.44E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.19E-09 | 2.34E-09 | -3 | 3 |

**Table G.63: Sensitivity Analysis for LCA of LSD Buses (Vehicle Maintenance Parameter)**

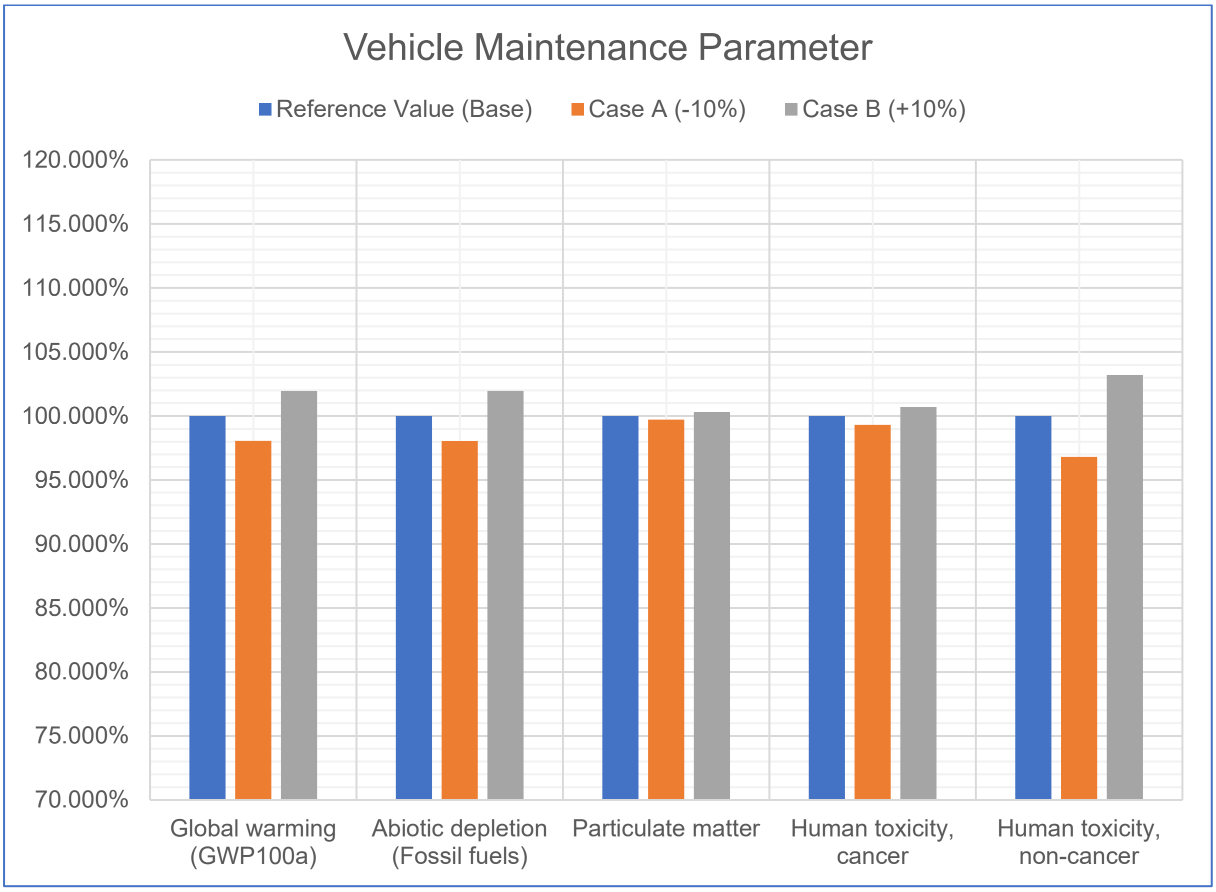


**Figure G.63: Sensitivity Analysis for LCA of LSD Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.068235326 | 0.068211987 | 0.068258666 | -0.03 | 0.03 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.81241359 | 0.81240498 | 0.8124222 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 5.34E-05 | 5.34E-05 | 5.34E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.41E-10 | 4.41E-10 | 4.41E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.26E-09 | 2.26E-09 | 2.26E-09 | -0.01 | 0.01 |

**Table G.64: Sensitivity Analysis for LCA of LSD Buses (Vehicle Disposal Parameter)**

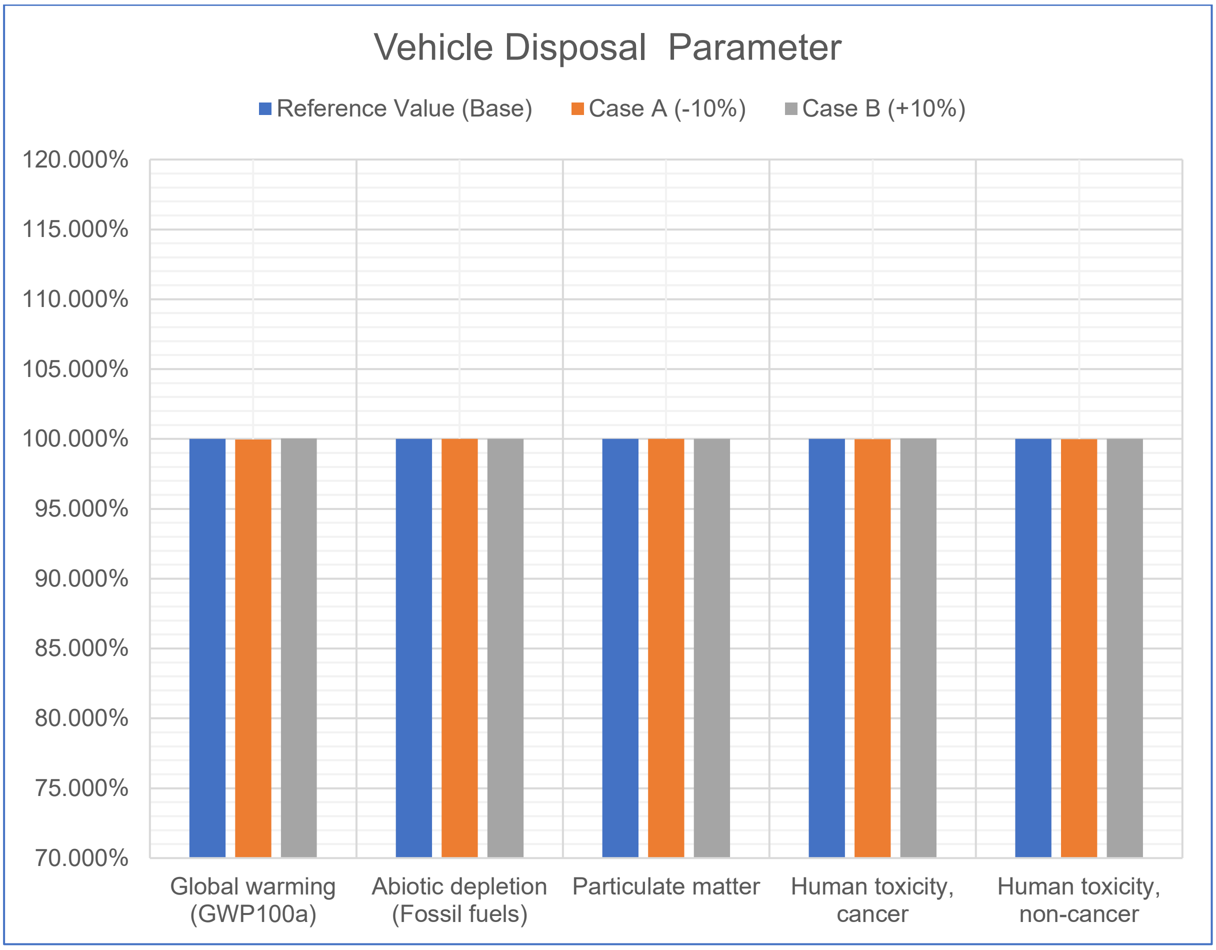


**Figure G.64: Sensitivity Analysis for LCA of LSD Buses (Vehicle Disposal Parameter)**

## Compressed Natural Gas Buses (CNG)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.025001709 | 0.020455944 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.31834875 | 0.26046716 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 5.71E-06 | 4.67E-06 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.55E-10 | 3.72E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 2.24E-09 | 1.83E-09 | 11 | -9 |

Table G.65: Sensitivity Analysis for LCA of CNG Buses (Occupancy Rate Parameter)

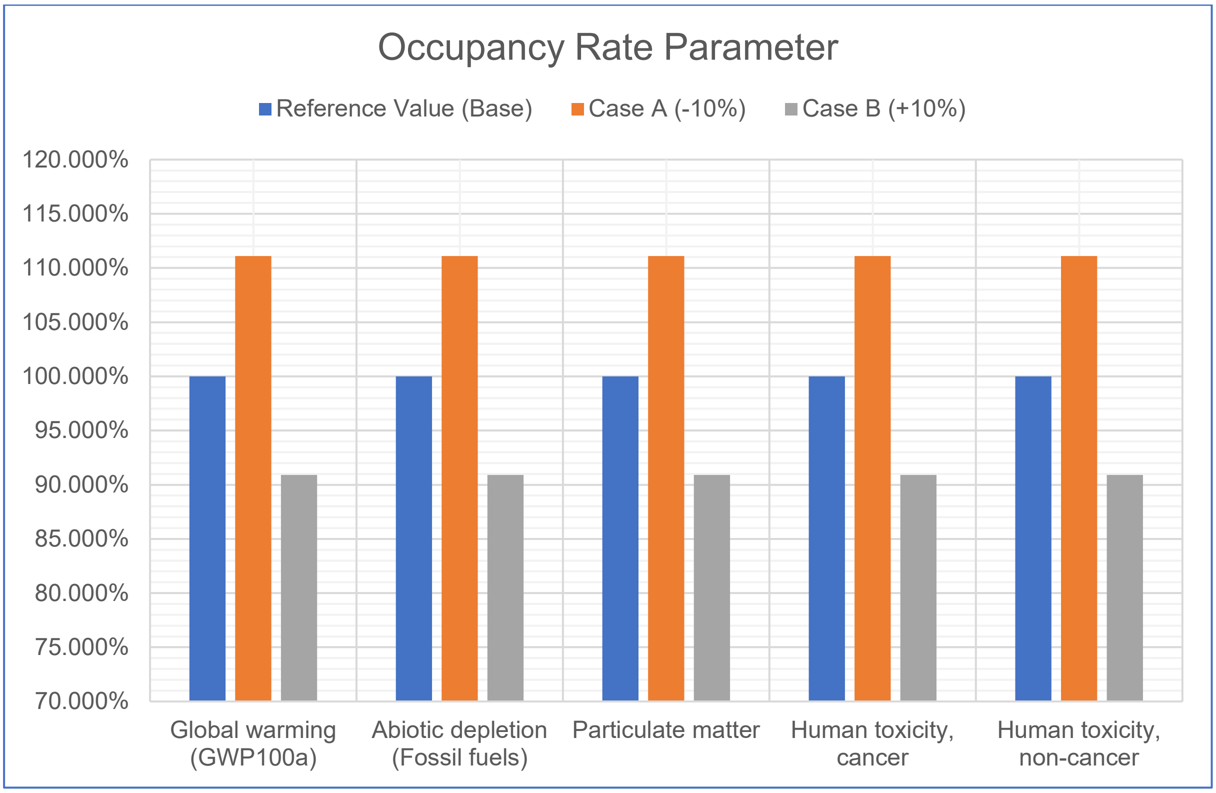


Figure G.65: Sensitivity Analysis for LCA of CNG Buses (Occupancy Rate Parameter)

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.021173898 | 0.023829179 | -6 | 6 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.27051127 | 0.30251649 | -6 | 6 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 4.99E-06 | 5.29E-06 | -3 | 3 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.07E-10 | 4.13E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 1.94E-09 | 2.08E-09 | -4 | 4 |

**Table G.66: Sensitivity Analysis for LCA of CNG Buses (Vehicle Maintenance Parameter)**

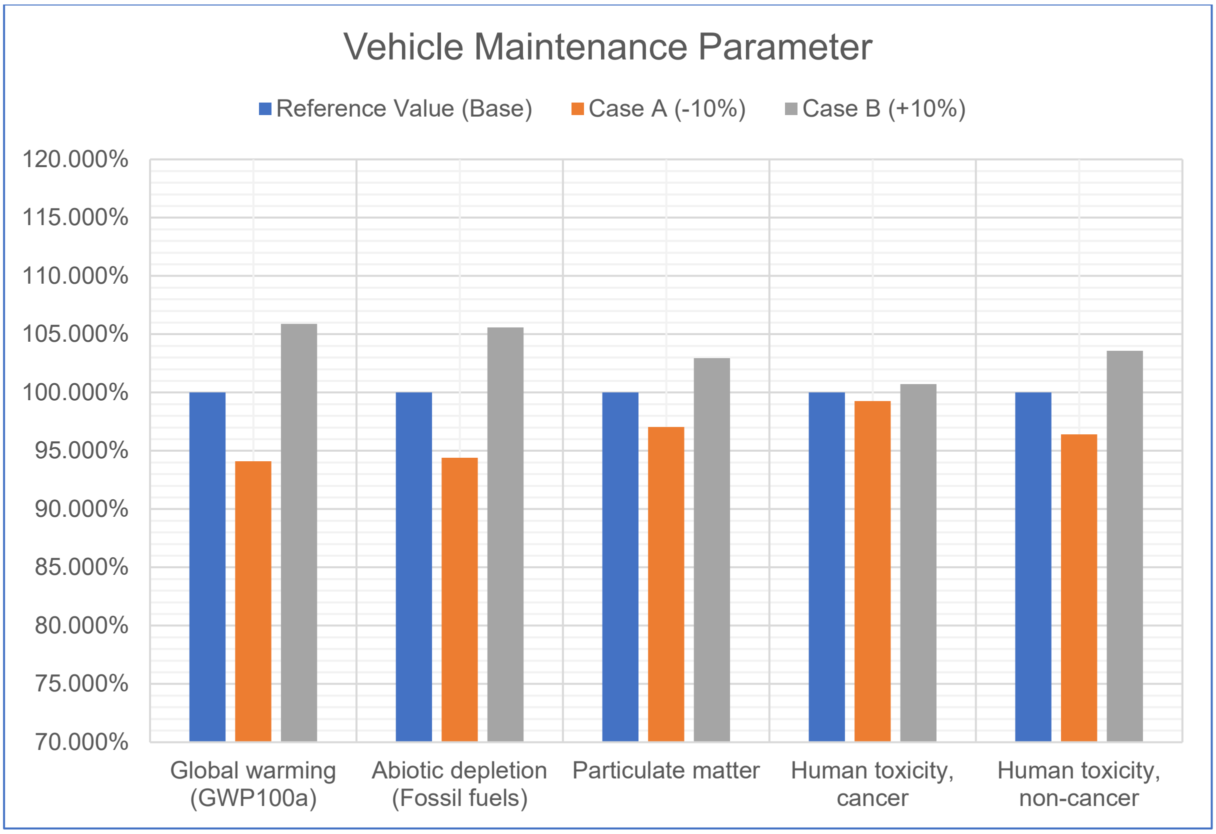


**Figure G.66: Sensitivity Analysis for LCA of CNG Buses (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.022517395 | 0.022488564 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.28815389 | 0.28517205 | 1 | 0 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 5.17E-06 | 5.11E-06 | 1 | -1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.10E-10 | 4.10E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 2.01E-09 | 2.01E-09 | 0 | 0 |

**Table G.67: Sensitivity Analysis for LCA of CNG Buses (Kilometres Travelled Parameter)**

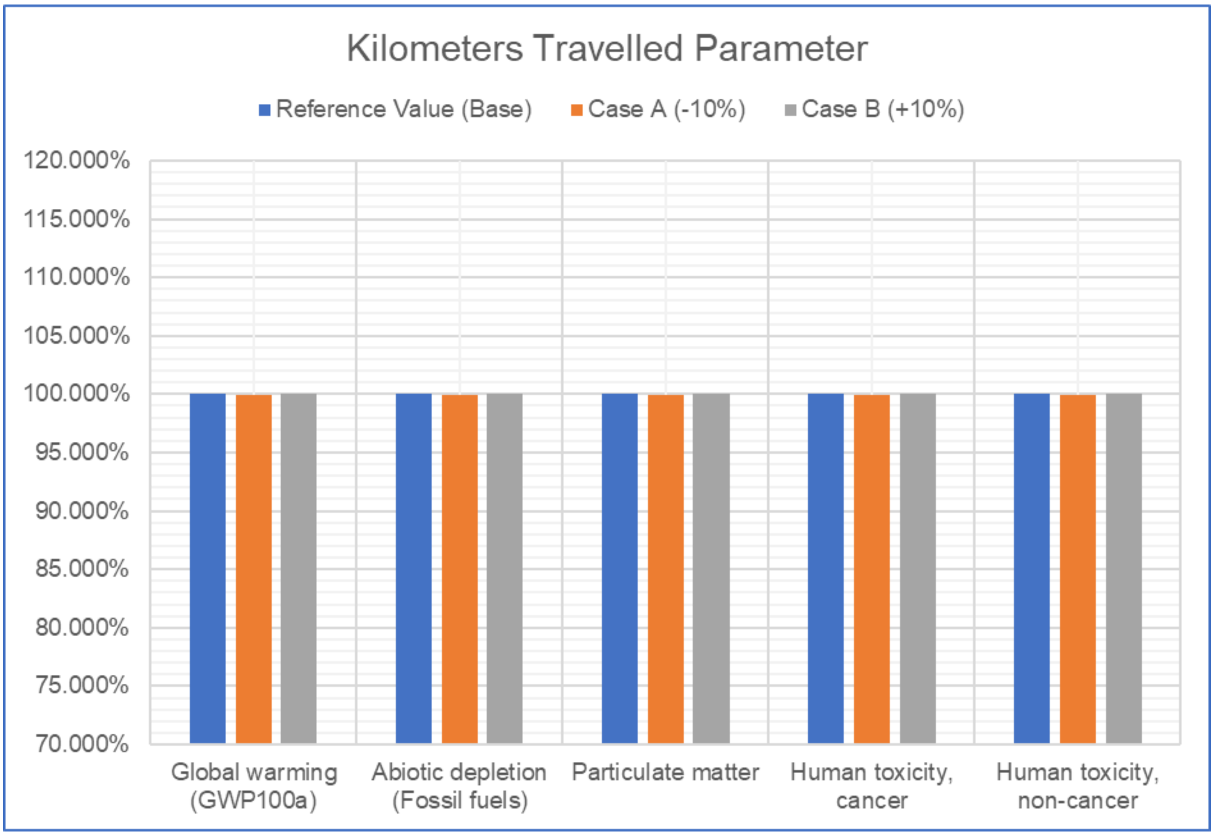


**Figure G.67: Sensitivity Analysis for LCA of CNG Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.022487267 | 0.022515809 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.28503787 | 0.28798989 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 5.11E-06 | 5.17E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.10E-10 | 4.10E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 2.01E-09 | 2.01E-09 | 0 | 0 |

**Table G.68: Sensitivity Analysis for LCA of CNG Buses (Fuel Consumption Parameter)**

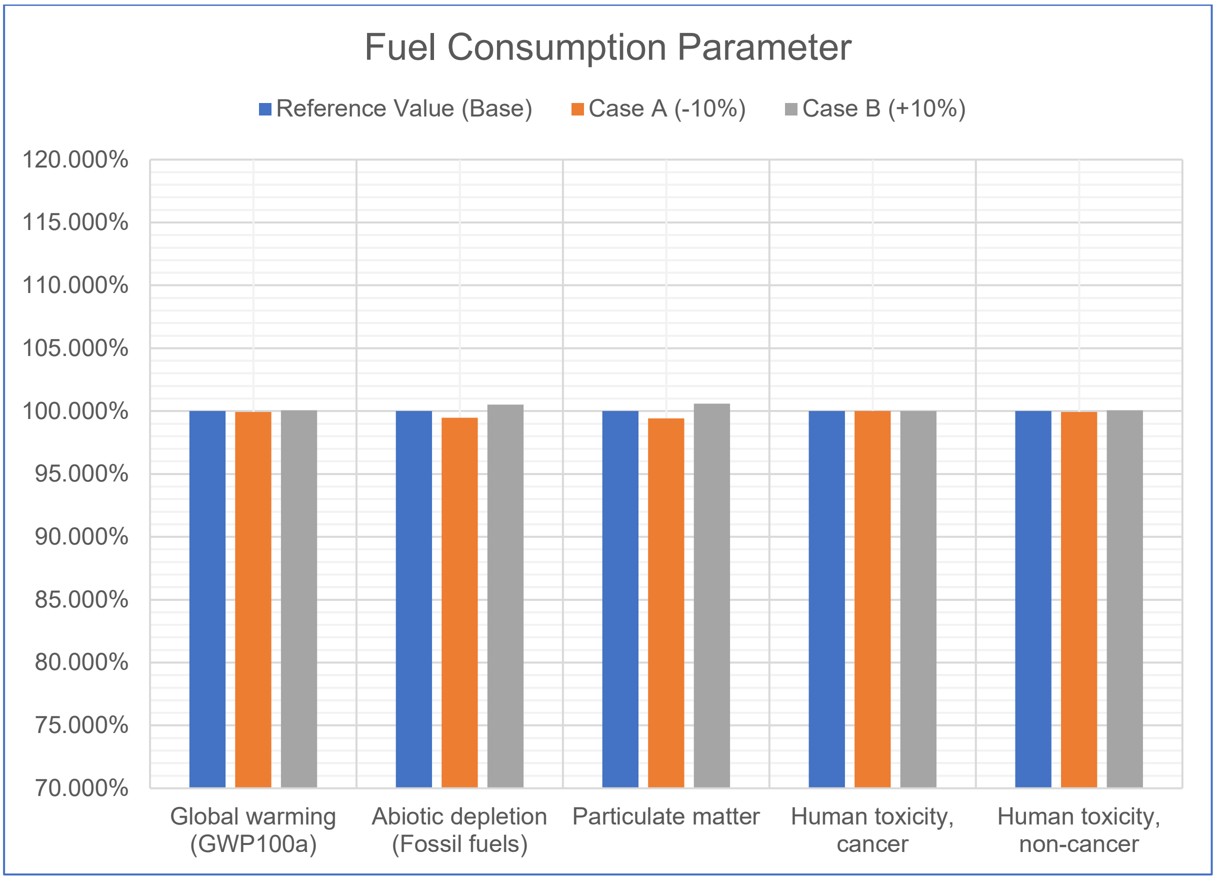


**Figure G.68: Sensitivity Analysis for LCA of CNG Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.022478199 | 0.022524878 | -0.10 | 0.10 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.28650527 | 0.28652249 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 5.14E-06 | 5.14E-06 | -0.01 | 0.01 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.10E-10 | 4.10E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 2.01E-09 | 2.01E-09 | -0.01 | 0.01 |

**Table G.69: Sensitivity Analysis for LCA of CNG Buses (Vehicle Disposal Parameter)**

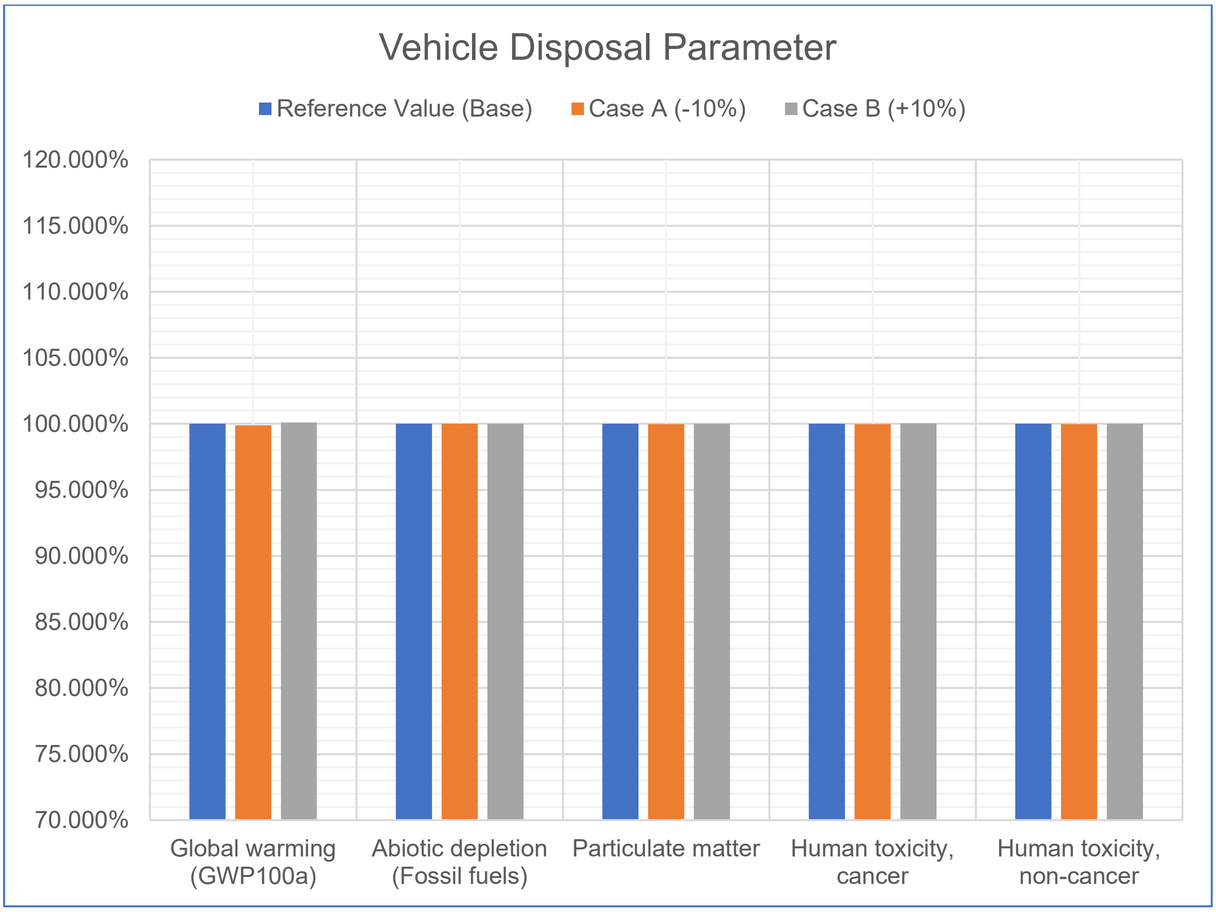


**Figure G.69: Sensitivity Analysis for LCA of CNG Buses (Vehicle Disposal Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.022491971 | 0.022511106 | -0.04 | 0.04 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.28503787 | 0.28798989 | -0.52 | 0.52 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 5.13E-06 | 5.14E-06 | -0.08 | 0.08 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.10E-10 | 4.10E-10 | 0.00 | 0.00 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 2.01E-09 | 2.01E-09 | -0.06 | 0.06 |

**Table G.70: Sensitivity Analysis for LCA of CNG Buses (Natural Gas Production Parameter)**

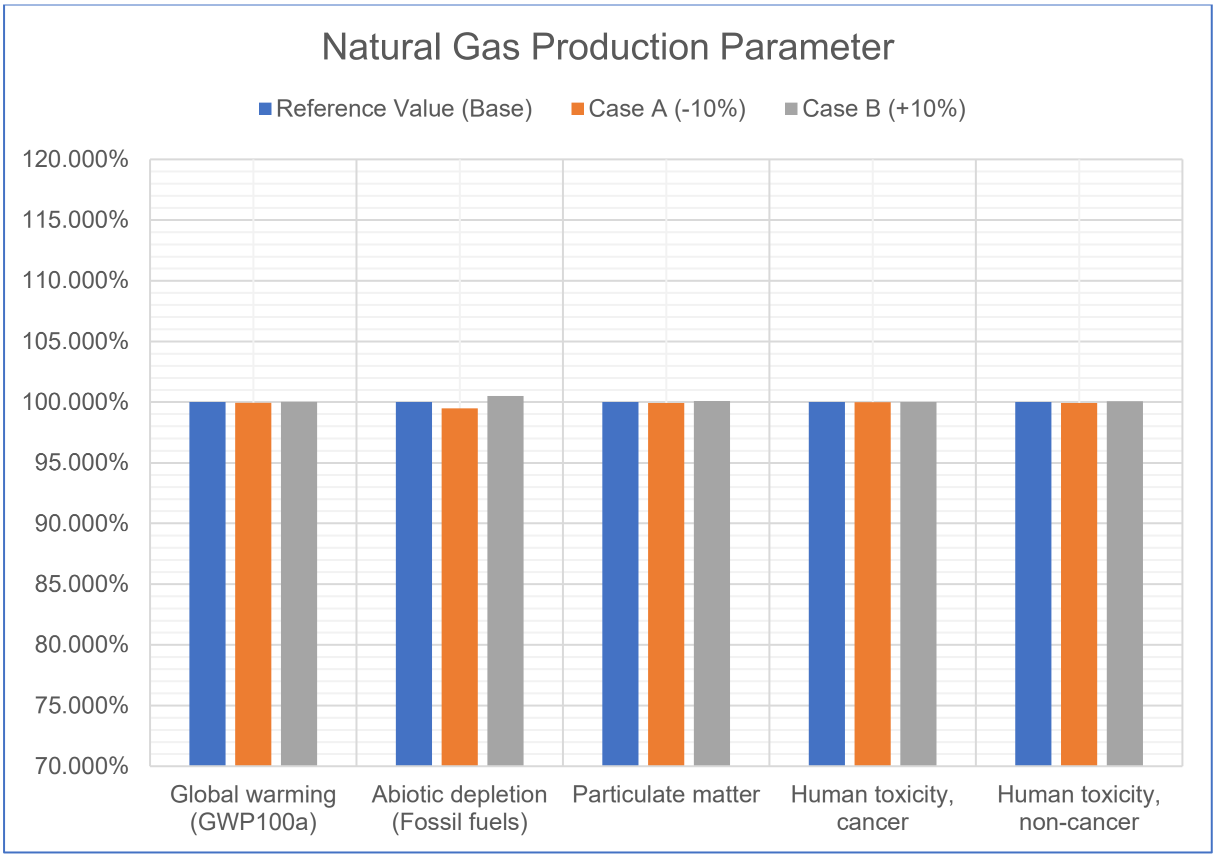


**Figure G.70: Sensitivity Analysis for LCA of CNG Buses (Natural Gas Production Parameter)**

| Impact Category | Reference value (base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.022501538 | 0.022500738 | 0.022502338 | 0.00 | 0.00 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.28651388 | 0.28650337 | 0.28652439 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 5.14E-06 | 5.14E-06 | 5.14E-06 | -0.01 | 0.01 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.10E-10 | 4.10E-10 | 4.10E-10 | 0.00 | 0.00 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.01E-09 | 2.01E-09 | 2.01E-09 | 0.00 | 0.00 |

**Table G.71: Sensitivity Analysis for LCA of CNG Buses (Natural Gas Processing Parameter)**

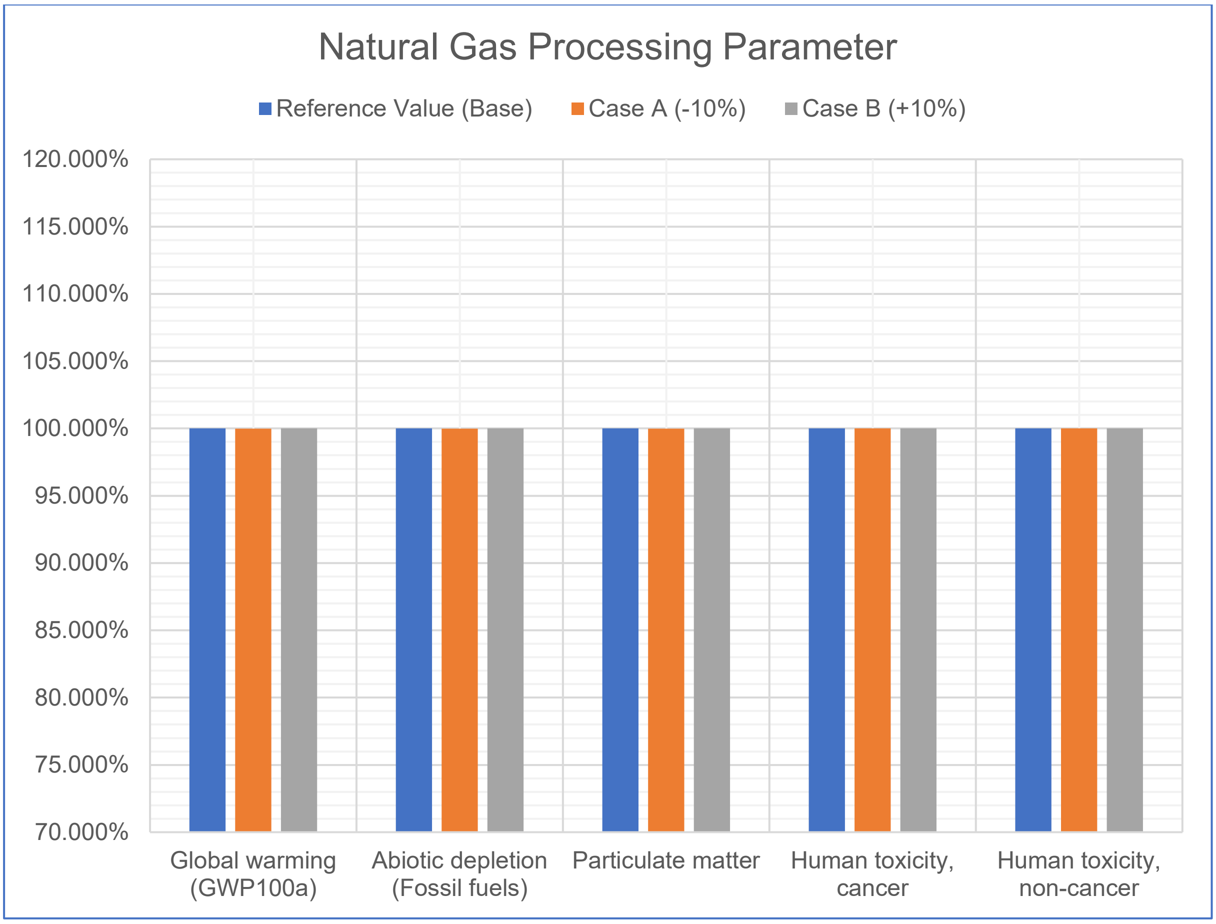


**Figure G.71: Sensitivity Analysis for LCA of CNG Buses (Natural Gas Processing Parameter)**

## Liquid Petroleum Gas Buses (LPG)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.070422884 | 0.057618723 | 11.11 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.85025064 | 0.69565961 | 11.11 | -9.09 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 8.80E-06 | 7.20E-06 | 11.11 | -9.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.72E-10 | 3.86E-10 | 11.11 | -9.09 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 2.20E-09 | 1.80E-09 | 11.11 | -9.09 |

**Table G.72: Sensitivity Analysis for LCA of LPG Buses (Occupancy Rate Parameter)**

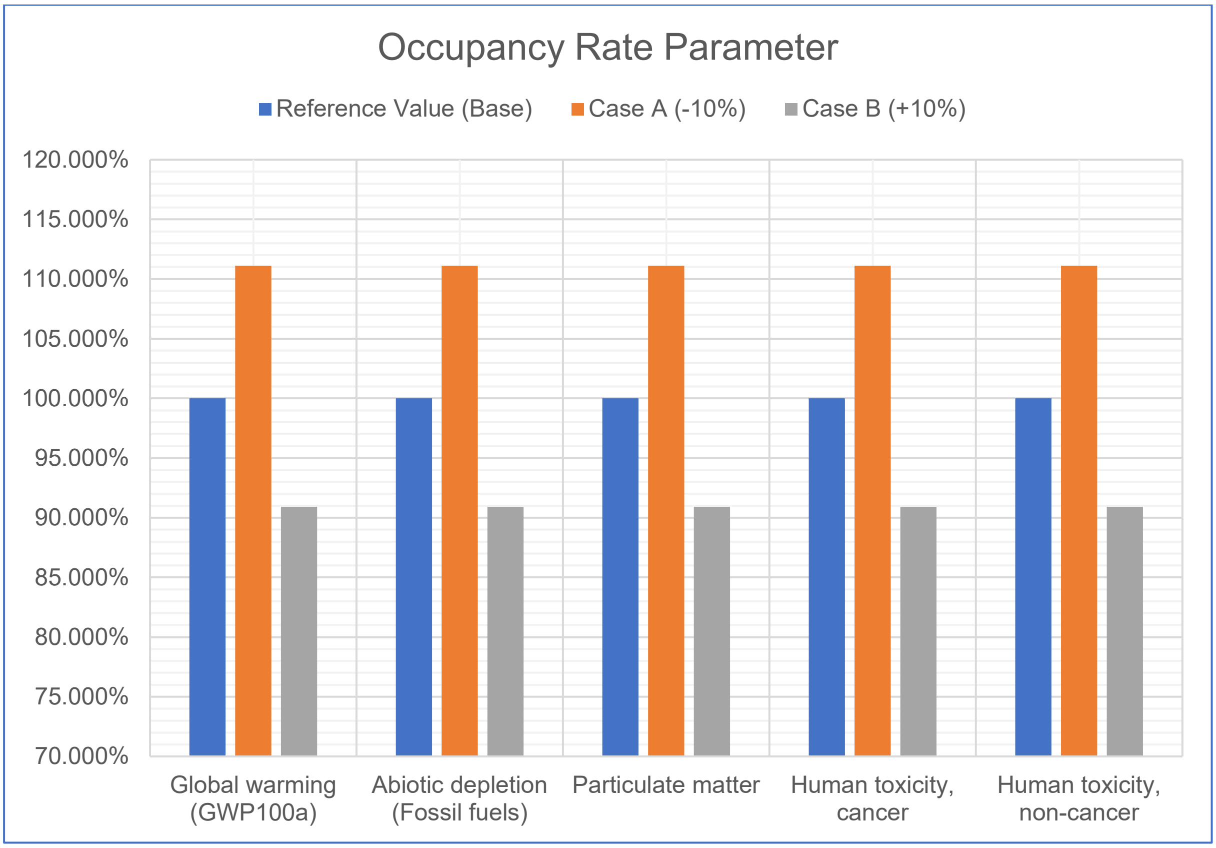


**Figure G.72: Sensitivity Analysis for LCA of LPG Buses (Occupancy Rate Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.067996283 | 0.059604123 | 7.28 | -5.96 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.82017383 | 0.72026791 | 7.18 | -5.88 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 8.27E-06 | 7.63E-06 | 4.47 | -3.66 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.27E-10 | 4.23E-10 | 0.50 | -0.41 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 2.01E-09 | 1.96E-09 | 1.40 | -1.15 |

**Table G.73: Sensitivity Analysis for LCA of LPG Buses (Kilometres Travelled Parameter)**

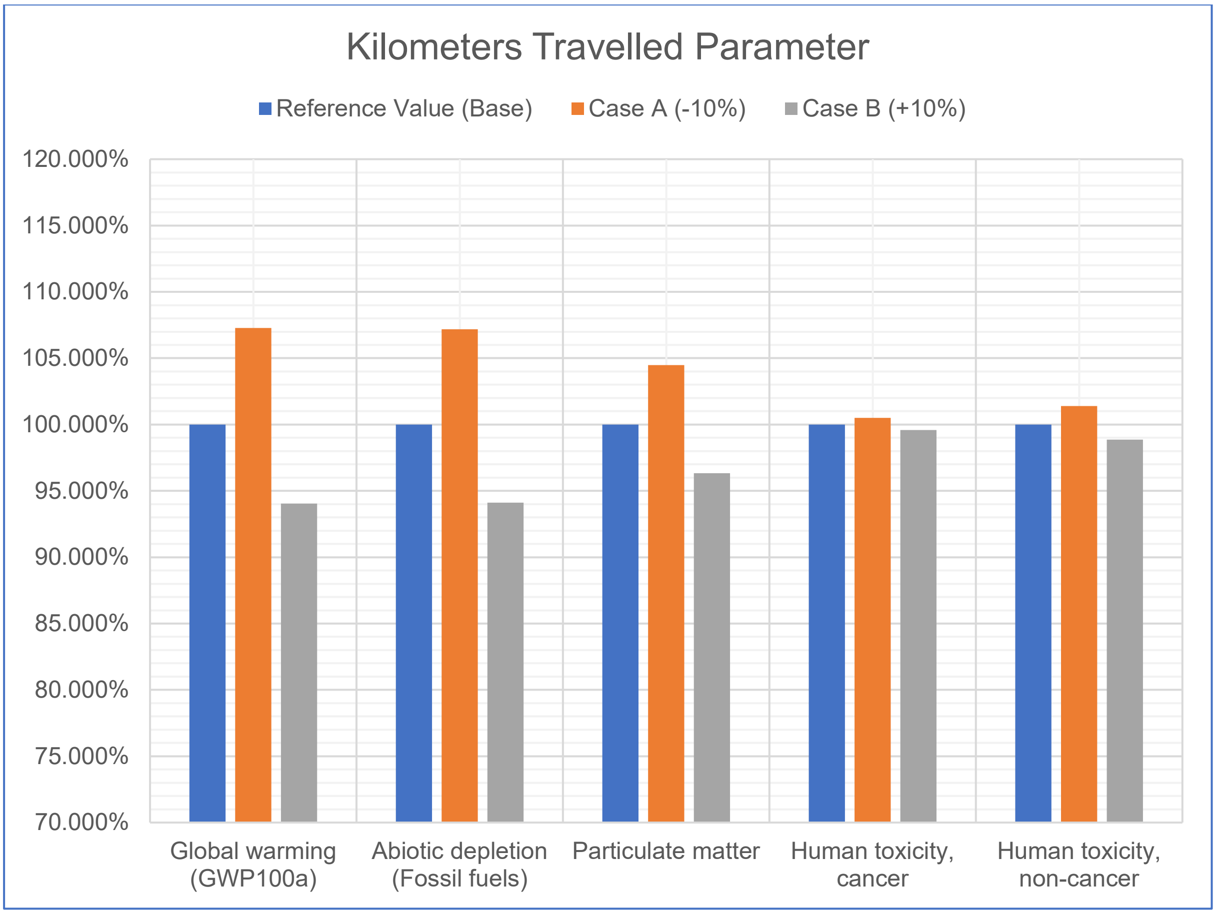


**Figure G.73: Sensitivity Analysis for LCA of LPG Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.059226476 | 0.067534715 | -6.55 | 6.55 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.71577214 | 0.814679 | -6.46 | 6.46 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 7.60E-06 | 8.23E-06 | -4.02 | 4.02 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.23E-10 | 4.27E-10 | -0.45 | 0.45 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 1.96E-09 | 2.01E-09 | -1.26 | 1.26 |

**Table G.74: Sensitivity Analysis for LCA of LPG Buses (Fuel Consumption Parameter)**

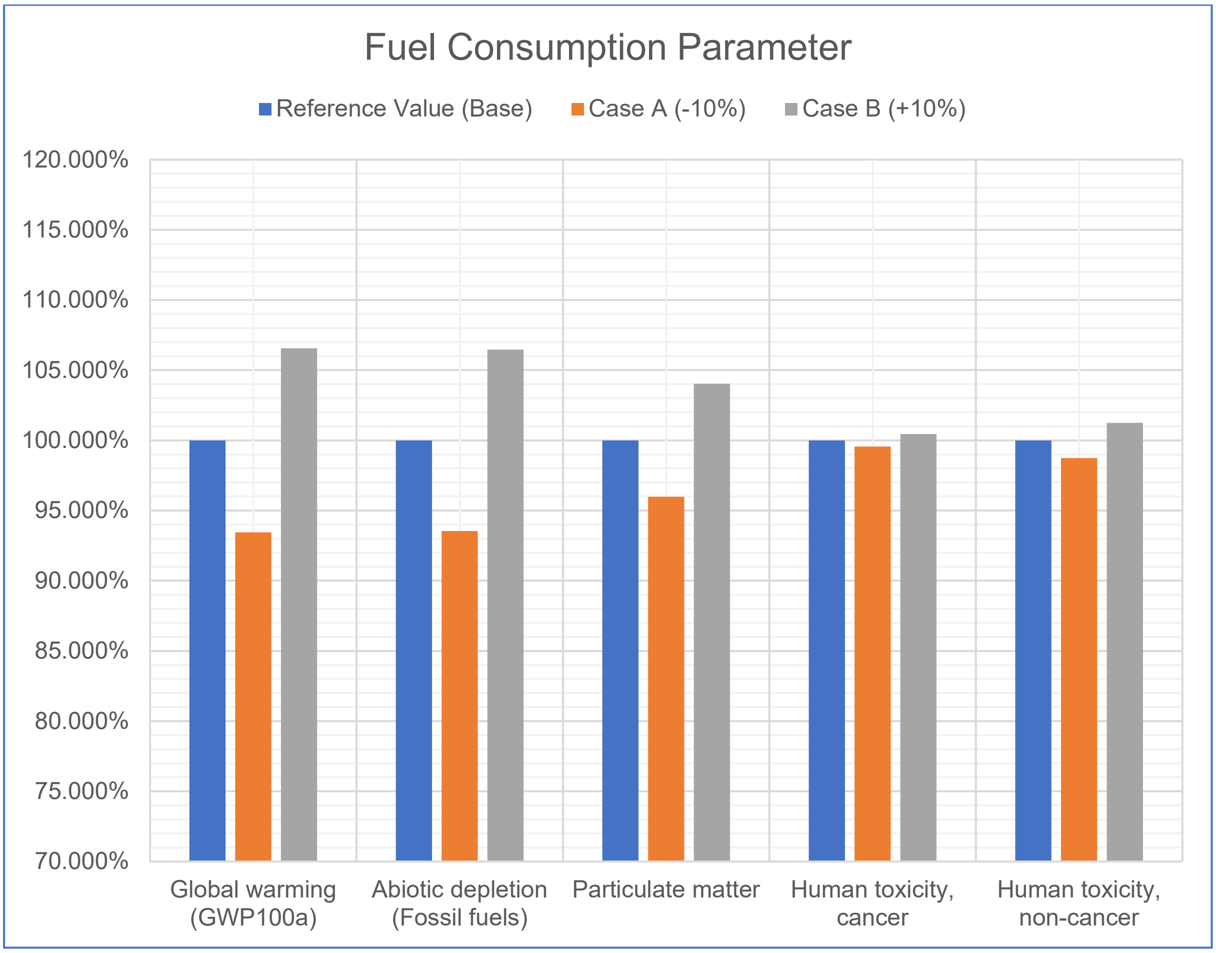


**Figure G.74: Sensitivity Analysis for LCA of LPG Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.062499883 | 0.064261308 | -1.39 | 1.39 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.75411618 | 0.77633496 | -1.45 | 1.45 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 7.59E-06 | 8.24E-06 | -4.10 | 4.10 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 3.87E-10 | 4.62E-10 | -8.89 | 8.89 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 1.86E-09 | 2.11E-09 | -6.34 | 6.34 |

**Table G.75: Sensitivity Analysis for LCA of LPG Buses (Vehicle Manufacture Parameter)**

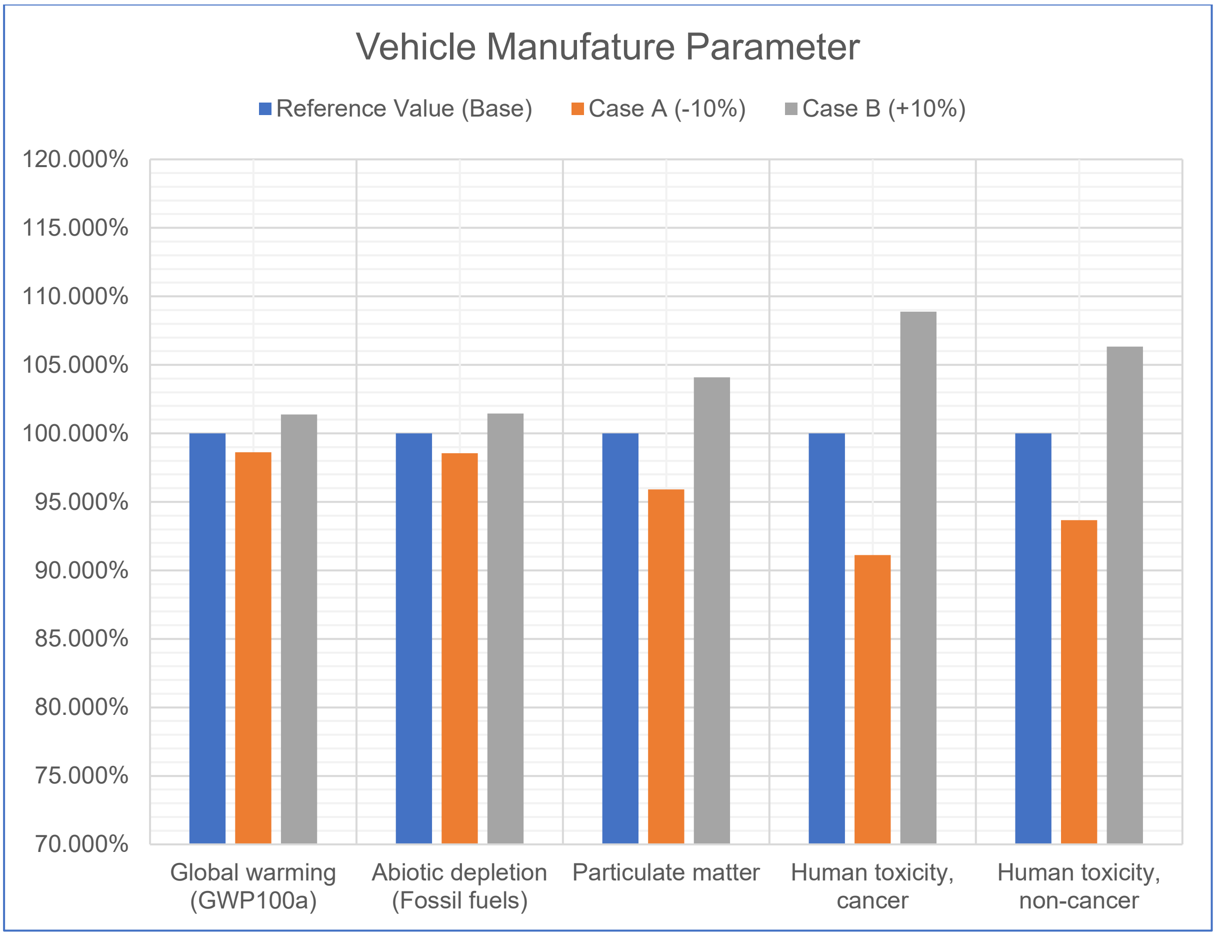


**Figure G.75: Sensitivity Analysis for LCA of LPG Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.06270002 | 0.064061171 | -1.07 | 1.07 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.71614542 | 0.81430572 | -6.41 | 6.41 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 7.65E-06 | 8.18E-06 | -3.38 | 3.38 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.23E-10 | 4.26E-10 | -0.39 | 0.39 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 1.96E-09 | 2.00E-09 | -1.17 | 1.17 |

**Table G.76: Sensitivity Analysis for LCA of LPG Buses (LPG Production Parameter)**

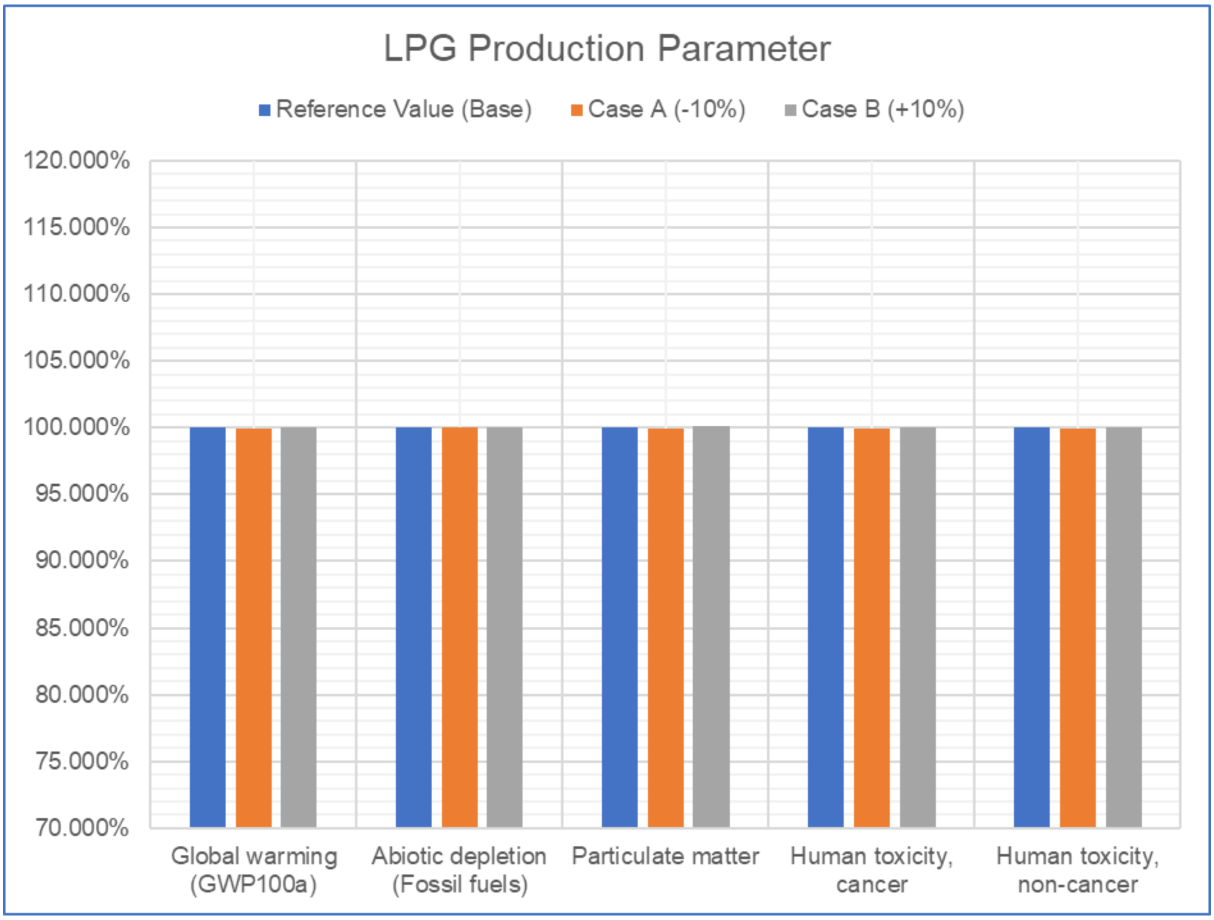


**Figure G.76: Sensitivity Analysis for LCA of LPG Buses (LPG Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.063380594 | 0.063380597 | 0.0000 | 0.0000 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.76522555 | 0.76522559 | 0.0000 | 0.0000 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 7.92E-06 | 7.92E-06 | -0.0001 | 0.0001 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.25E-10 | 4.25E-10 | 0.0000 | 0.0000 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 1.98E-09 | 1.98E-09 | 0.0000 | 0.0000 |

**Table G.77: Sensitivity Analysis for LCA of LPG Buses (LPG Processing Parameter)**

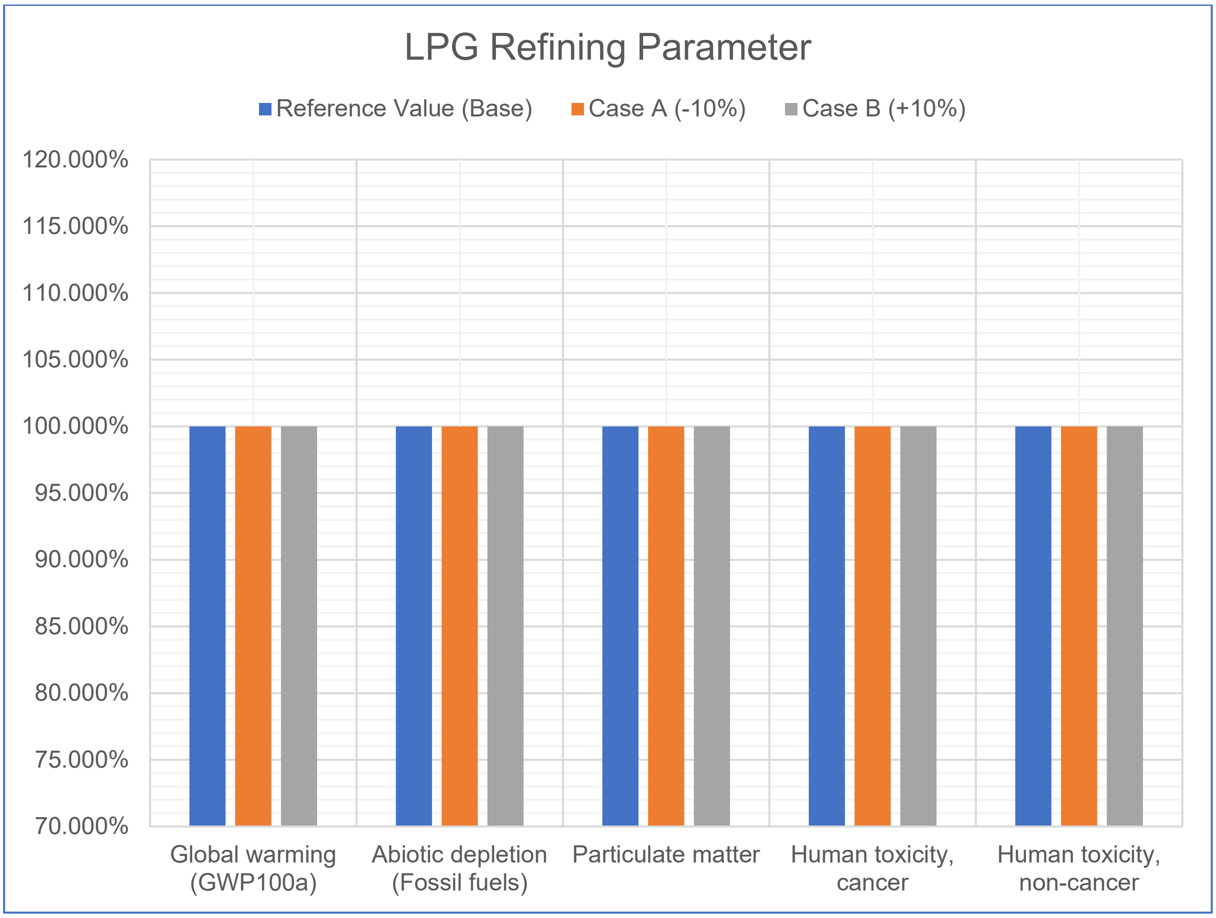


**Figure G.77: Sensitivity Analysis for LCA of LPG Buses (LPG Processing Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.062100708 | 0.064660483 | -2.02 | 2.02 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.74927444 | 0.7811767 | -2.08 | 2.08 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 7.77E-06 | 8.06E-06 | -1.87 | 1.87 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.22E-10 | 4.27E-10 | -0.64 | 0.64 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 1.93E-09 | 2.03E-09 | -2.39 | 2.39 |

**Table G.78: Sensitivity Analysis for LCA of LPG Buses (Vehicle Maintenance Parameter)**

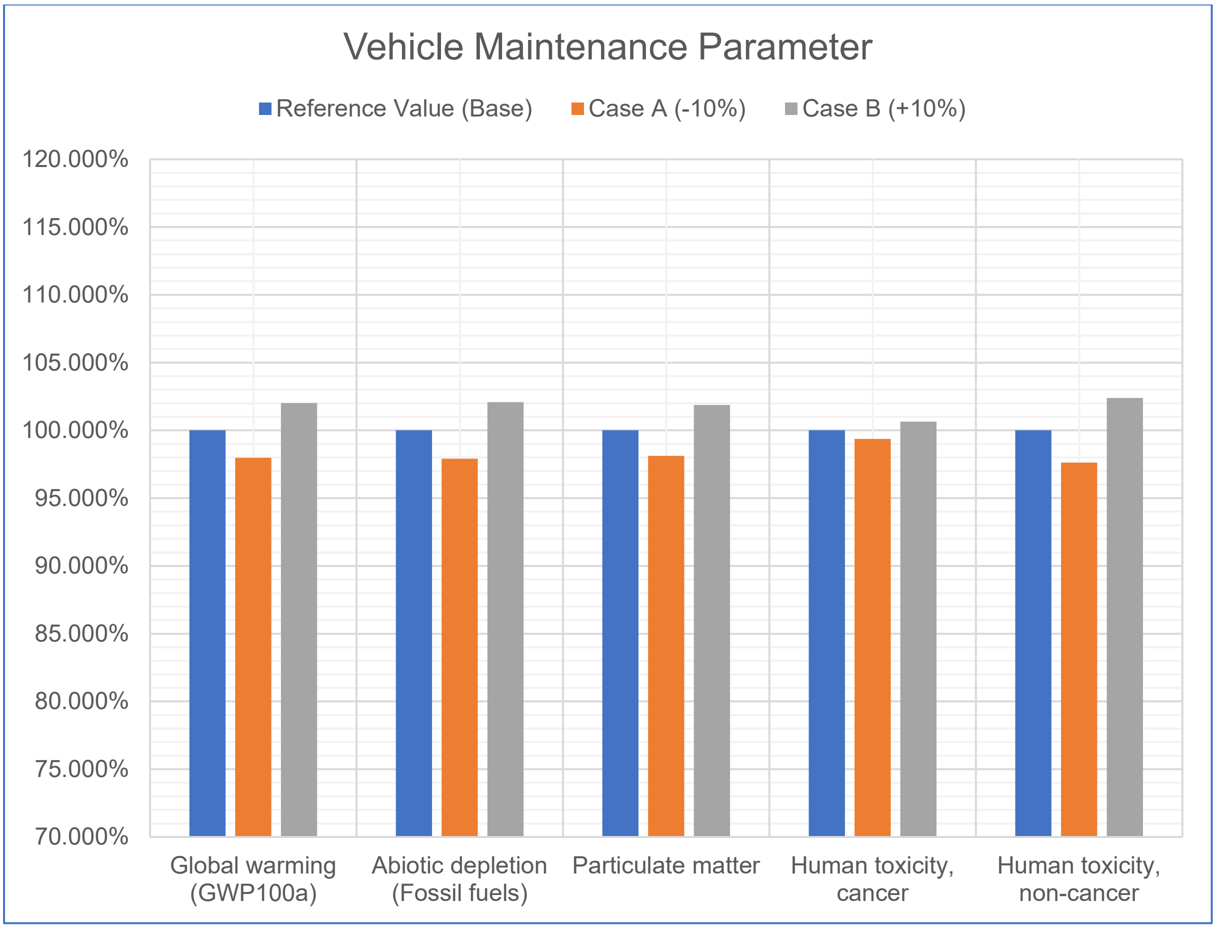


**Figure G.78: Sensitivity Analysis for LCA of LPG Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063380595 | 0.063357256 | 0.063403935 | -0.04 | 0.04 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76522557 | 0.76521696 | 0.76523418 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 7.92E-06 | 7.92E-06 | 7.92E-06 | -0.01 | 0.01 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.25E-10 | 4.25E-10 | 4.25E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.98E-09 | 1.98E-09 | 1.98E-09 | -0.01 | 0.01 |

**Table G.79: Sensitivity Analysis for LCA of LPG Buses (Vehicle Disposal Parameter)**

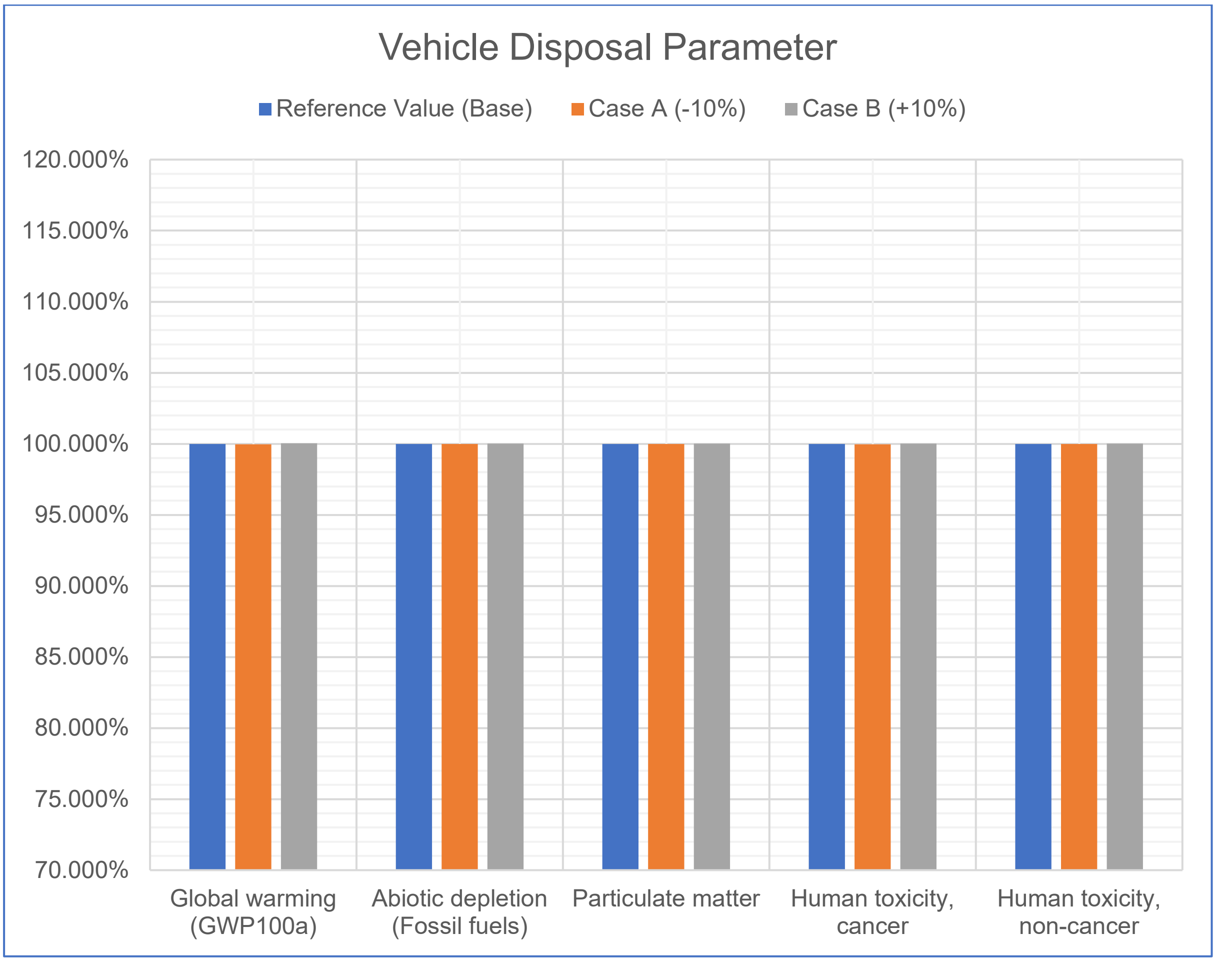


**Figure G.79: Sensitivity Analysis for LCA of LPG Buses (Vehicle Disposal Parameter)**

## Hybrid Electric Buses

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.088297323 | 0.072243264 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 1.0541144 | 0.86245724 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 7.30E-05 | 5.98E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 5.14E-10 | 4.20E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.45E-09 | 2.00E-09 | 11 | -9 |

**Table G.80: Sensitivity Analysis for LCA of Hybrid Electric Buses (Occupancy Rate Parameter)**

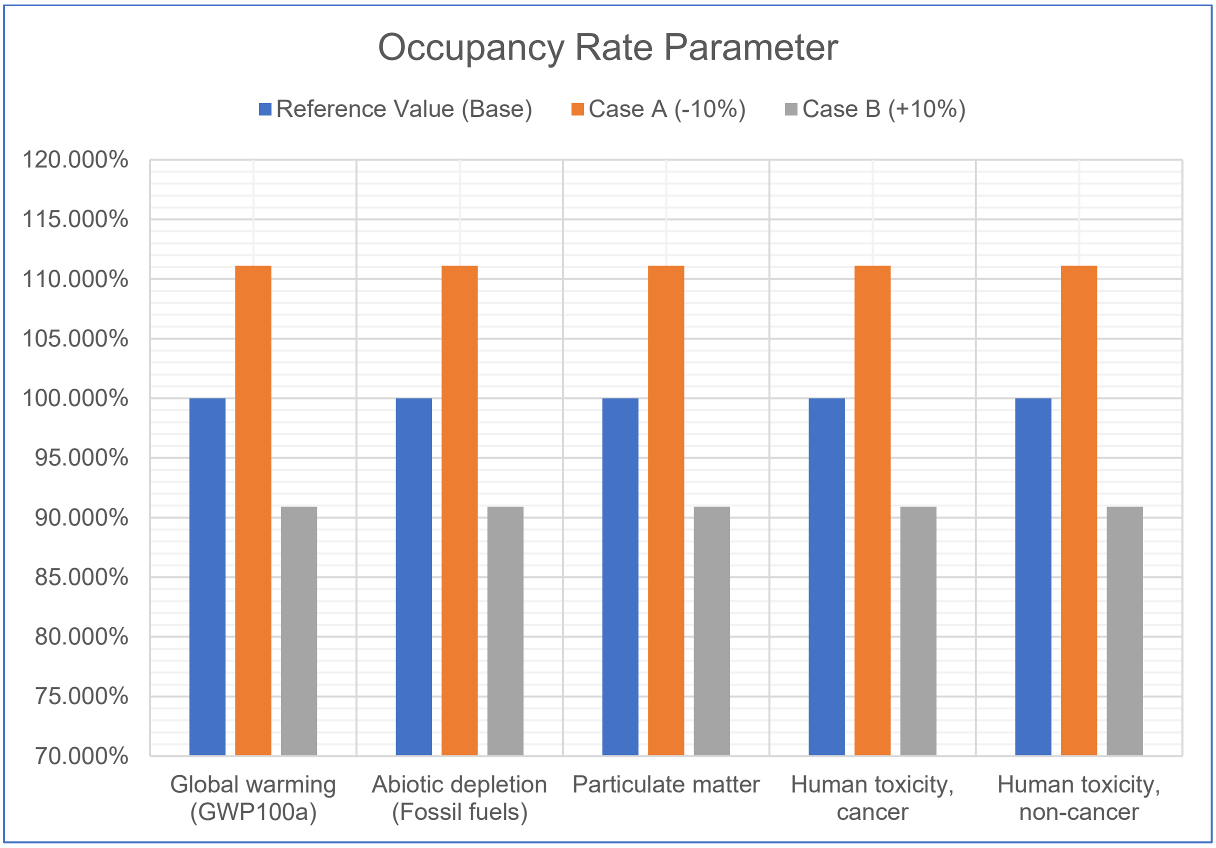


**Figure G.80: Sensitivity Analysis for LCA of Hybrid Electric Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.085844859 | 0.074249825 | 8 | -7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 1.023792 | 0.88726651 | 8 | -6 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 7.25E-05 | 6.02E-05 | 10 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 4.67E-10 | 4.59E-10 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.24E-09 | 2.17E-09 | 2 | -1 |

**Table G.81: Sensitivity Analysis for LCA of Hybrid Electric Buses (Kilometres Travelled Parameter)**

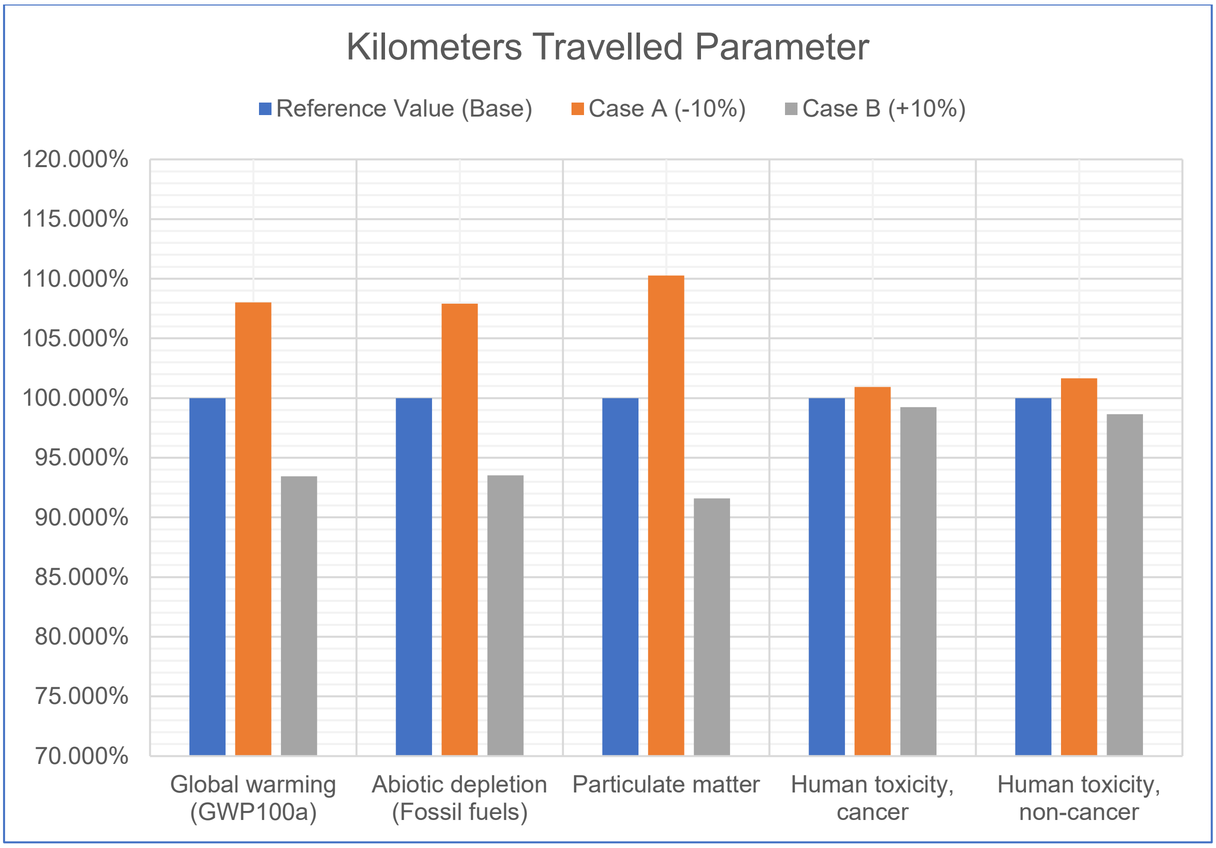


**Figure G.81: Sensitivity Analysis for LCA of Hybrid Electric Buses (Kilometres Travelled Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.078566209 | 0.080368971 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 0.93737643 | 0.9600295 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 6.54E-05 | 6.61E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 4.23E-10 | 5.02E-10 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.06E-09 | 2.34E-09 | -6 | 6 |

**Table G.82: Sensitivity Analysis for LCA of Hybrid Electric Buses (Vehicle Manufacture Parameter)**

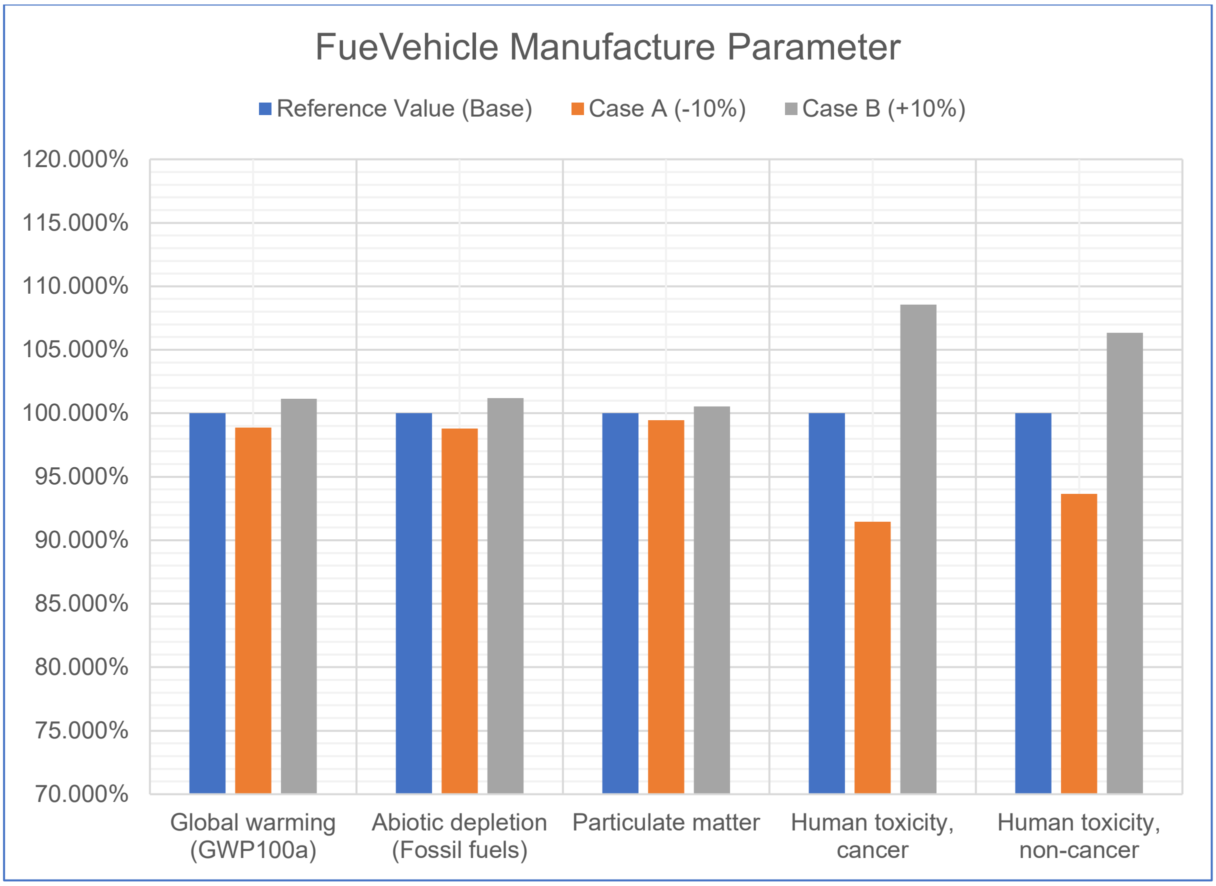


**Figure G.82: Sensitivity Analysis for LCA of Hybrid Electric Buses (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.078187702 | 0.080747478 | -2 | 2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 0.93275184 | 0.96465409 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 6.56E-05 | 6.59E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 4.60E-10 | 4.65E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.16E-09 | 2.25E-09 | -2 | 2 |

**Table G.83: Sensitivity Analysis for LCA of Hybrid Electric Buses (Vehicle Maintenance Parameter)**

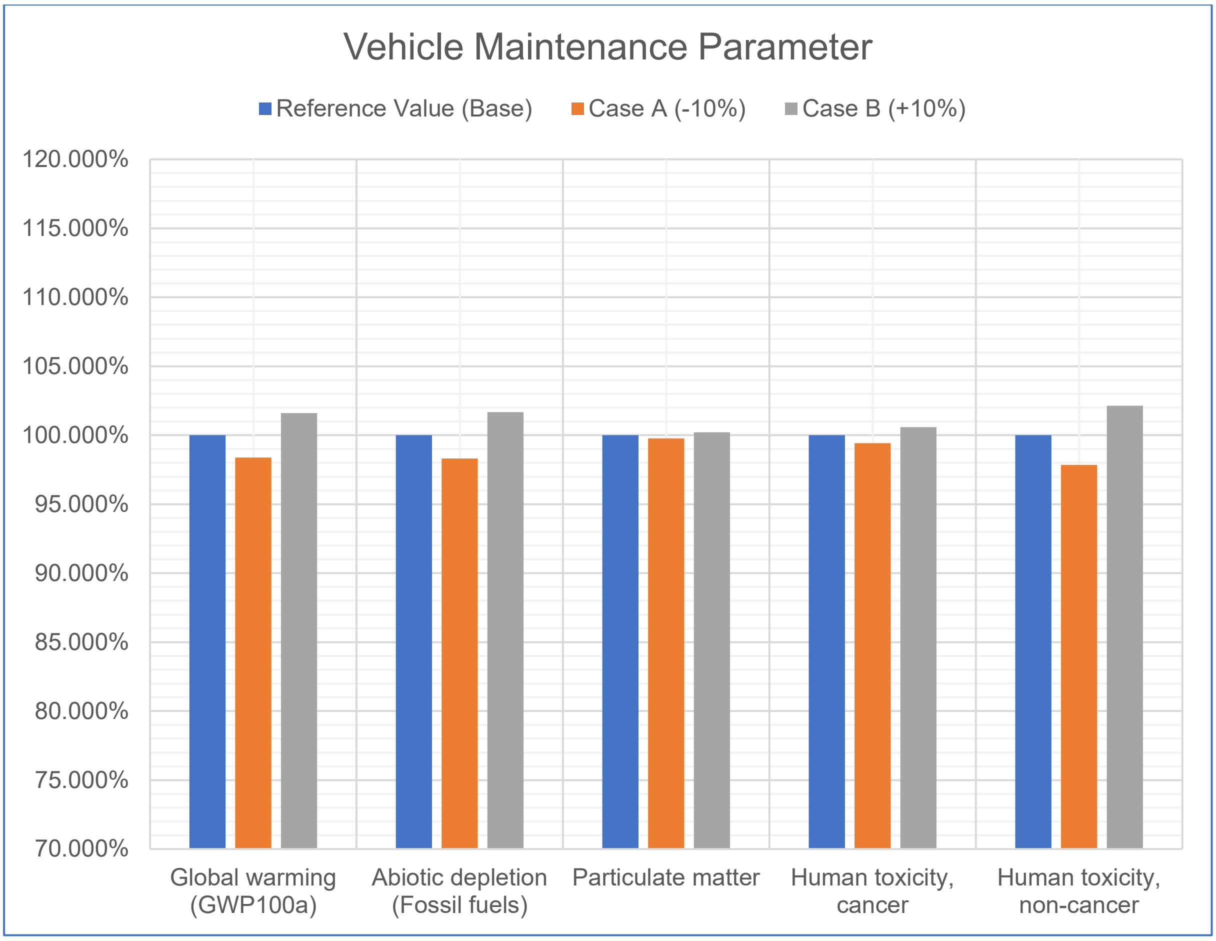


**Figure G.83: Sensitivity Analysis for LCA of Hybrid Electric Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.079057842 | 0.079877338 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 0.89014029 | 1.0072656 | -6 | 6 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 6.54E-05 | 6.61E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 4.60E-10 | 4.65E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.18E-09 | 2.22E-09 | -1 | 1 |

**Table G.84: Sensitivity Analysis for LCA of Hybrid Electric Buses (Crude Oil Refining Parameter)**

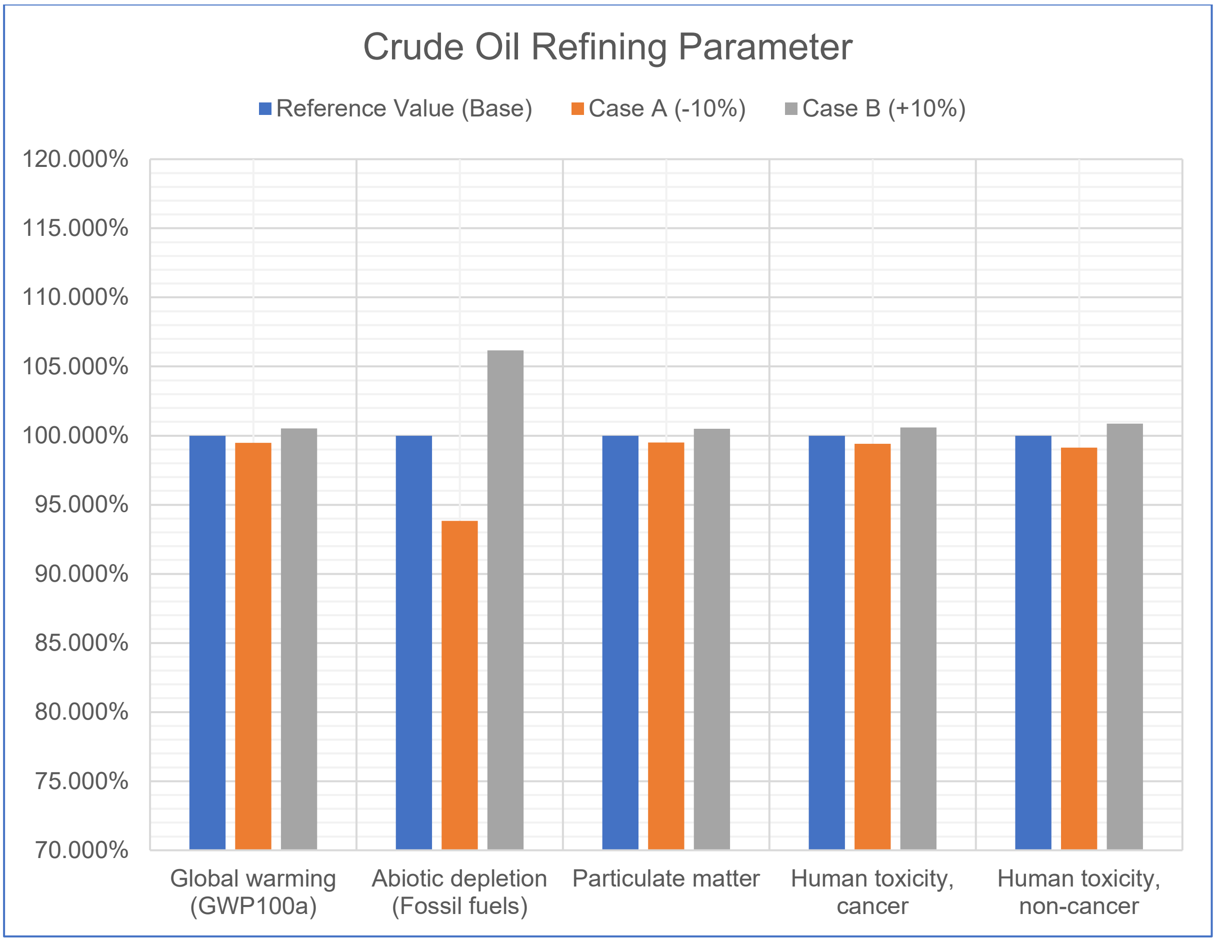


**Figure G.84: Sensitivity Analysis for LCA of Hybrid Electric Buses (Crude Oil Refining Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.079441642 | 0.079493539 | -0.03 | 0.03 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 0.94869042 | 0.94871551 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 6.57E-05 | 6.57E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 4.62E-10 | 4.62E-10 | -0.03 | 0.03 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.20E-09 | 2.20E-09 | -0.01 | 0.01 |

**Table G.85: Sensitivity Analysis for LCA of Hybrid Electric Buses (Vehicle Disposal Parameter)**

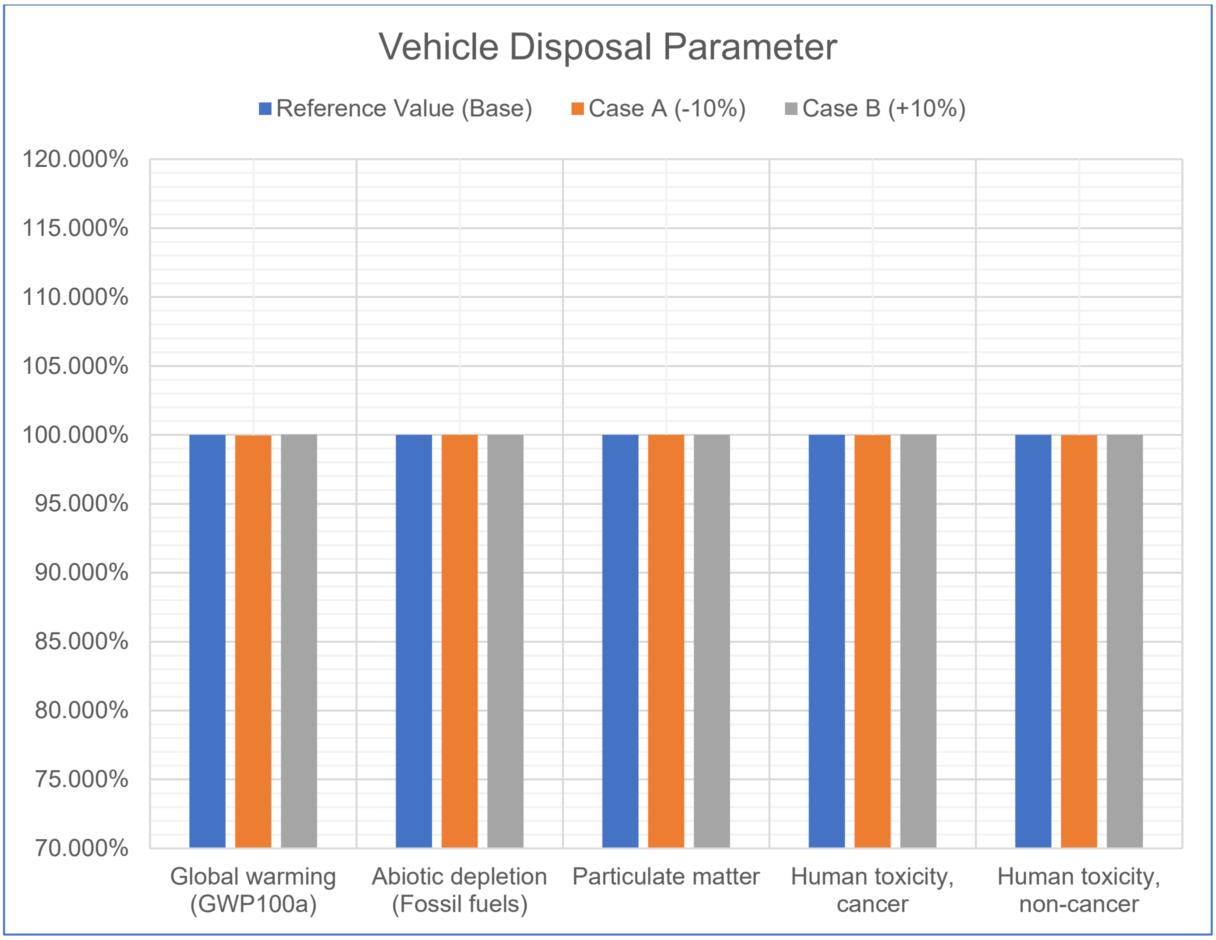


**Figure G.85: Sensitivity Analysis for LCA of Hybrid Electric Buses (Vehicle Disposal Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.07946759 | 0.079416316 | 0.079518864 | -0.06 | 0.06 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.94870297 | 0.93168228 | 0.96572365 | -1.79 | 1.79 |
| **Particulate Matter (kg/pkm)** | 6.57E-05 | 6.57E-05 | 6.58E-05 | -0.04 | 0.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.62E-10 | 4.62E-10 | 4.62E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.20E-09 | 2.20E-09 | 2.21E-09 | -0.08 | 0.08 |

**Table G.86: Sensitivity Analysis for LCA of Hybrid Electric Buses (Crude Oil Extraction Parameter)**

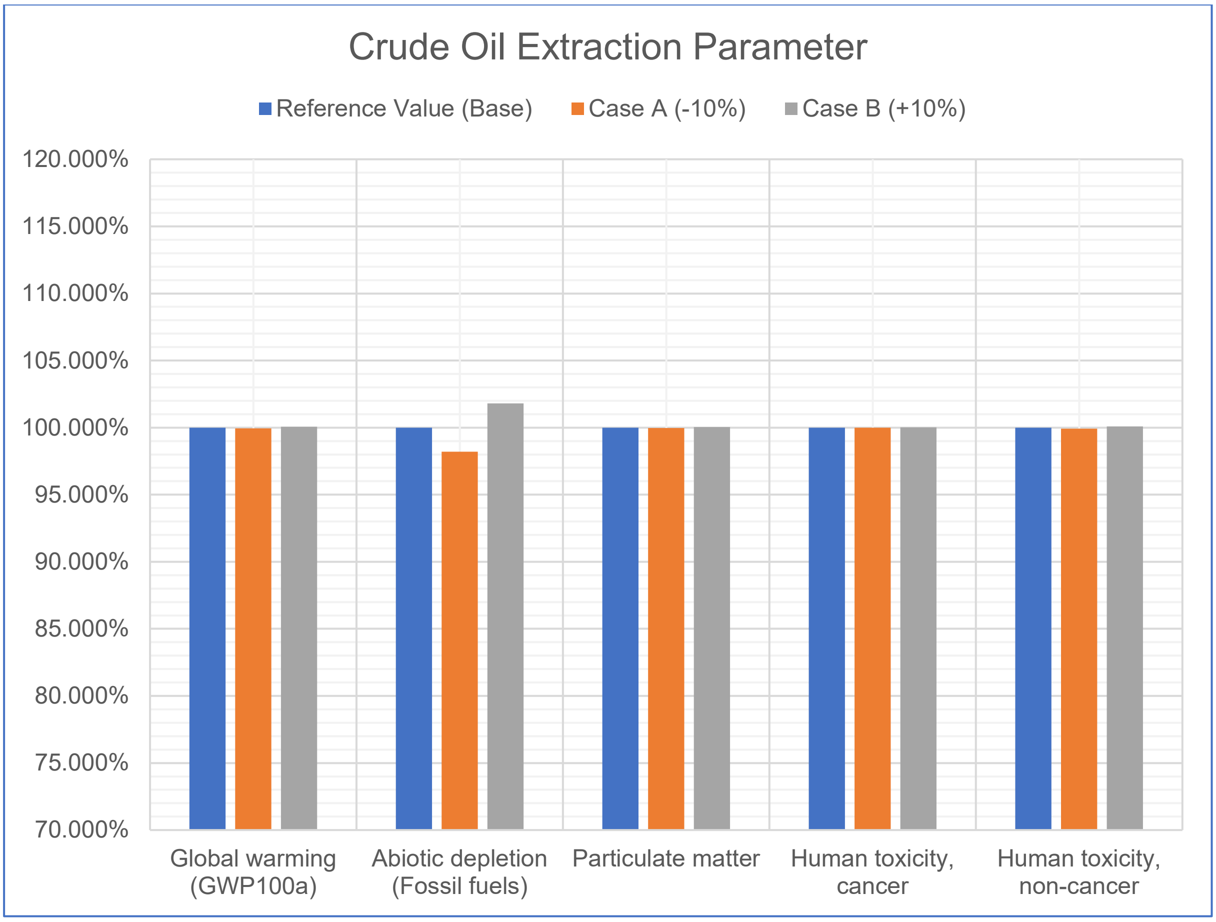


**Figure G.86: Sensitivity Analysis for LCA of Hybrid Electric Buses (Crude Oil Extraction Parameter)**

## Fuel Cell Buses

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.027215817 | 0.022267486 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.33429151 | 0.27351124 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.82E-06 | 4.76E-06 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.87E-10 | 3.99E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.62E-09 | 2.14E-09 | 11 | -9 |

**Table G.87: Sensitivity Analysis for LCA of Fuel Cell Buses (Occupancy Rate Parameter)**

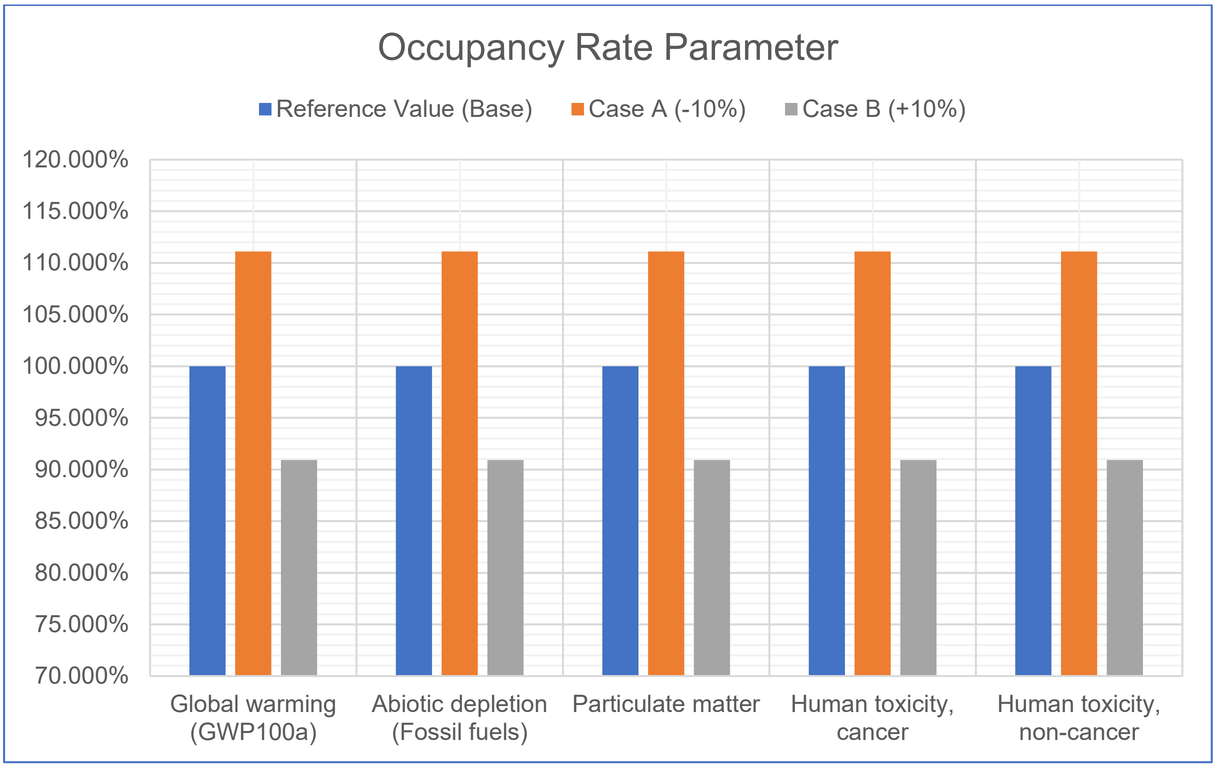


**Figure G.87: Sensitivity Analysis for LCA of Fuel Cell Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.023578757 | 0.025409713 | -4 | 4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.28936145 | 0.31236327 | -4 | 4 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 4.90E-06 | 5.58E-06 | -7 | 7 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 3.99E-10 | 4.78E-10 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.22E-09 | 2.50E-09 | -6 | 6 |

**Table G.88: Sensitivity Analysis for LCA of Fuel Cell Buses (Vehicle Manufacture Parameter)**

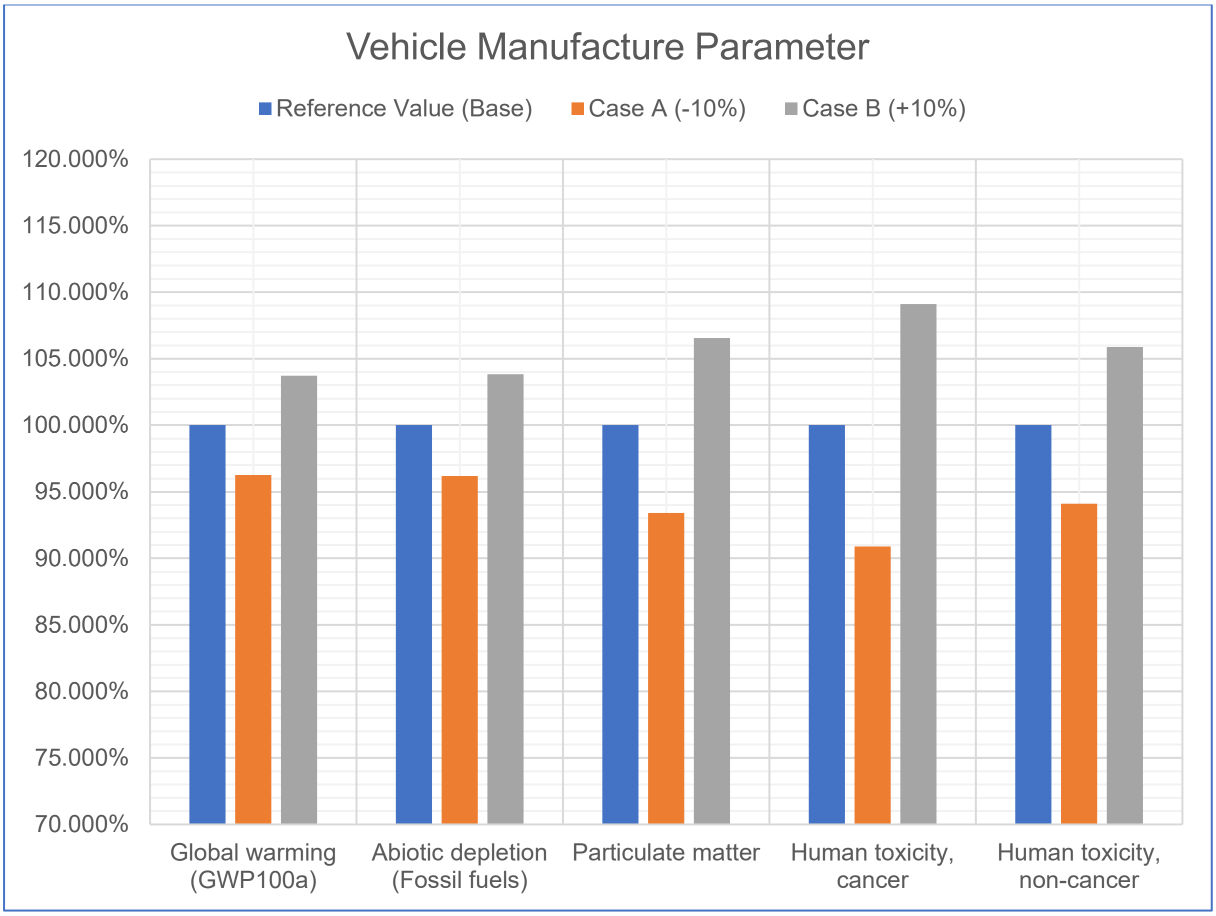


**Figure G.88: Sensitivity Analysis for LCA of Fuel Cell Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.024750588 | 0.024284491 | 1 | -1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.30377968 | 0.29847546 | 1 | -1 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.27E-06 | 5.21E-06 | 1 | -1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.40E-10 | 4.37E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.41E-09 | 2.31E-09 | 2 | -2 |

**Figure G.89: Sensitivity Analysis for LCA of Fuel Cell Buses (Kilometres Travelled Parameter)**

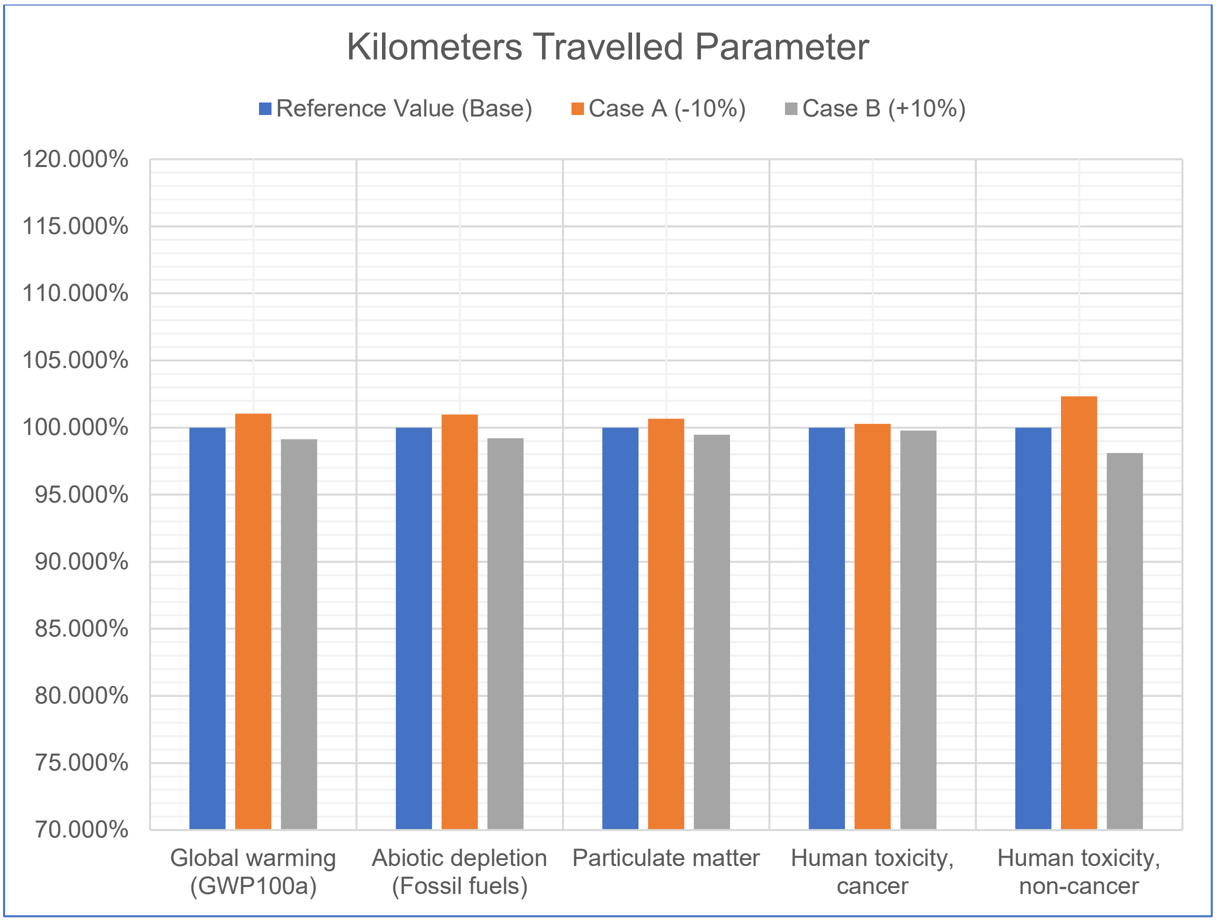


**Figure G.89: Sensitivity Analysis for LCA of Fuel Cell Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.024263517 | 0.024724953 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.29823677 | 0.30348795 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.21E-06 | 5.27E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.37E-10 | 4.40E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.31E-09 | 2.41E-09 | -2 | 2 |

**Table G.90: Sensitivity Analysis for LCA of Fuel Cell Buses (Fuel Consumption Parameter)**

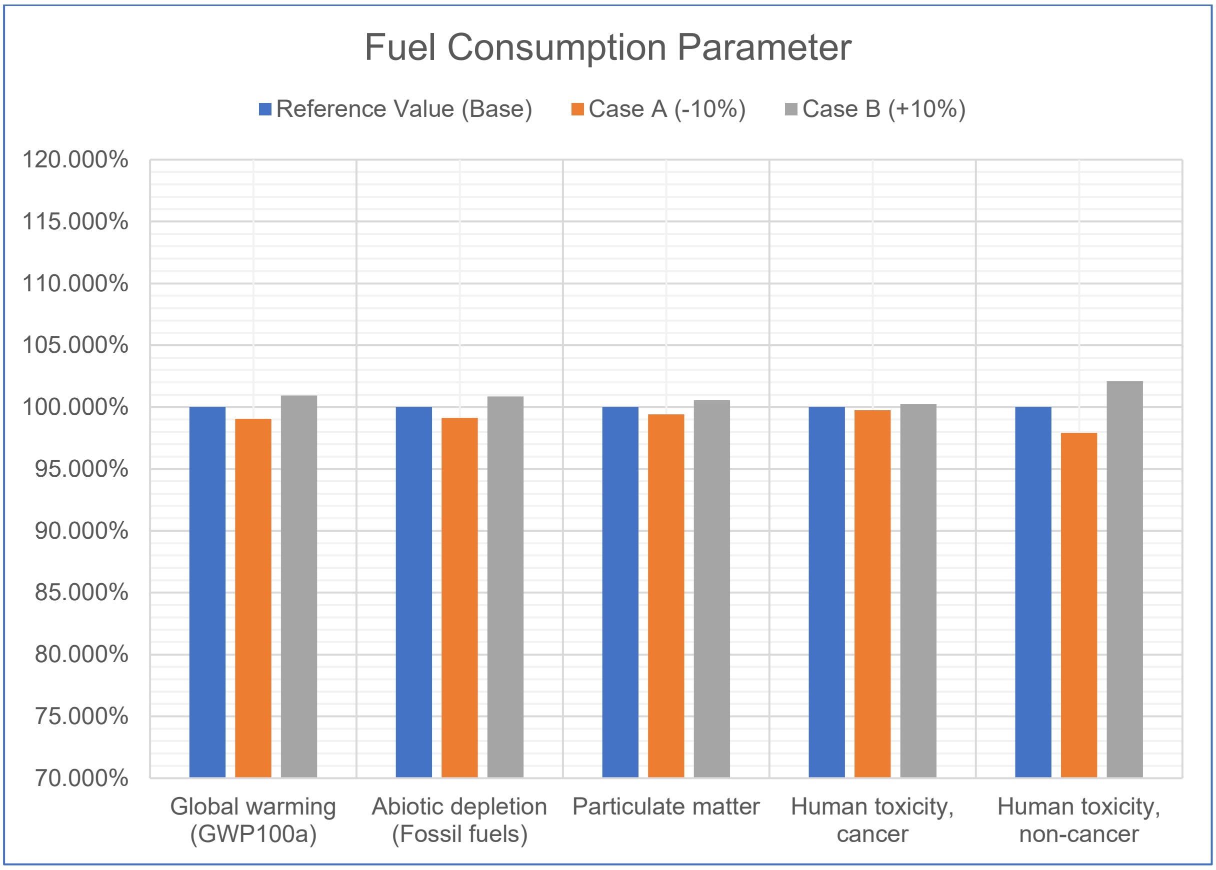


**Figure G.90: Sensitivity Analysis for LCA of Fuel Cell Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.023214347 | 0.025774123 | -5 | 5 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.28491124 | 0.31681349 | -5 | 5 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.09E-06 | 5.39E-06 | -3 | 3 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.36E-10 | 4.41E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.31E-09 | 2.41E-09 | -2 | 2 |

**Table G.91: Sensitivity Analysis for LCA of Fuel Cell Buses (Vehicle Maintenance Parameter)**

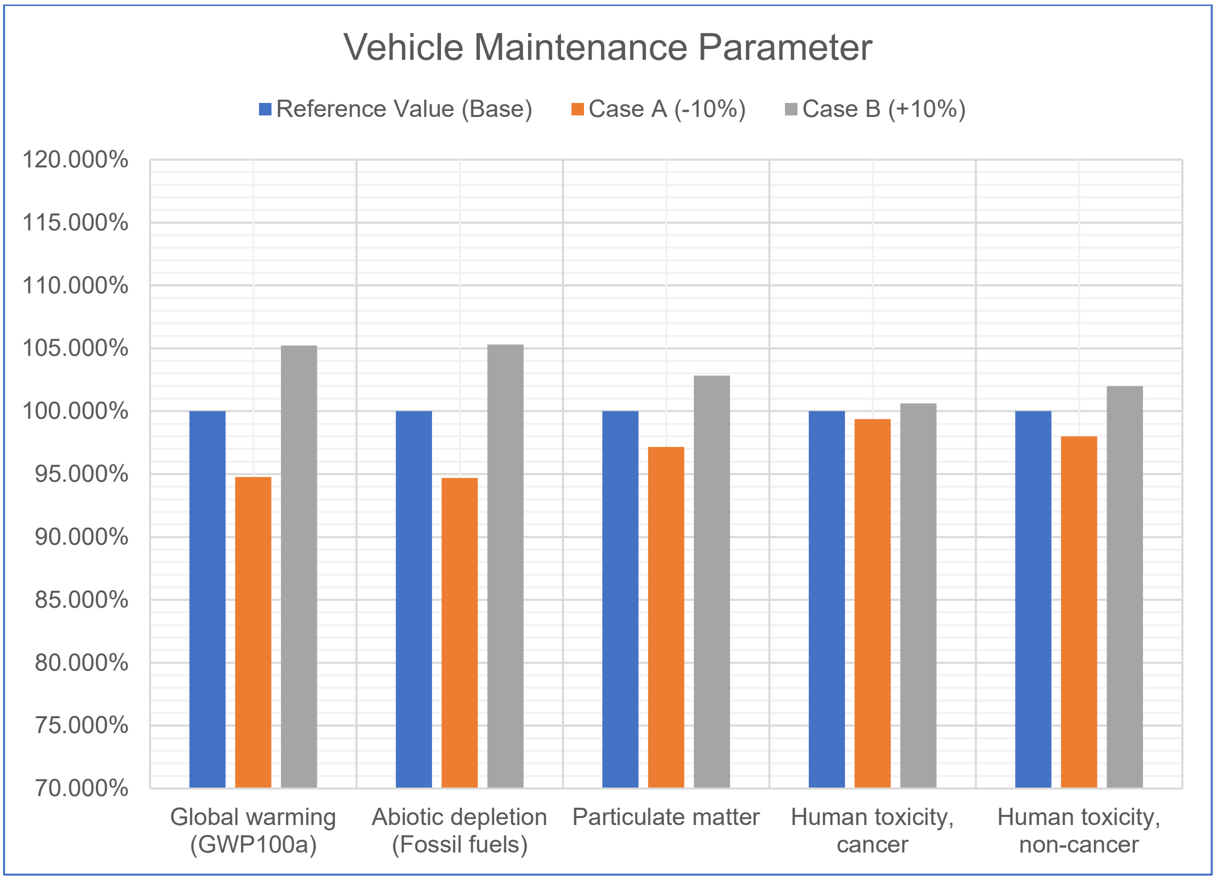


**Figure G.91: Sensitivity Analysis for LCA of Fuel Cell Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.024263517 | 0.024724953 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.29823677 | 0.30348795 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.21E-06 | 5.27E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.37E-10 | 4.40E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.31E-09 | 2.41E-09 | -2 | 2 |

**Table G.92: Sensitivity Analysis for LCA of Fuel Cell Buses (Hydrogen Production Parameter)**

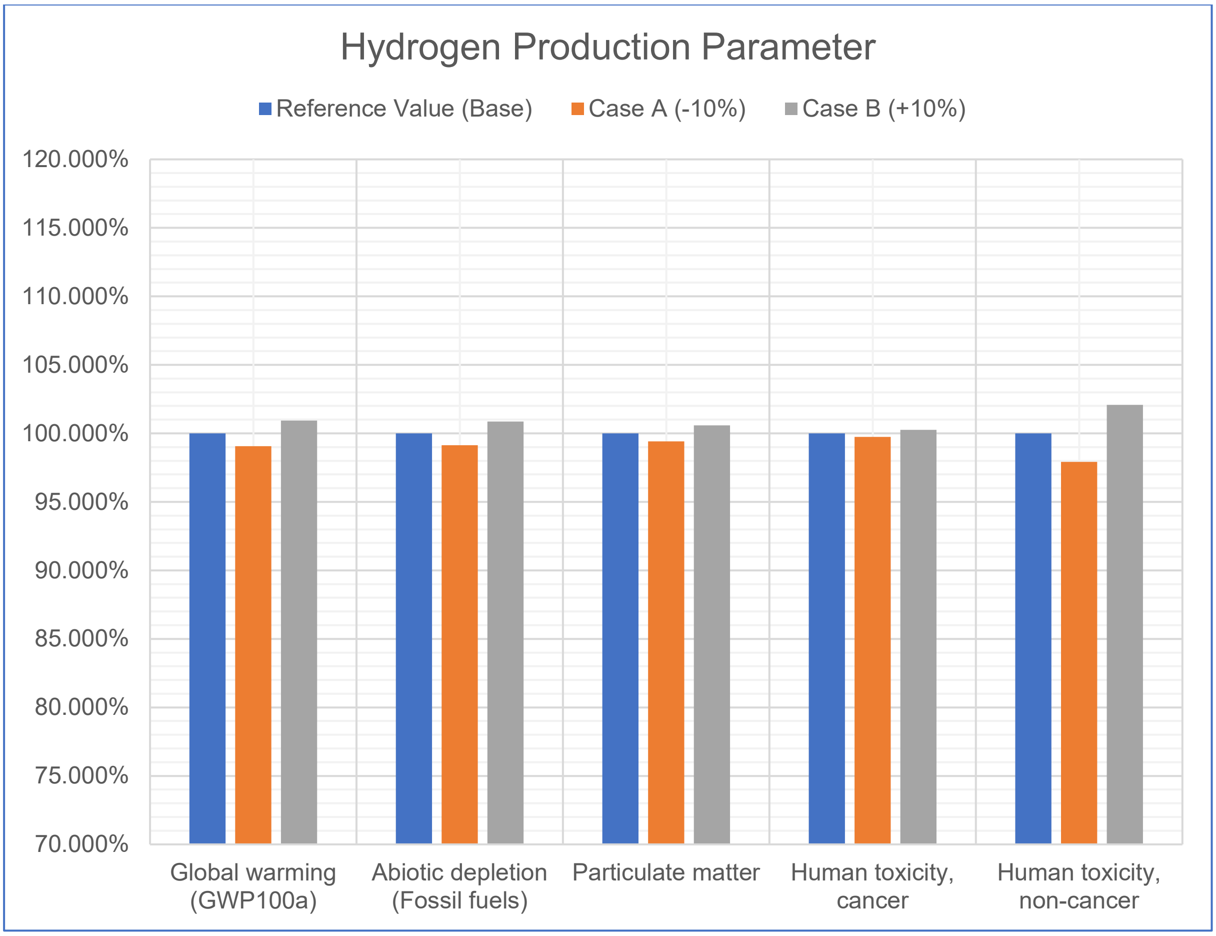


**Figure G.92: Sensitivity Analysis for LCA of Fuel Cell Buses (Hydrogen Production Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.024470895 | 0.024517575 | -0.10 | 0.10 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.30085375 | 0.30087097 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.24E-06 | 5.24E-06 | -0.01 | 0.01 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.38E-10 | 4.39E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.36E-09 | 2.36E-09 | -0.01 | 0.01 |

**Table G.93: Sensitivity Analysis for LCA of Fuel Cell Buses (Vehicle Disposal Parameter)**

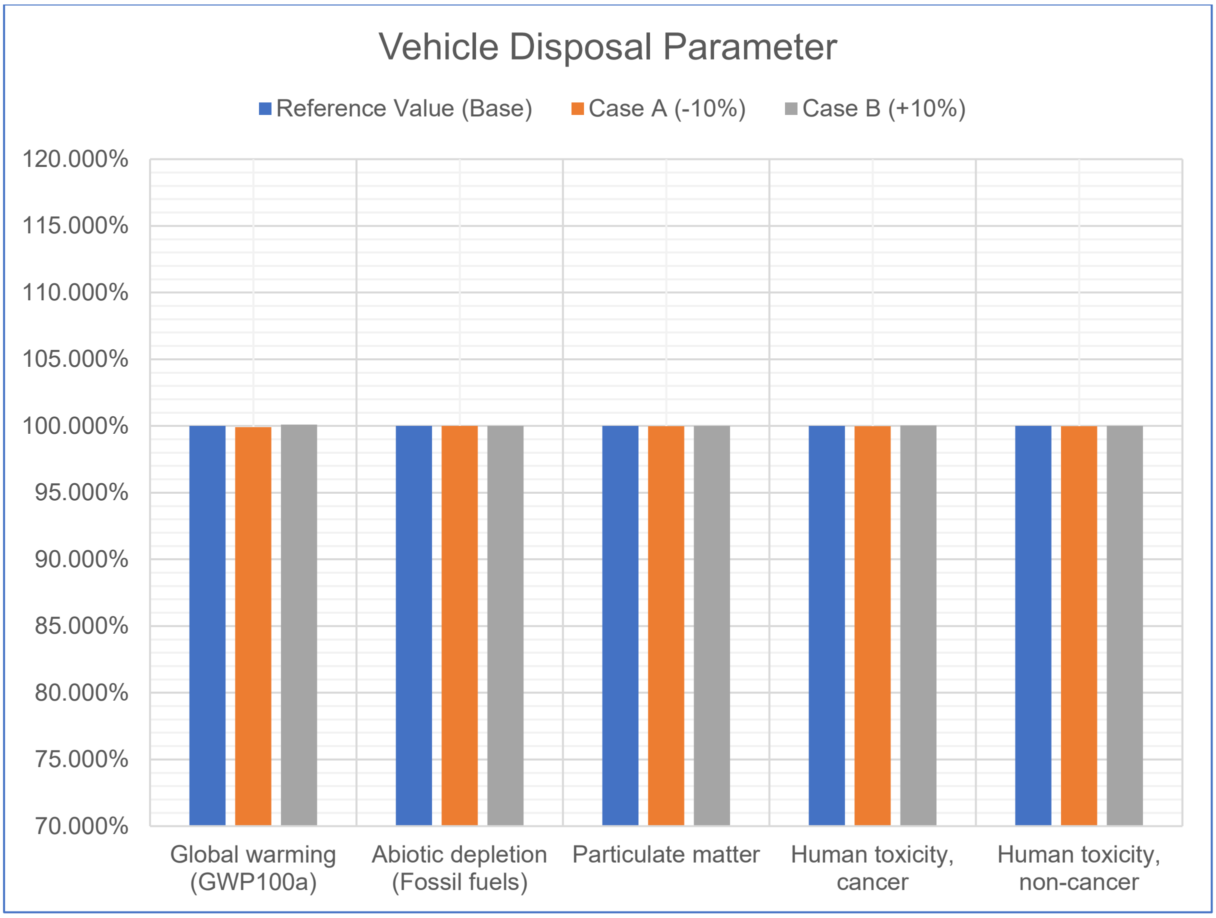


**Figure G.93: Sensitivity Analysis for LCA of Fuel Cell Buses (Vehicle Disposal Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.024494235 | 0.024493192 | 0.024495278 | 0.00 | 0.00 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.30086236 | 0.3008505 | 0.30087423 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 5.24E-06 | 5.24E-06 | 5.24E-06 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.38E-10 | 4.38E-10 | 4.38E-10 | 0.00 | 0.00 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.36E-09 | 2.36E-09 | 2.36E-09 | -0.01 | 0.01 |

**Table G.94: Sensitivity Analysis for LCA of Fuel Cell Buses (Hydrogen Processing Parameter)**

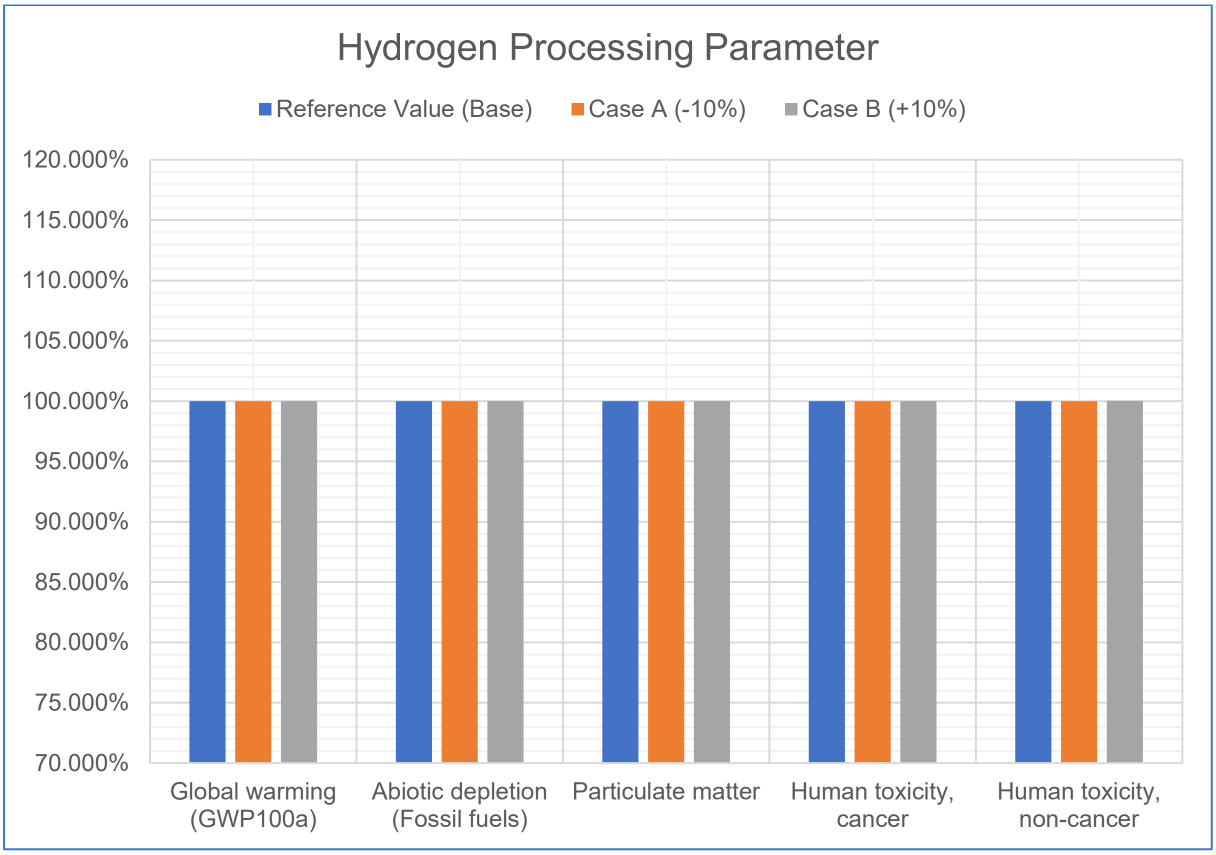


**Figure G.94: Sensitivity Analysis for LCA of Fuel Cell Buses (Hydrogen Processing Parameter)**

## Battery Electric Buses

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.09743295 | 0.10825883 | 0.088575409 | 11.11 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.1308484 | 1.2564982 | 1.028044 | 11.11 | -9.09 |
| **Particulate Matter (kg/pkm)** | 1.47E-05 | 1.63E-05 | 1.33E-05 | 11.11 | -9.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 6.73E-10 | 7.48E-10 | 6.12E-10 | 11.11 | -9.09 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.14E-09 | 6.82E-09 | 5.58E-09 | 11.11 | -9.09 |

**Table G.95: Sensitivity Analysis for LCA of Battery Electric Bus (Occupancy Rate Parameter)**

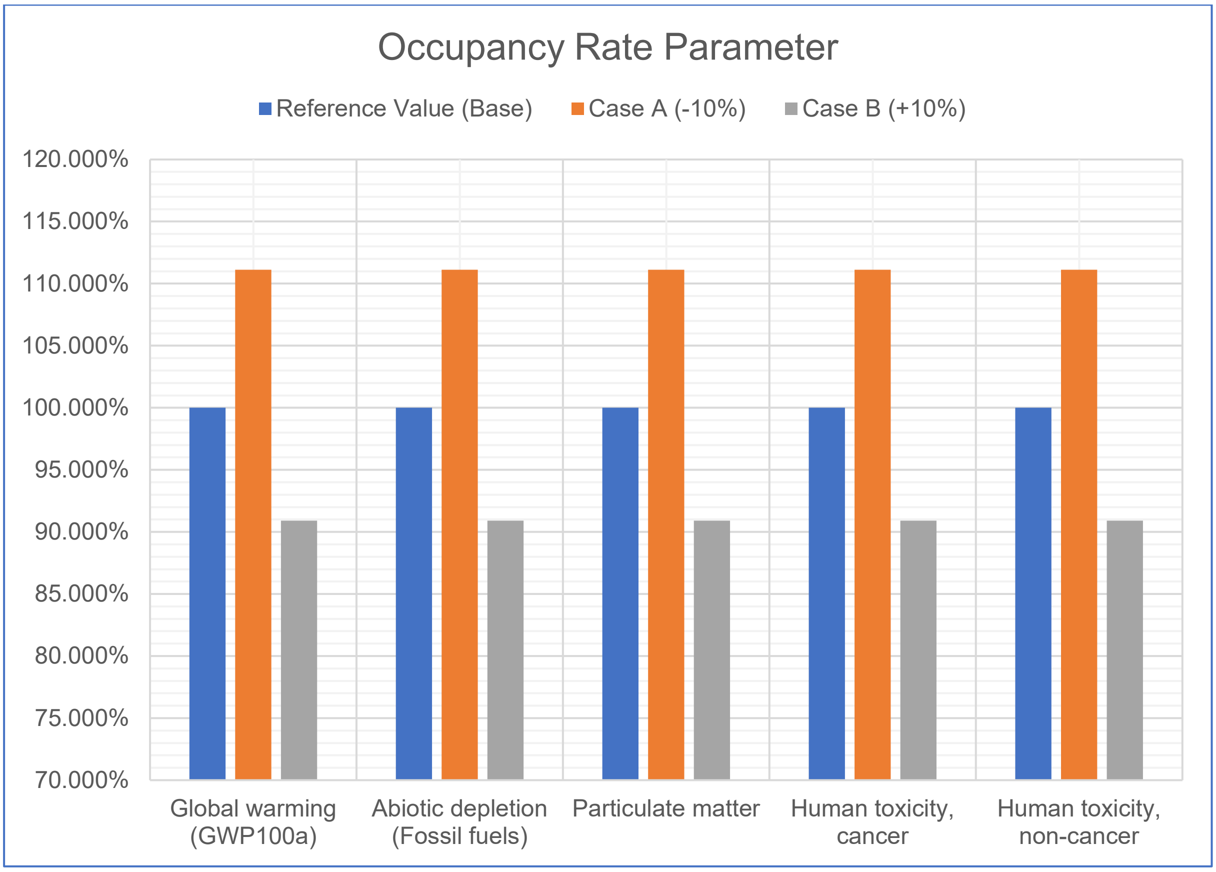


**Figure G.95: Sensitivity Analysis for LCA of Battery Electric Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.09743295 | 0.10535146 | 0.090954165 | 8.13 | -6.65 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.1308484 | 1.2210231 | 1.0570691 | 7.97 | -6.52 |
| **Particulate Matter (kg/pkm)** | 1.47E-05 | 1.55E-05 | 1.40E-05 | 5.70 | -4.67 |
| **Human Toxicity, Cancer (kg/pkm)** | 6.73E-10 | 6.89E-10 | 6.60E-10 | 2.34 | -1.91 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.14E-09 | 6.44E-09 | 5.89E-09 | 4.86 | -3.97 |

**Figure G.96: Sensitivity Analysis for LCA of Battery Electric Buses (Kilometres Travelled Parameter)**

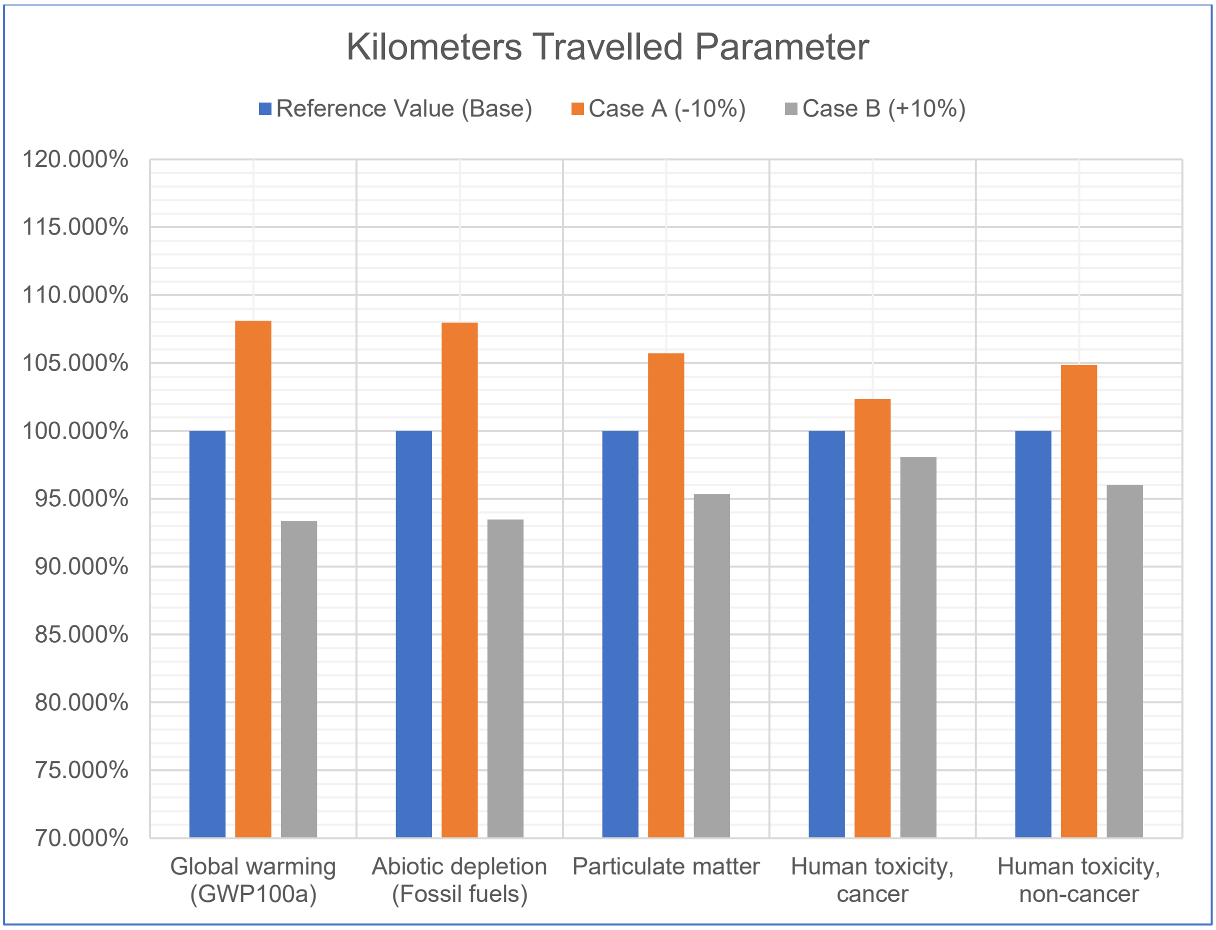


**Figure G.96: Sensitivity Analysis for LCA of Battery Electric Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.09743295 | 0.096340749 | 0.09852515 | -1.12 | 1.12 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.1308484 | 1.1170898 | 1.144607 | -1.22 | 1.22 |
| **Particulate Matter (kg/pkm)** | 1.47E-05 | 1.42E-05 | 1.51E-05 | -3.12 | 3.12 |
| **Human Toxicity, Cancer (kg/pkm)** | 6.73E-10 | 6.27E-10 | 7.19E-10 | -6.81 | 6.81 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.14E-09 | 5.93E-09 | 6.35E-09 | -3.44 | 3.44 |

**Table G.97: Sensitivity Analysis for LCA of Battery Electric Buses (Vehicle Manufacture Parameter)**

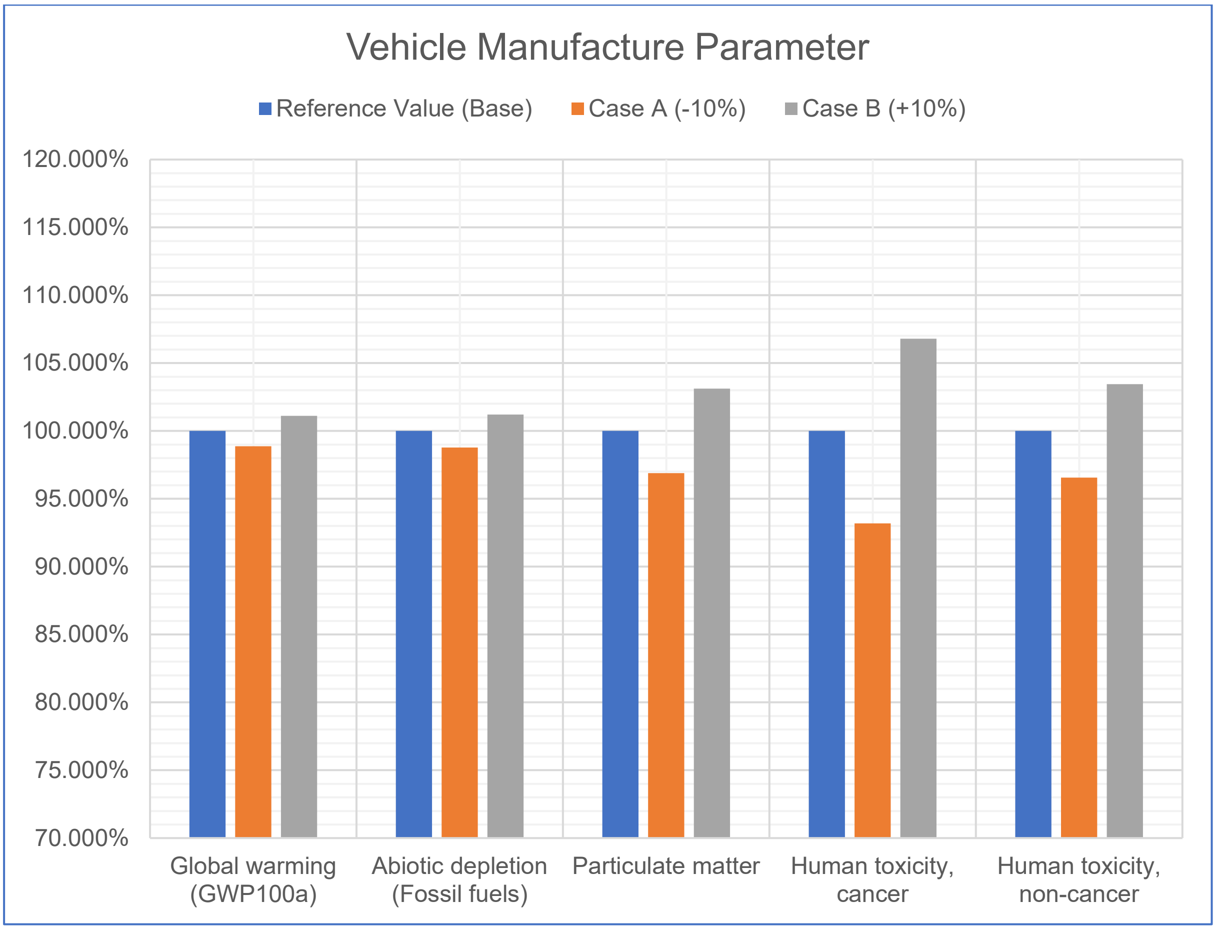


**Figure G.97: Sensitivity Analysis for LCA of Battery Electric Buses (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.09743295 | 0.095956888 | 0.098909011 | -1.51 | 1.51 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.1308484 | 1.1129046 | 1.1487922 | -1.59 | 1.59 |
| **Particulate Matter (kg/pkm)** | 1.47E-05 | 1.44E-05 | 1.49E-05 | -1.66 | 1.66 |
| **Human Toxicity, Cancer (kg/pkm)** | 6.73E-10 | 6.66E-10 | 6.80E-10 | -1.06 | 1.06 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.14E-09 | 6.01E-09 | 6.27E-09 | -2.15 | 2.15 |

**Figure G.98: Sensitivity Analysis for LCA of Battery Electric Buses (Vehicle Maintenance Parameter)**

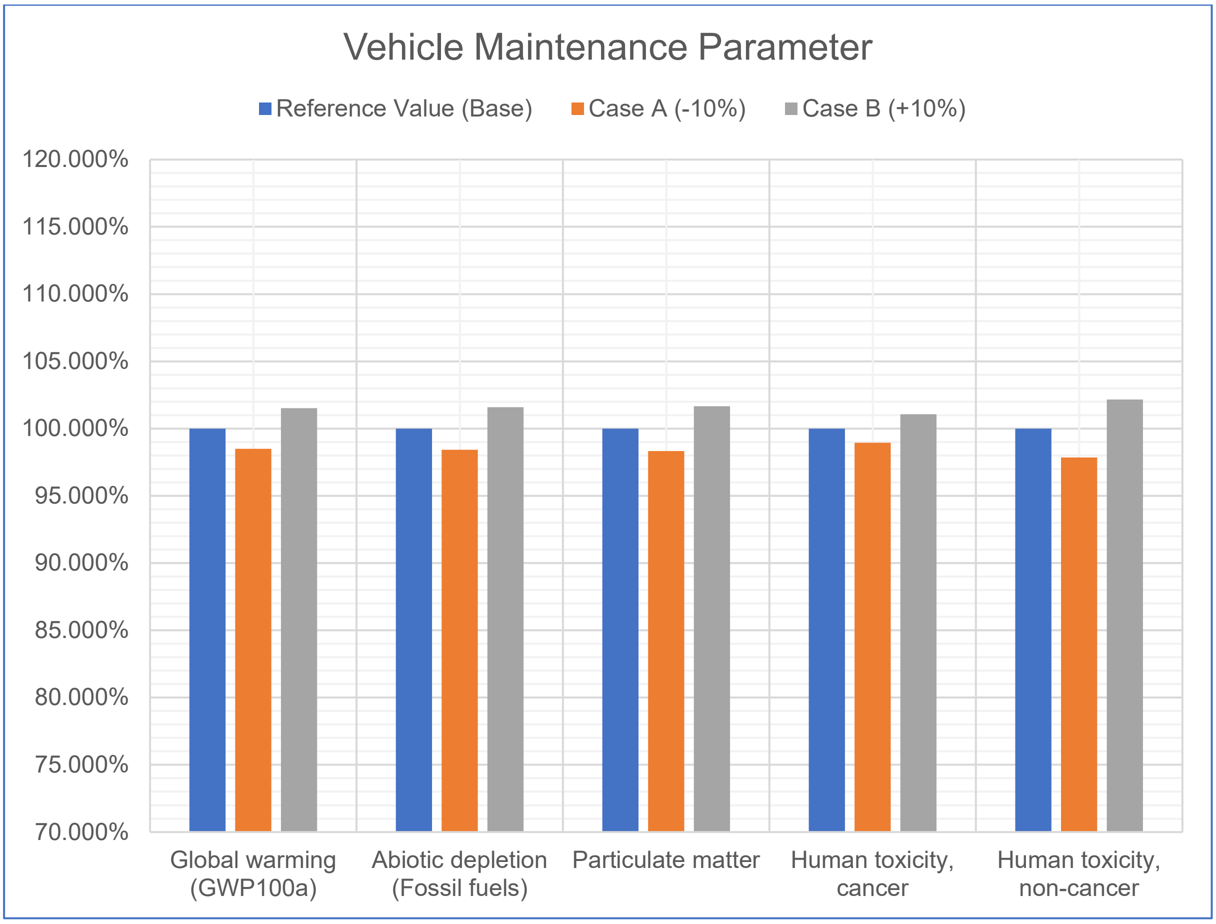


**Figure G.98: Sensitivity Analysis for LCA of Battery Electric Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.09743295 | 0.09738458 | 0.09748132 | -0.05 | 0.05 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.1308484 | 1.1306231 | 1.1310736 | -0.02 | 0.02 |
| **Particulate Matter (kg/pkm)** | 1.47E-05 | 1.46E-05 | 1.47E-05 | -0.09 | 0.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 6.73E-10 | 6.73E-10 | 6.73E-10 | -0.03 | 0.03 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.14E-09 | 6.14E-09 | 6.14E-09 | -0.04 | 0.04 |

**Table G.99: Sensitivity Analysis for LCA of Battery Electric Buses (Vehicle Disposal Parameter)**

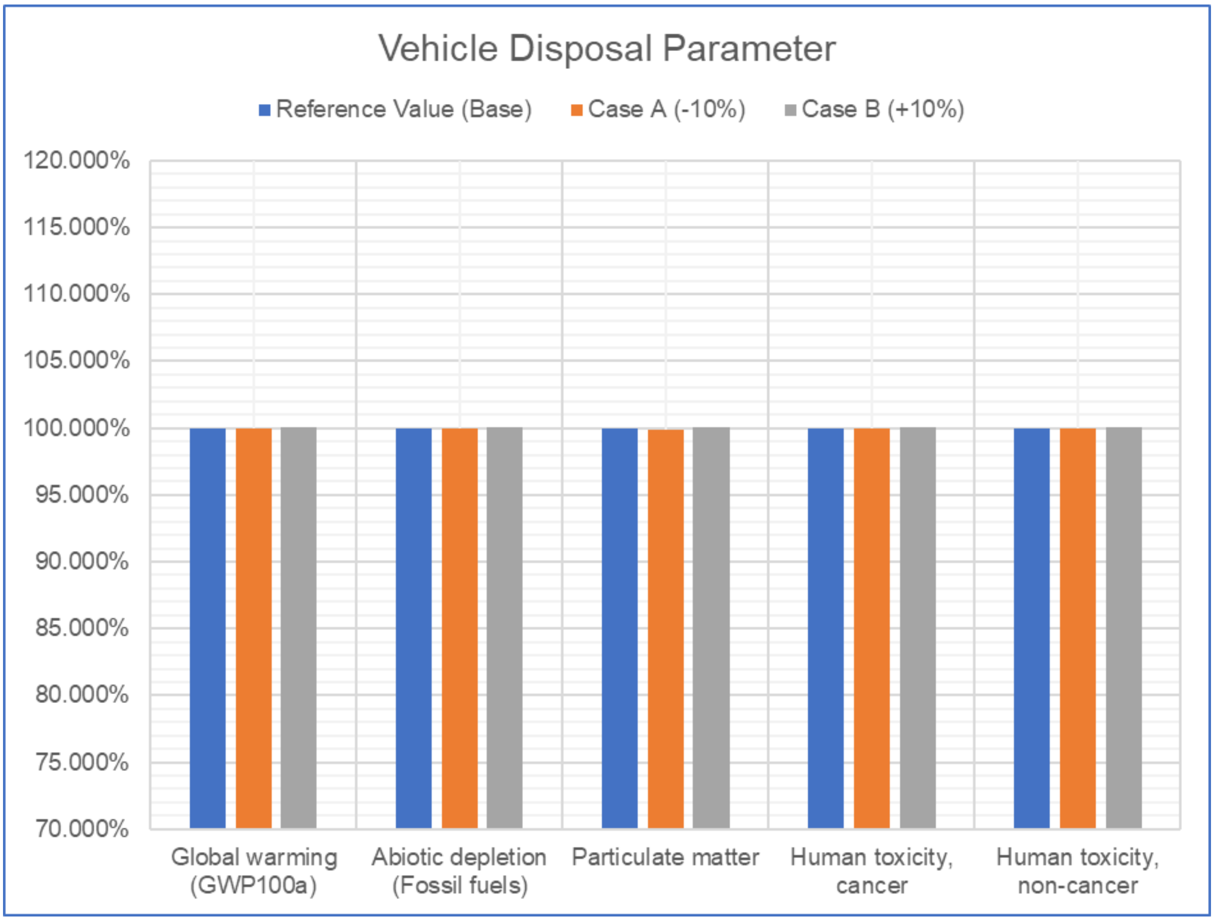


**Figure G.99: Sensitivity Analysis for LCA of Battery Electric Buses (Vehicle Disposal Parameter)**

### Low Sulphur Diesel Rigid Trucks (LSD)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.28567213 | 0.34161154 | -9 | 9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 3.5112739 | 4.1707929 | -9 | 9 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.000232552 | 0.000281832 | -10 | 10 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.36E-09 | 1.40E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 6.74E-09 | 7.06E-09 | -2 | 2 |

**Table G.100: Sensitivity Analysis for LCA of LSD Rigid Trucks (Fuel Consumption Parameter)**

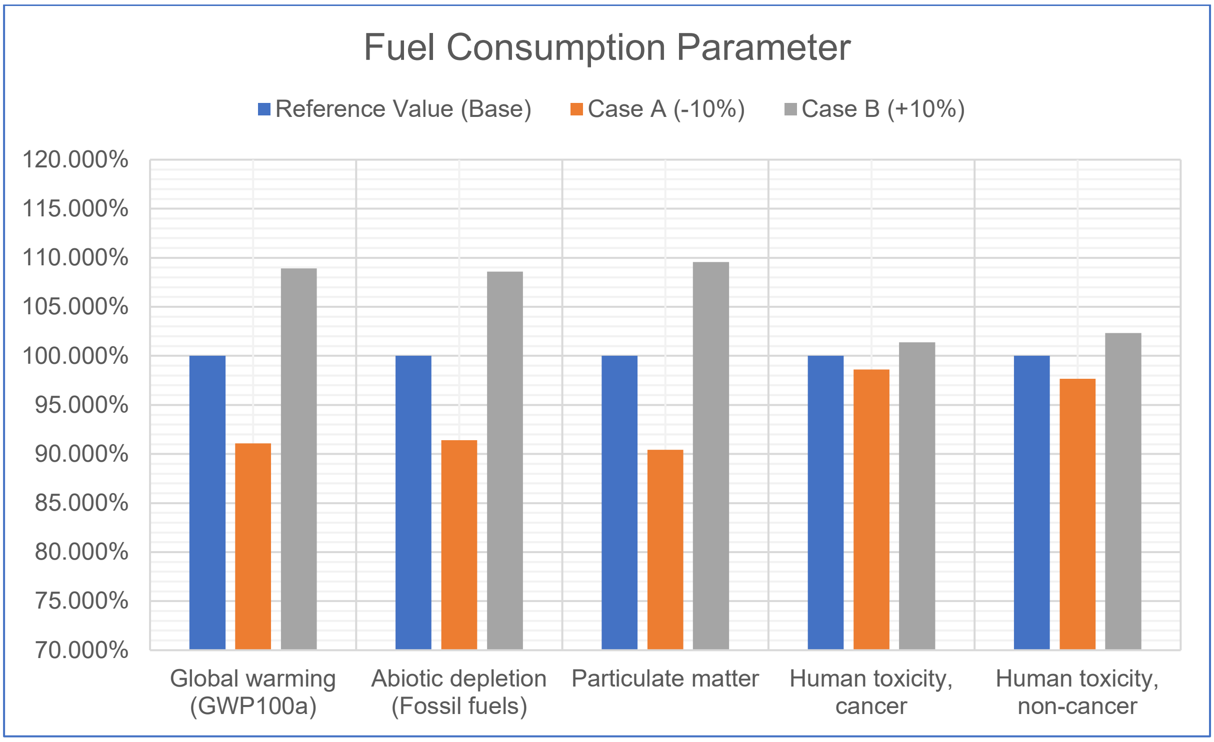


**Figure G.100: Sensitivity Analysis for LCA of LSD Rigid Trucks (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.34849093 | 0.28512894 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 4.2678149 | 3.4918486 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.000285769 | 0.000233811 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.53E-09 | 1.25E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 7.67E-09 | 6.28E-09 | 11 | -9 |

**Table G.101: Sensitivity Analysis for LCA of LSD Rigid Trucks (Average Load Factor)**

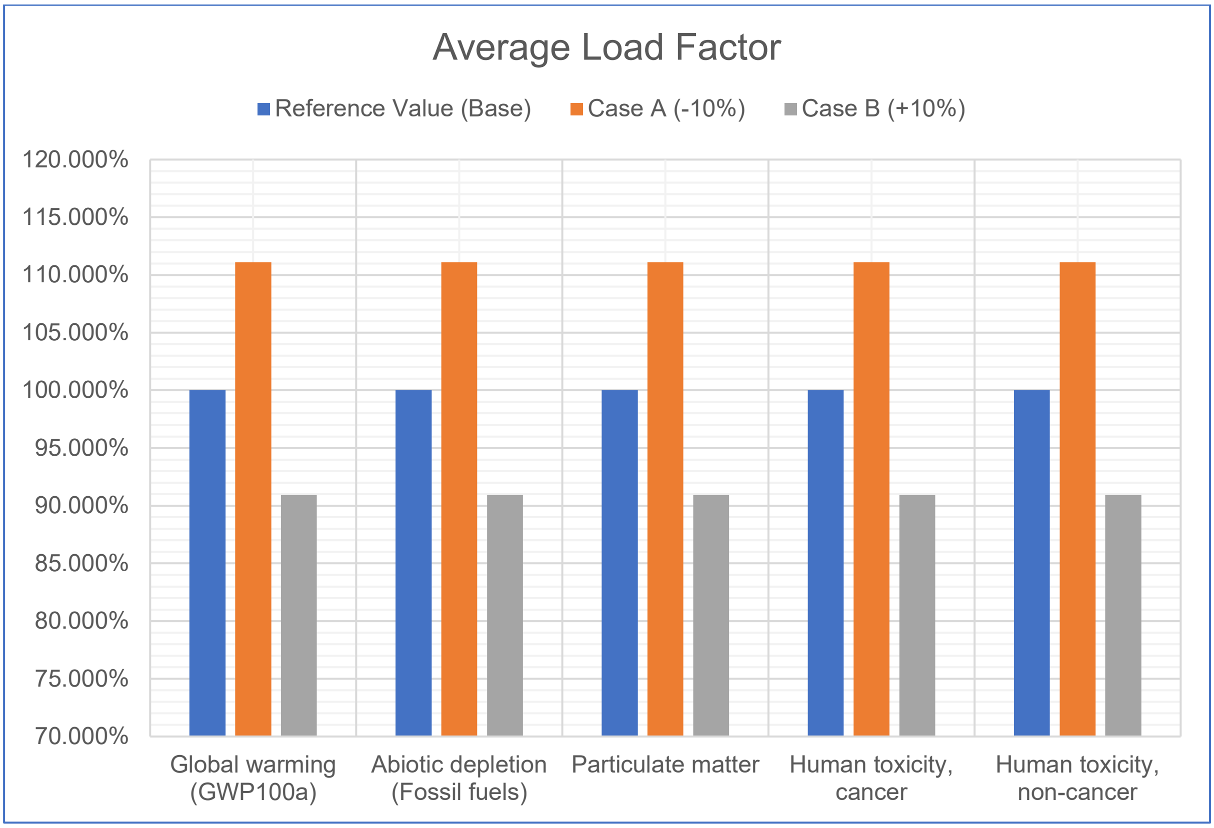


**Figure G.101: Sensitivity Analysis for LCA of LSD Rigid Trucks (Average Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.34471929 | 0.28821483 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 4.2074329 | 3.541252 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.00028457 | 0.000234792 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.40E-09 | 1.36E-09 | 2 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 7.08E-09 | 6.76E-09 | 3 | -2 |

**Table G.102: Sensitivity Analysis for LCA of LSD Rigid Trucks (Fraction Load Factor)**

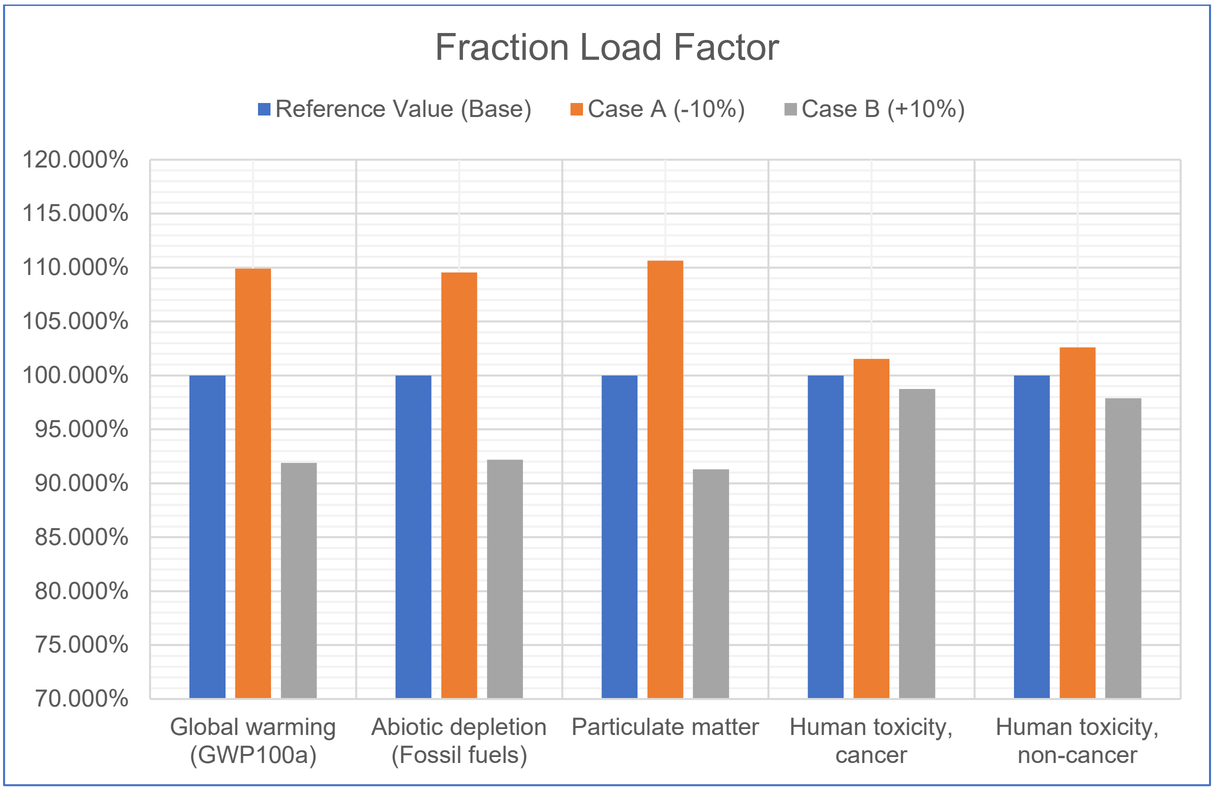


**Figure G.102: Sensitivity Analysis for LCA of LSD Rigid Trucks (Fraction Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.31163828 | 0.3156454 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 3.8131858 | 3.868881 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.000256523 | 0.000257861 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.27E-09 | 1.48E-09 | -8 | 8 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 6.50E-09 | 7.31E-09 | -6 | 6 |

Table G.103: Sensitivity Analysis for LCA of LSD Rigid Trucks (Vehicle Manufacture Parameter)

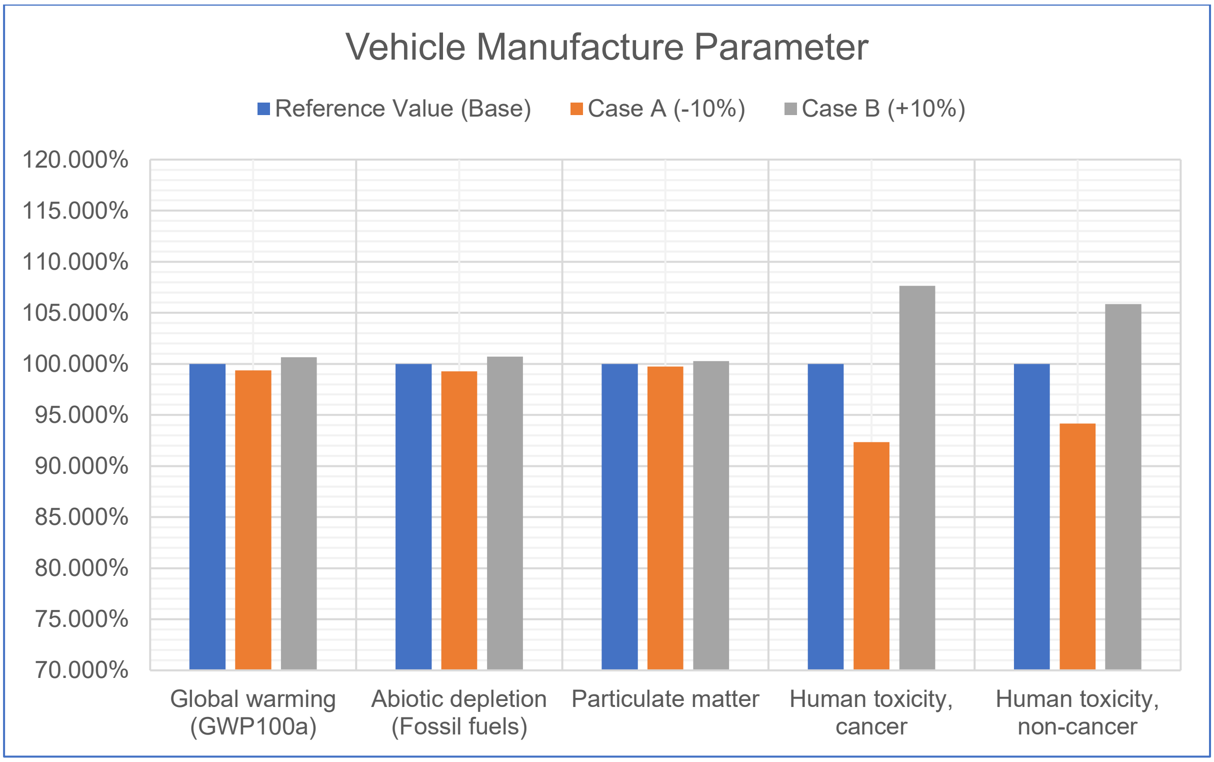


Figure G.103: Sensitivity Analysis for LCA of LSD Rigid Trucks (Vehicle Manufacture Parameter)

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.31339164 | 0.31389203 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 3.7579803 | 3.9240865 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.000257068 | 0.000257316 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.38E-09 | 1.38E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 6.89E-09 | 6.91E-09 | 0 | 0 |

**Table G.104: Sensitivity Analysis for LCA of LSD Rigid Trucks (Crude Oil Extraction Parameter)**

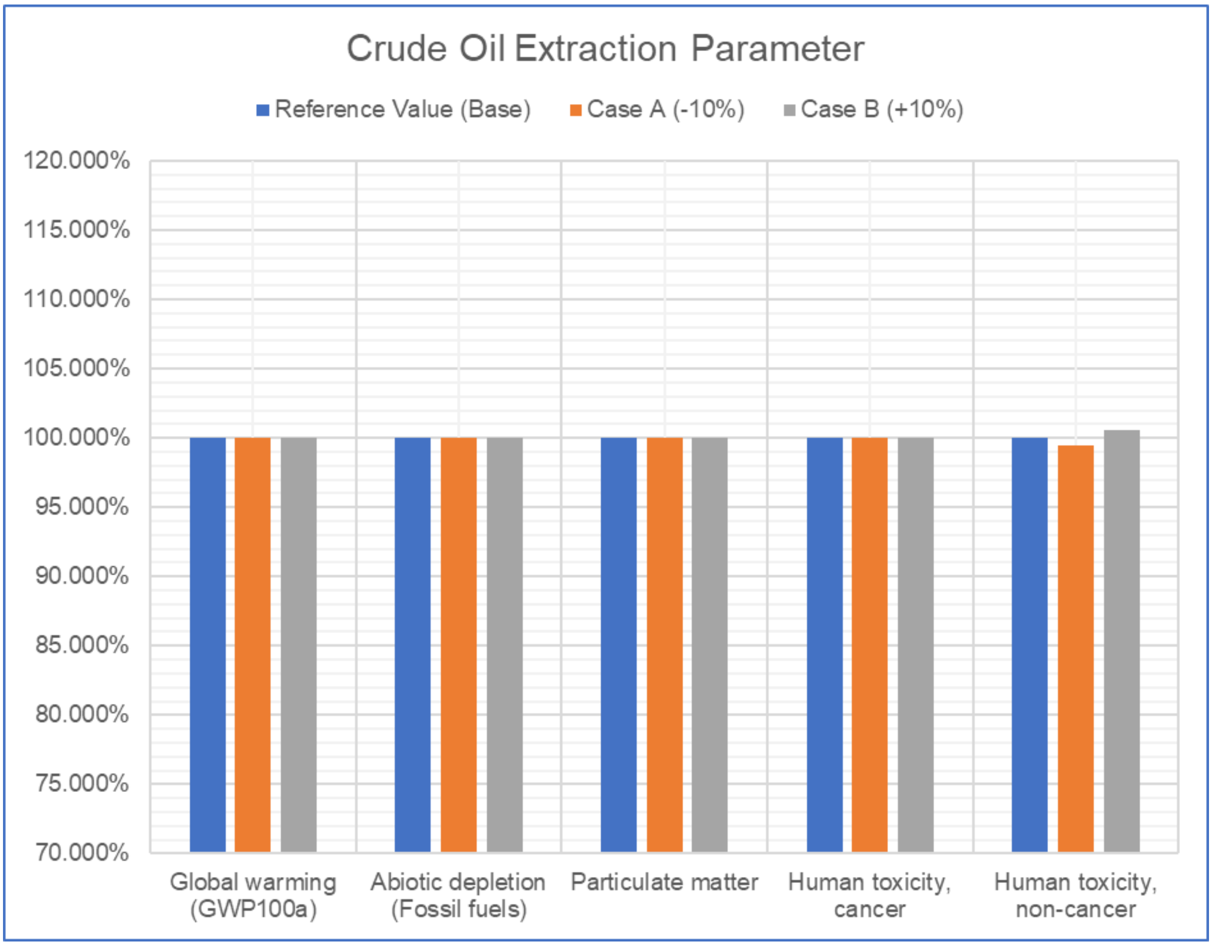


**Figure G.104: Sensitivity Analysis for LCA of LSD Rigid Trucks (Crude Oil Extraction Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.31164246 | 0.31564122 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 3.5552747 | 4.1267921 | -7 | 7 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.000255612 | 0.000258772 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.36E-09 | 1.39E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 6.81E-09 | 7.00E-09 | -1 | 1 |

**Table G.105: Sensitivity Analysis for LCA of LSD Rigid Trucks (Crude Oil Refining Parameter)**

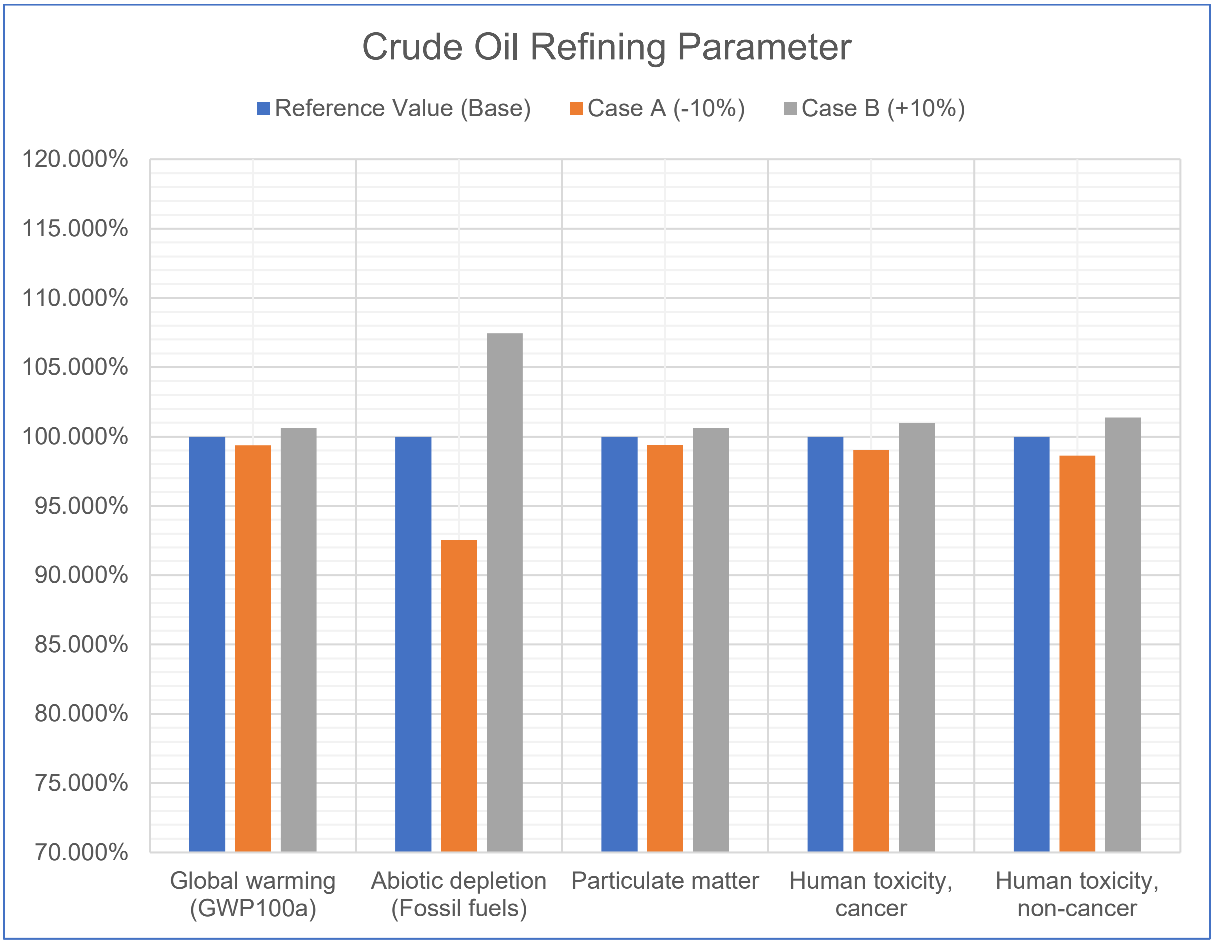


**Figure G.105: Sensitivity Analysis for LCA of Rigid Trucks (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.31230954 | 0.31497414 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 3.8146127 | 3.8674541 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.000256784 | 0.0002576 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.36E-09 | 1.39E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 6.81E-09 | 6.99E-09 | -1 | 1 |

**Table G.106: Sensitivity Analysis for LCA of LSD Rigid Trucks (Vehicle Maintenance Parameter)**

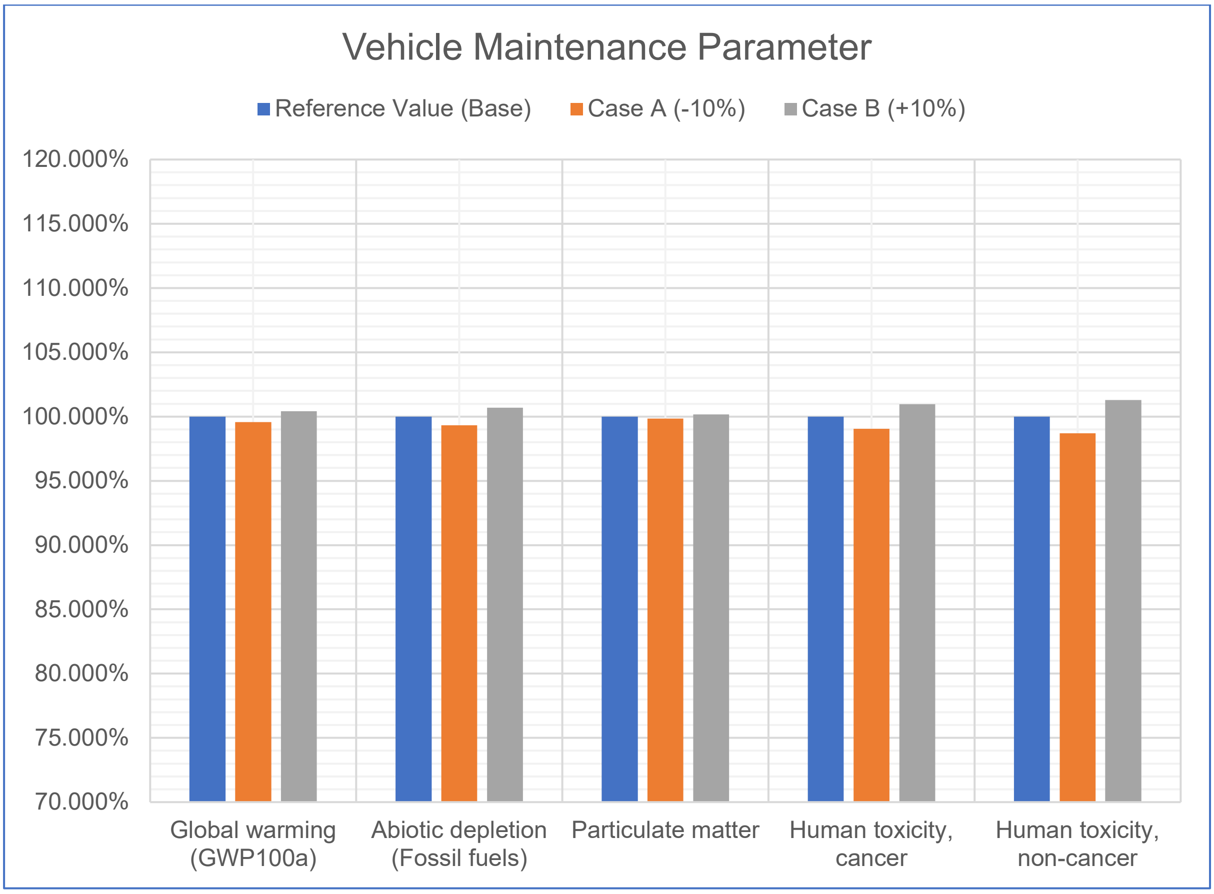


**Figure G.106: Sensitivity Analysis for LCA of LSD Rigid Trucks (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.31364184 | 0.31358322 | 0.31370045 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.8410334 | 3.8409578 | 3.841109 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 0.000257192 | 0.00025719 | 0.000257194 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.38E-09 | 1.38E-09 | 1.38E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.90E-09 | 6.87E-09 | 6.94E-09 | -1 | 1 |

Table G.107: Sensitivity Analysis for LCA of LSD Rigid Trucks (Vehicle Disposal Parameter)

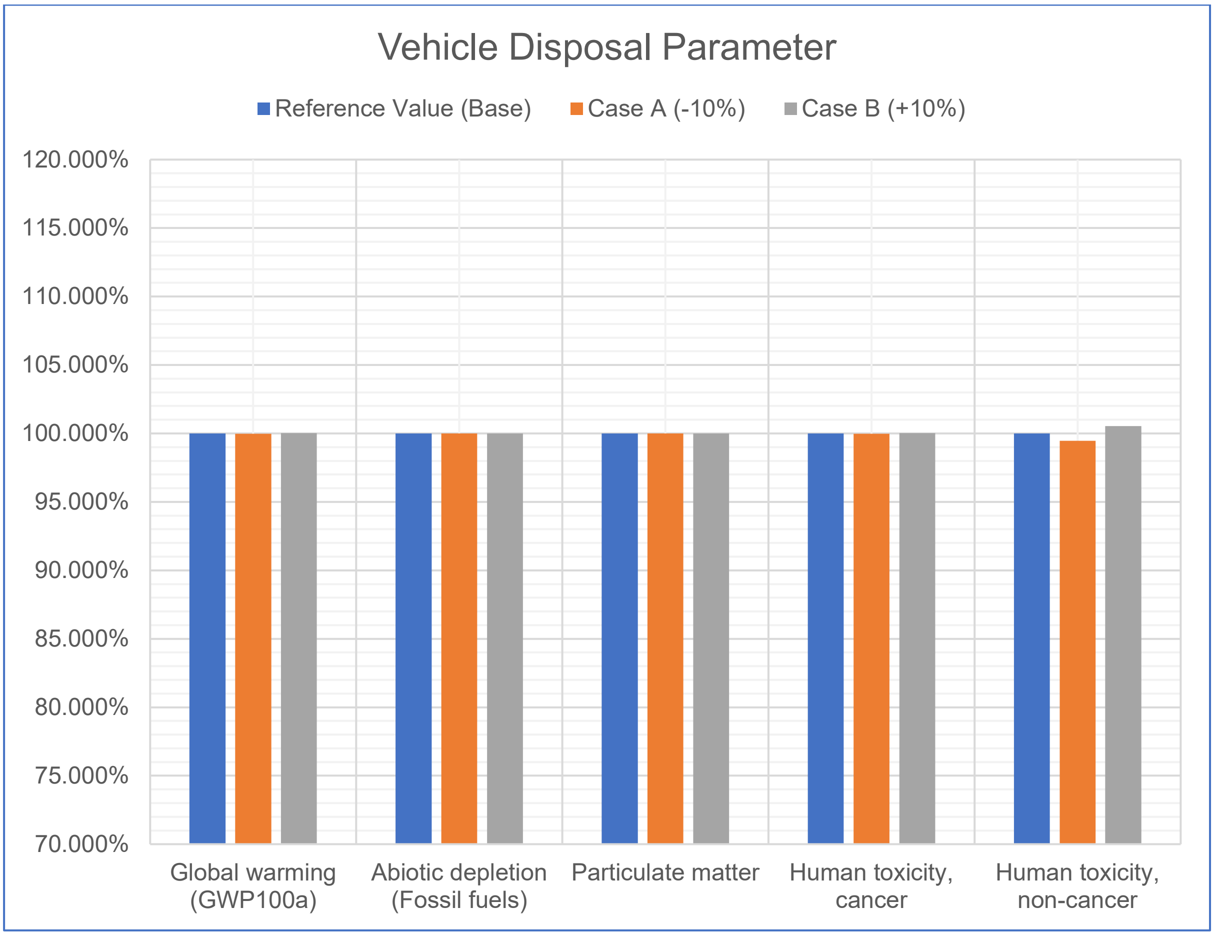


Figure G.107: Sensitivity Analysis for LCA of LSD Rigid Trucks (Vehicle Disposal Parameter)

## Hybrid Electric Rigid Trucks

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.52982624 | 0.43978814 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 6.4000046 | 5.3364944 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000450889 | 0.000371062 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.58E-09 | 1.52E-09 | 2 | -2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.67E-09 | 8.15E-09 | 3 | -3 |

**Table G.108: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Kilometres Travelled Parameter)**

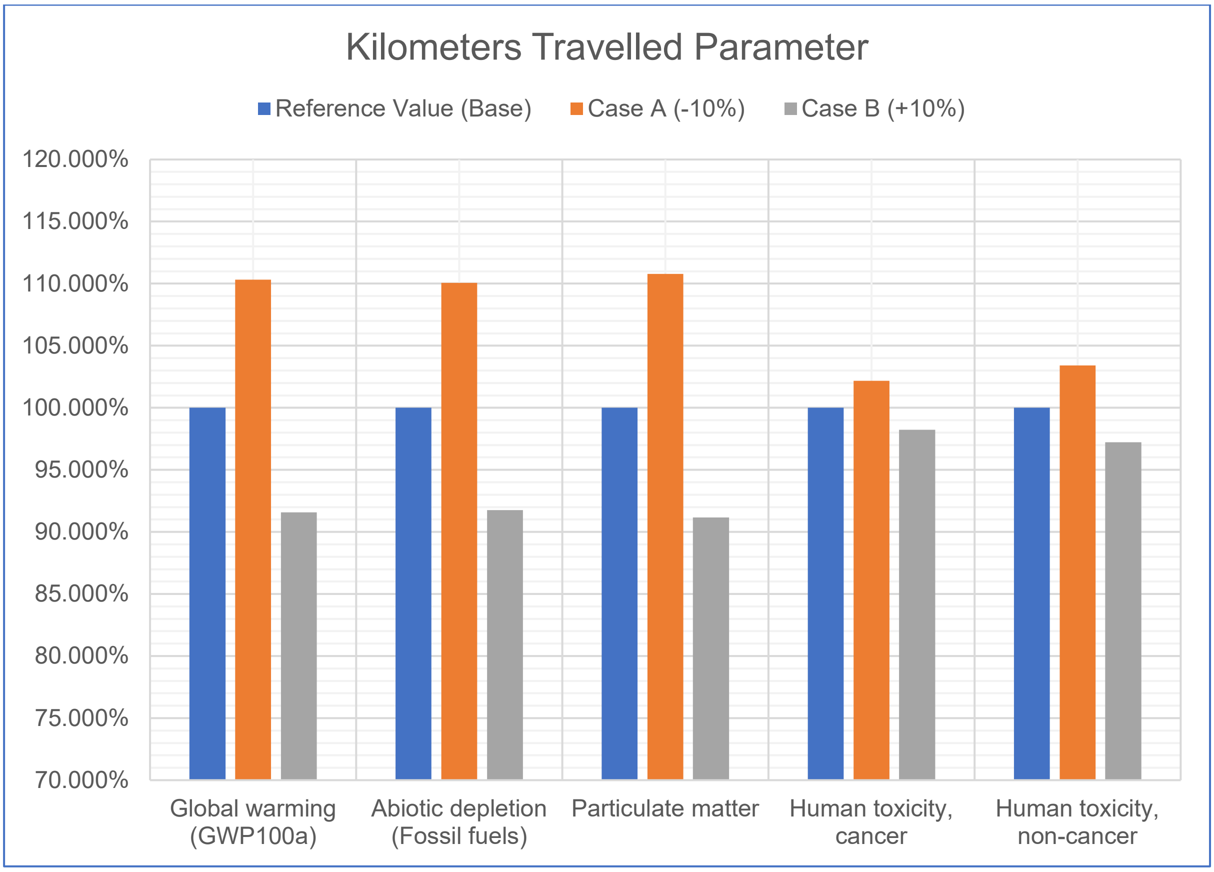


**Figure G.108: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.43573642 | 0.52487414 | -9 | 9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 5.2886364 | 6.3415115 | -9 | 9 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000367469 | 0.000446498 | -10 | 10 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.52E-09 | 1.58E-09 | -2 | 2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.13E-09 | 8.64E-09 | -3 | 3 |

**Table G.109: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Fuel Consumption Parameter)**

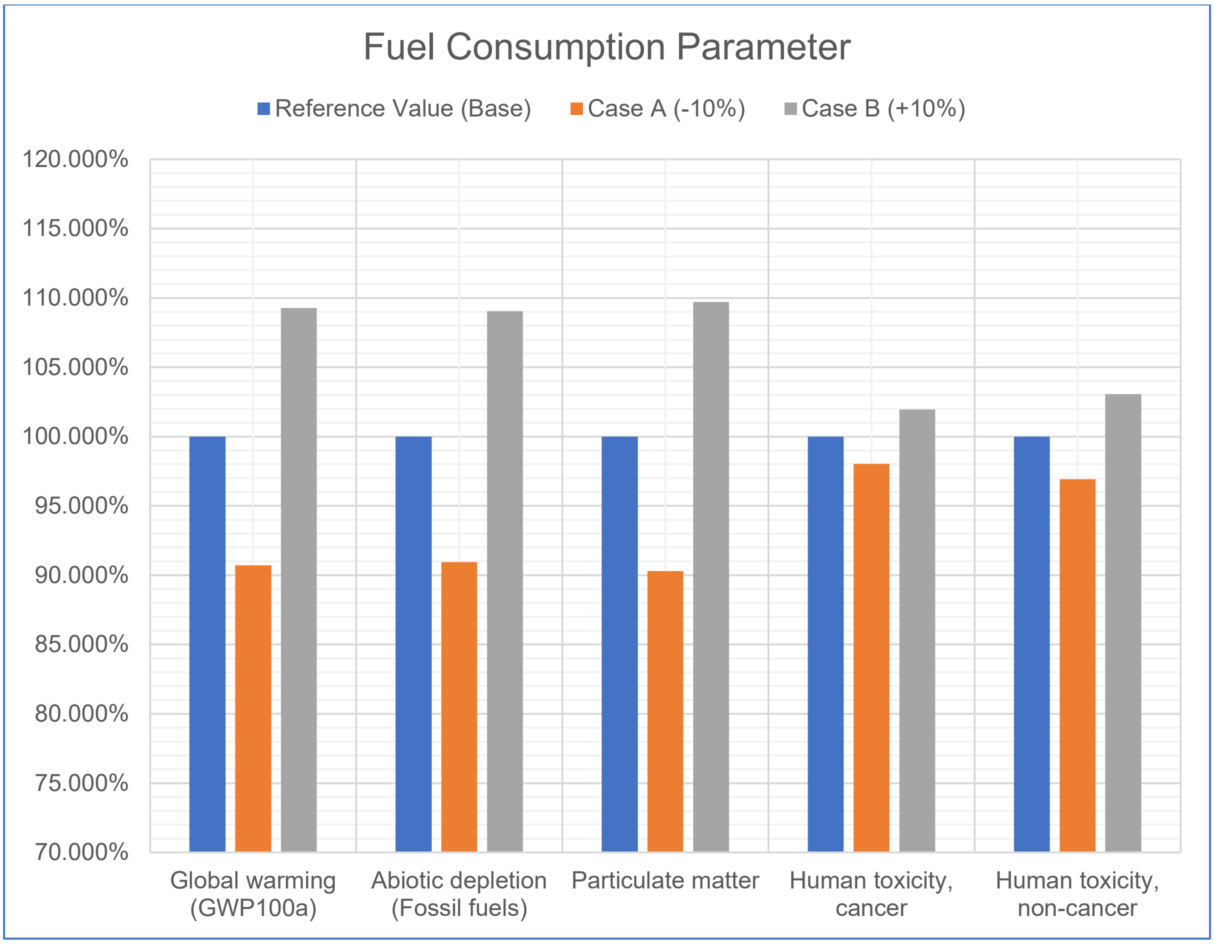


**Figure G.109: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Fuel Consumption Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.53367253 | 0.43664116 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 6.4611933 | 5.2864309 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000452204 | 0.000369985 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.72E-09 | 1.41E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 9.31E-09 | 7.62E-09 | 11 | -9 |

**Table G.110: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Average Load Factor)**

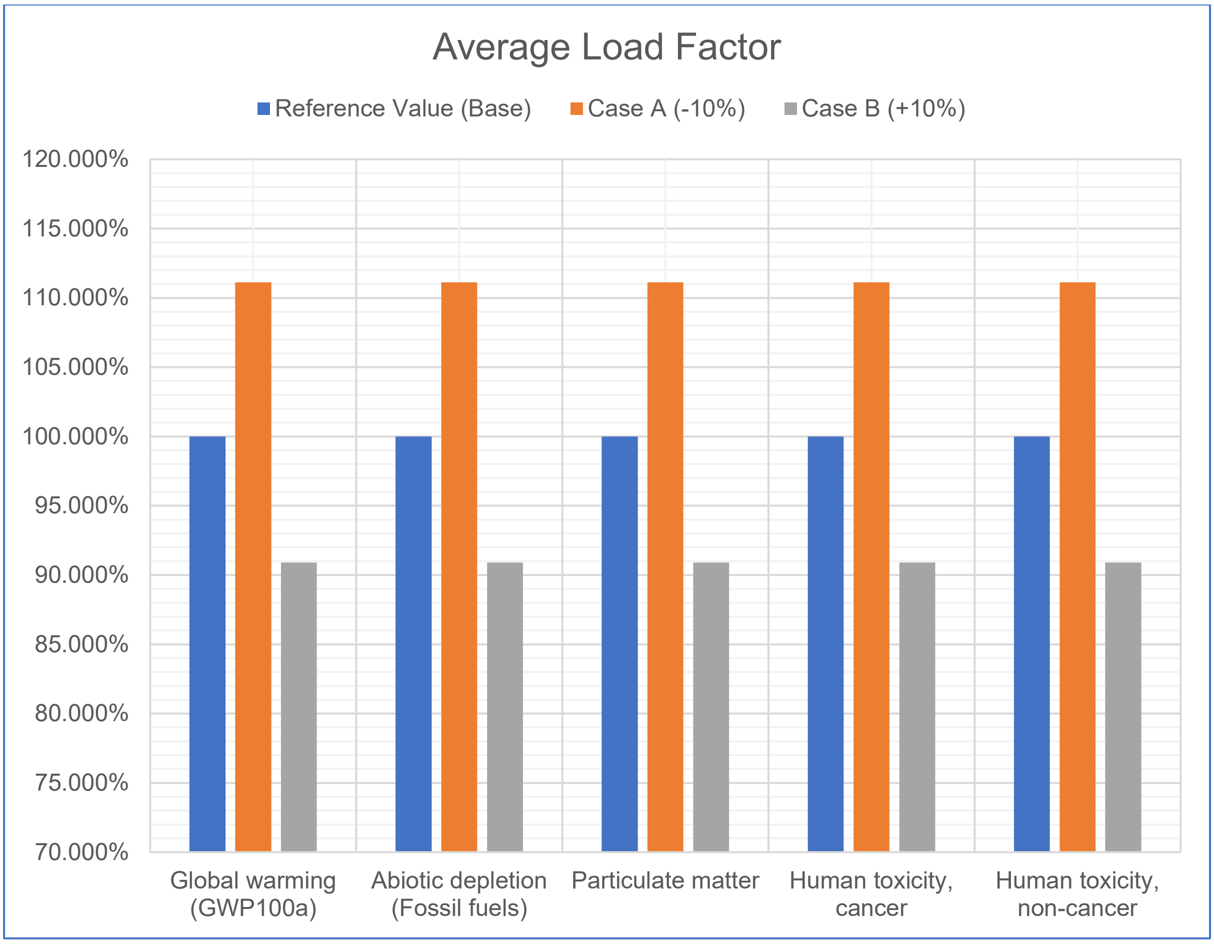


**Figure G.110: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Average Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.52982624 | 0.43978814 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 6.4000046 | 5.3364944 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000450889 | 0.000371062 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.58E-09 | 1.52E-09 | 2 | -2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.67E-09 | 8.15E-09 | 3 | -3 |

**Table G.111: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Friction Load Factor)**

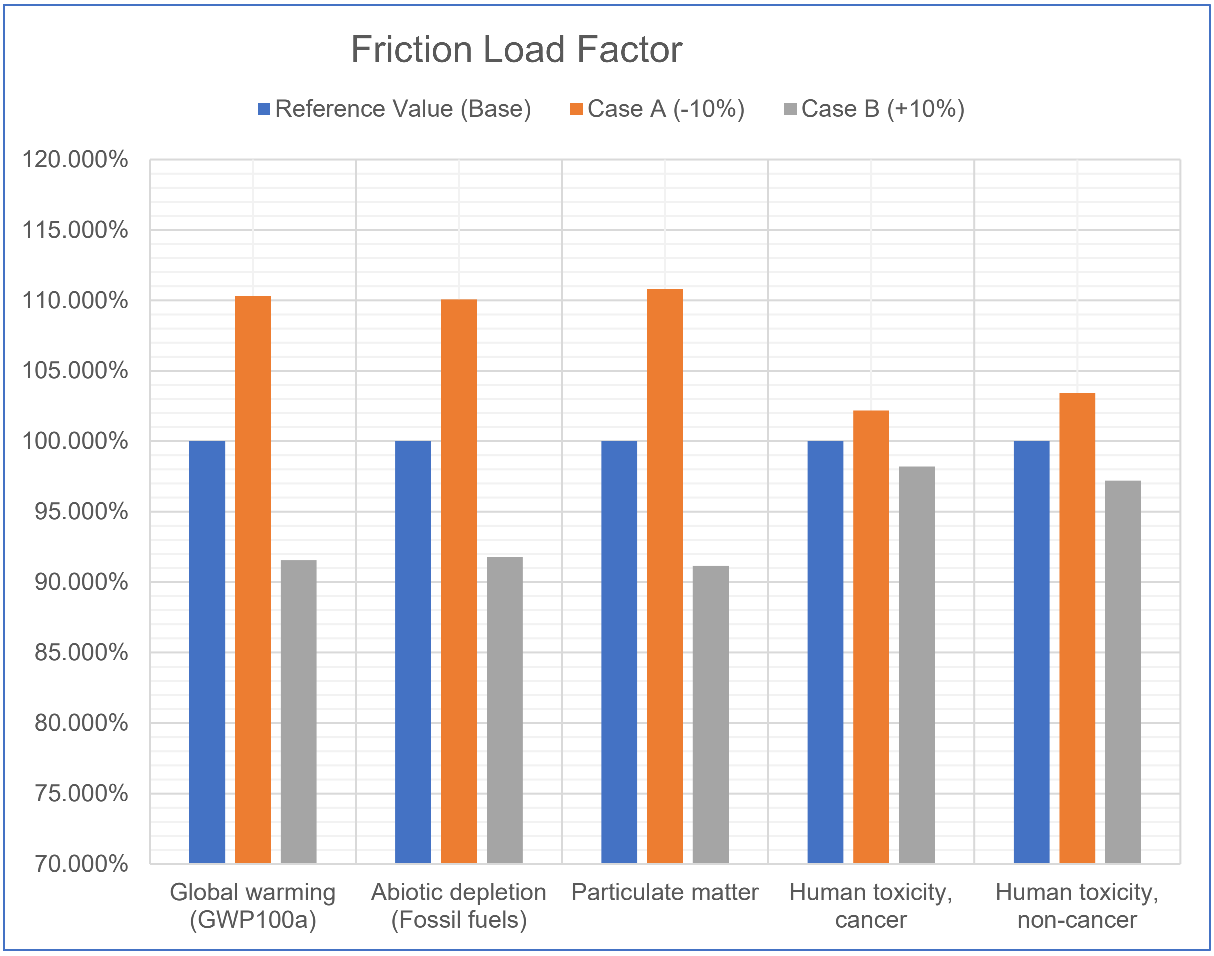


**Figure G.111: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Friction Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.47823741 | 0.48237316 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 5.7865252 | 5.8436227 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000406212 | 0.000407756 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.44E-09 | 1.66E-09 | -7 | 7 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 7.93E-09 | 8.84E-09 | -5 | 5 |

**Table G.112: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Vehicle Manufacture Parameter)**

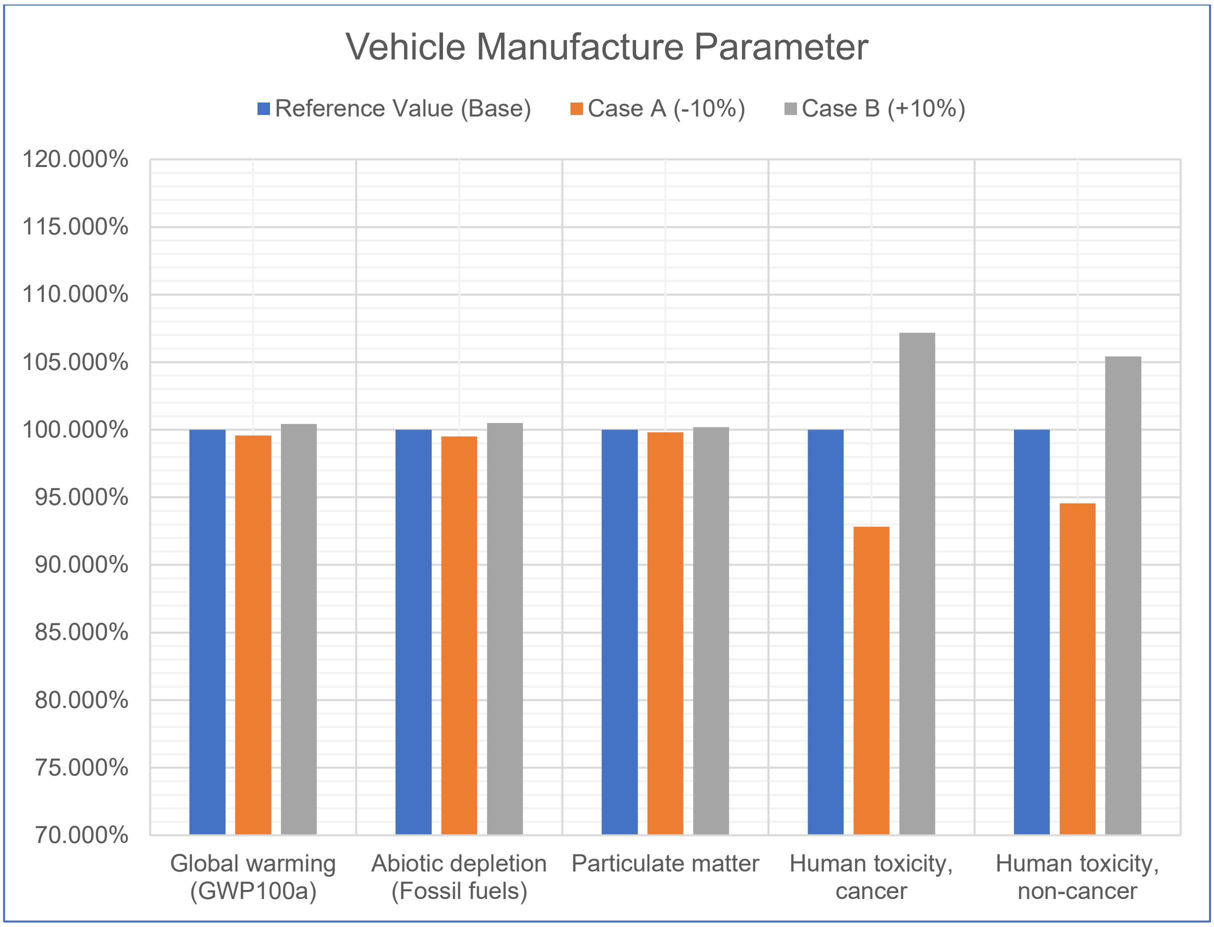


**Figure G.112: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.47897298 | 0.48163758 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 5.7886533 | 5.8414946 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000406576 | 0.000407392 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.54E-09 | 1.56E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.29E-09 | 8.47E-09 | -1 | 1 |

**Table G.113: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Vehicle Maintenance Parameter)**

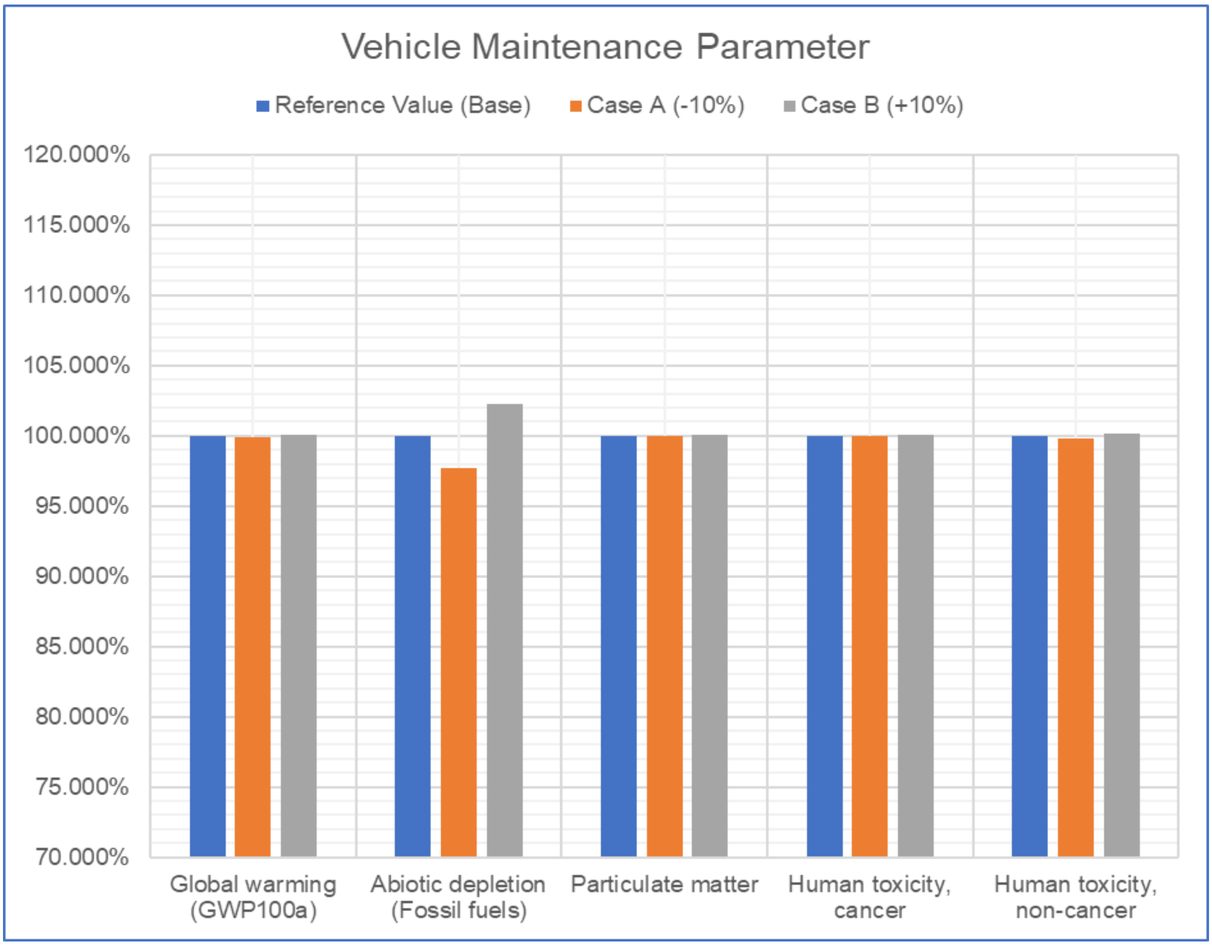


**Figure G.113: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.47711342 | 0.48349715 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 5.3588806 | 6.2712673 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000404461 | 0.000409507 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.53E-09 | 1.57E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.23E-09 | 8.53E-09 | -2 | 2 |

**Table G.114: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Crude Oil Refining Parameter)**

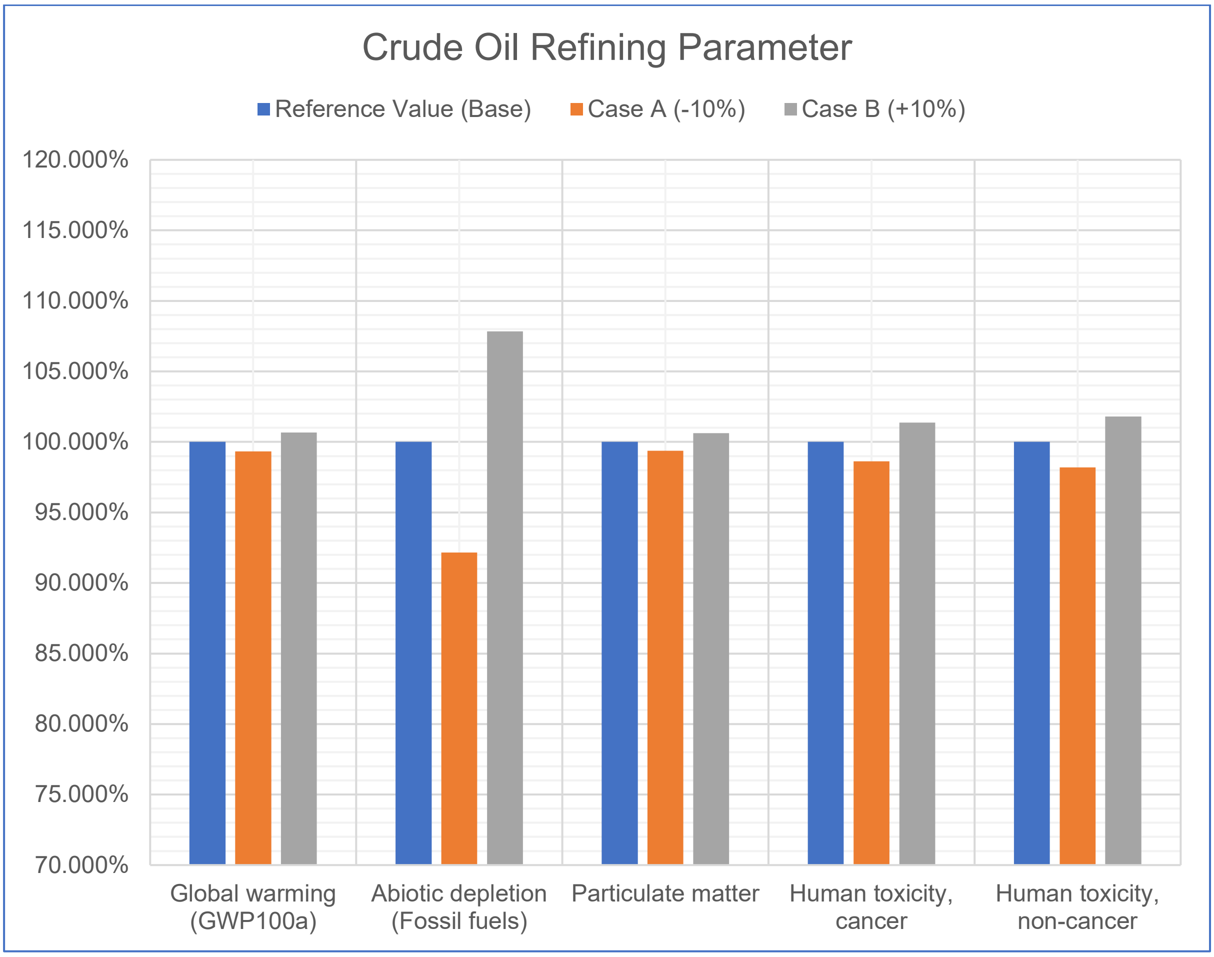


**Figure G.114: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.48024379 | 0.48036677 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 5.8149735 | 5.8151744 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.00040698 | 0.000406988 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.55E-09 | 1.55E-09 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.35E-09 | 8.42E-09 | -0.44 | 0.44 |

**Table G.115: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Vehicle Disposal Parameter)**

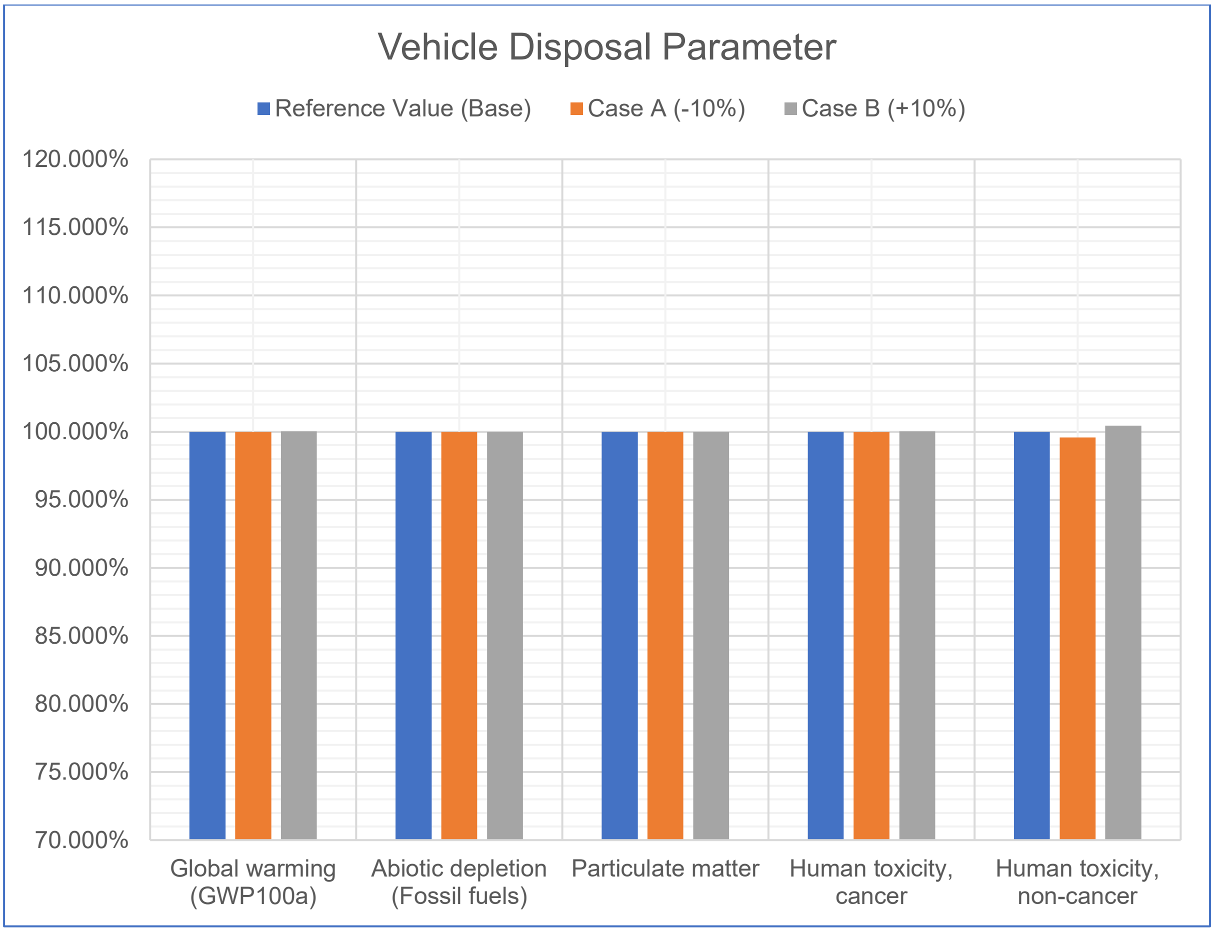


**Figure G.115: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Vehicle Disposal Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.48030528 | 0.47990587 | 0.4807047 | -0.08 | 0.08 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 5.815074 | 5.6824857 | 5.9476623 | -2.28 | 2.28 |
| **Particulate Matter (kg/pkm)** | 0.000406984 | 0.000406785 | 0.000407182 | -0.05 | 0.05 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.55E-09 | 1.55E-09 | 1.55E-09 | -0.03 | 0.03 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.38E-09 | 8.37E-09 | 8.40E-09 | -0.17 | 0.17 |

**Table G.116: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Crude Oil Extraction Parameter)**

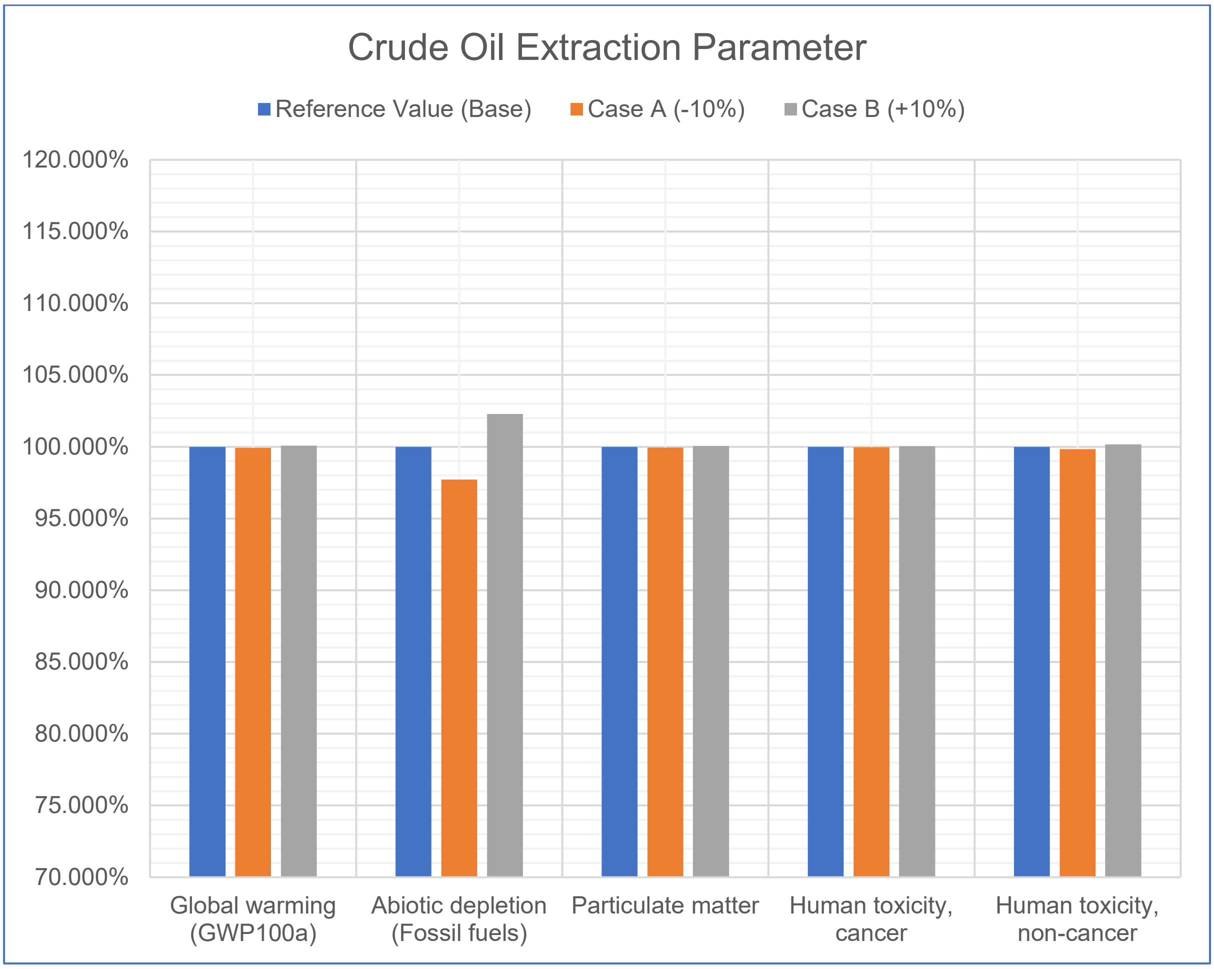


**Figure G.116: Sensitivity Analysis for LCA of Hybrid Rigid Trucks (Crude Oil Extraction Parameter)**

## Battery Electric Rigid Trucks

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.309141 | 0.26243079 | 9 | -7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.6990341 | 3.1671063 | 9 | -7 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.90E-05 | 4.40E-05 | 6 | -5 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.25E-09 | 2.16E-09 | 2 | -2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.19E-08 | 2.01E-08 | 5 | -4 |

**Figure G.117: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Kilometres Travelled Parameter)**

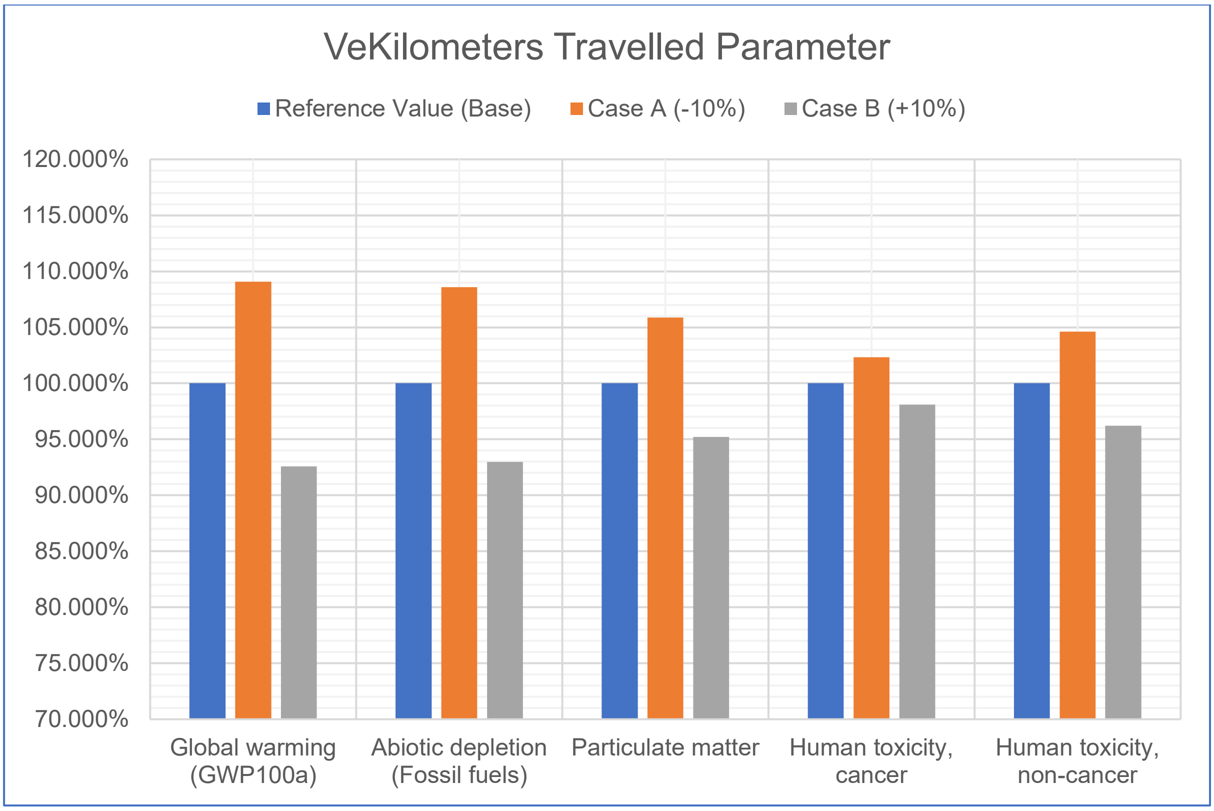


**Figure G.117: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Kilometres Travelled Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.26032883 | 0.30657193 | -8 | 8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.1431696 | 3.6697781 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.38E-05 | 4.87E-05 | -5 | 5 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.15E-09 | 2.24E-09 | -2 | 2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.01E-08 | 2.18E-08 | -4 | 4 |

**Table G.118: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Electricity Mix Consumption Parameter)**

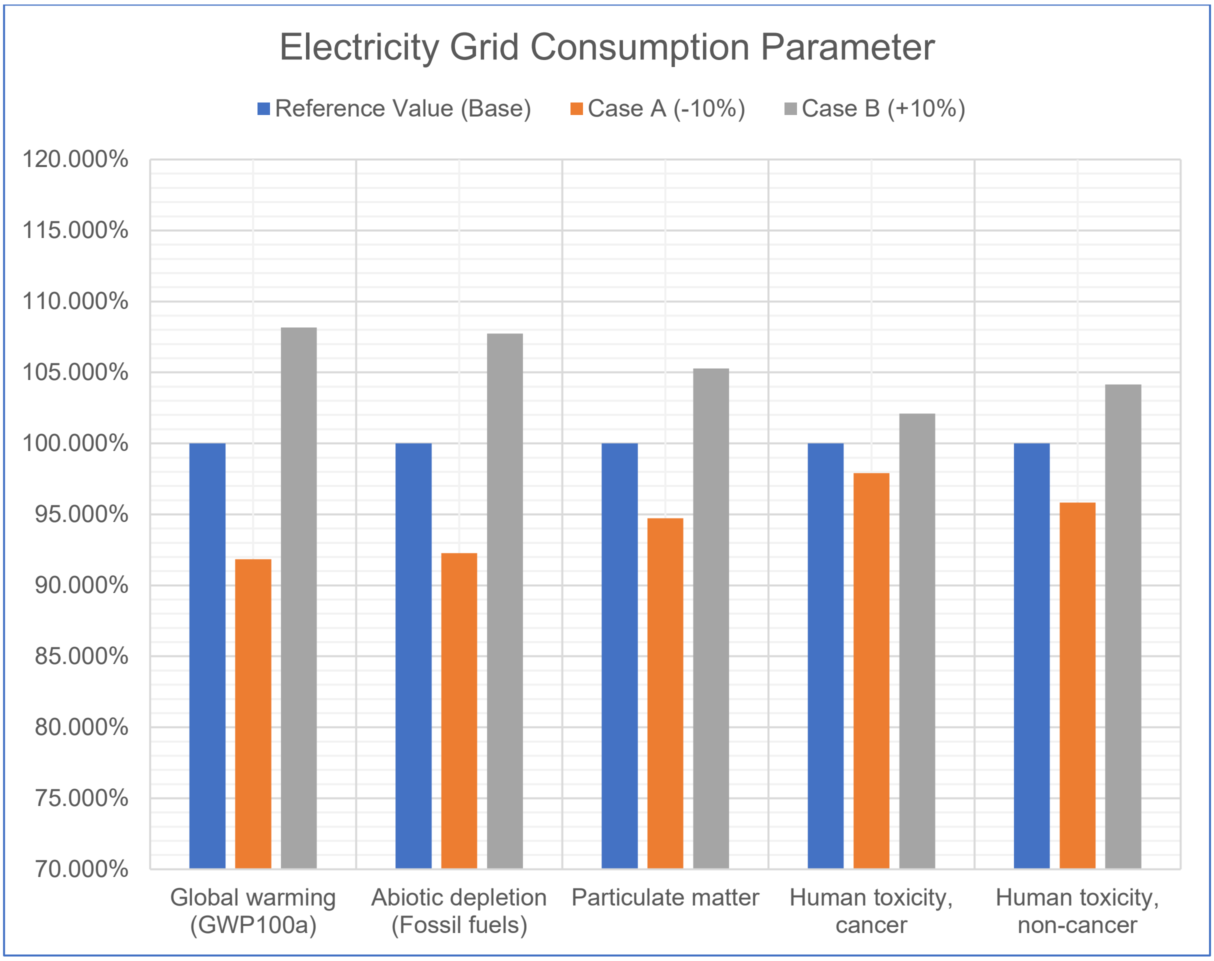


**Figure G.118: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Electricity Mix Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.31494487 | 0.25768217 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.7849709 | 3.0967944 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 5.14E-05 | 4.21E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.44E-09 | 2.00E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.33E-08 | 1.90E-08 | 11 | -9 |

**Figure G.119: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Average Load Factor)**

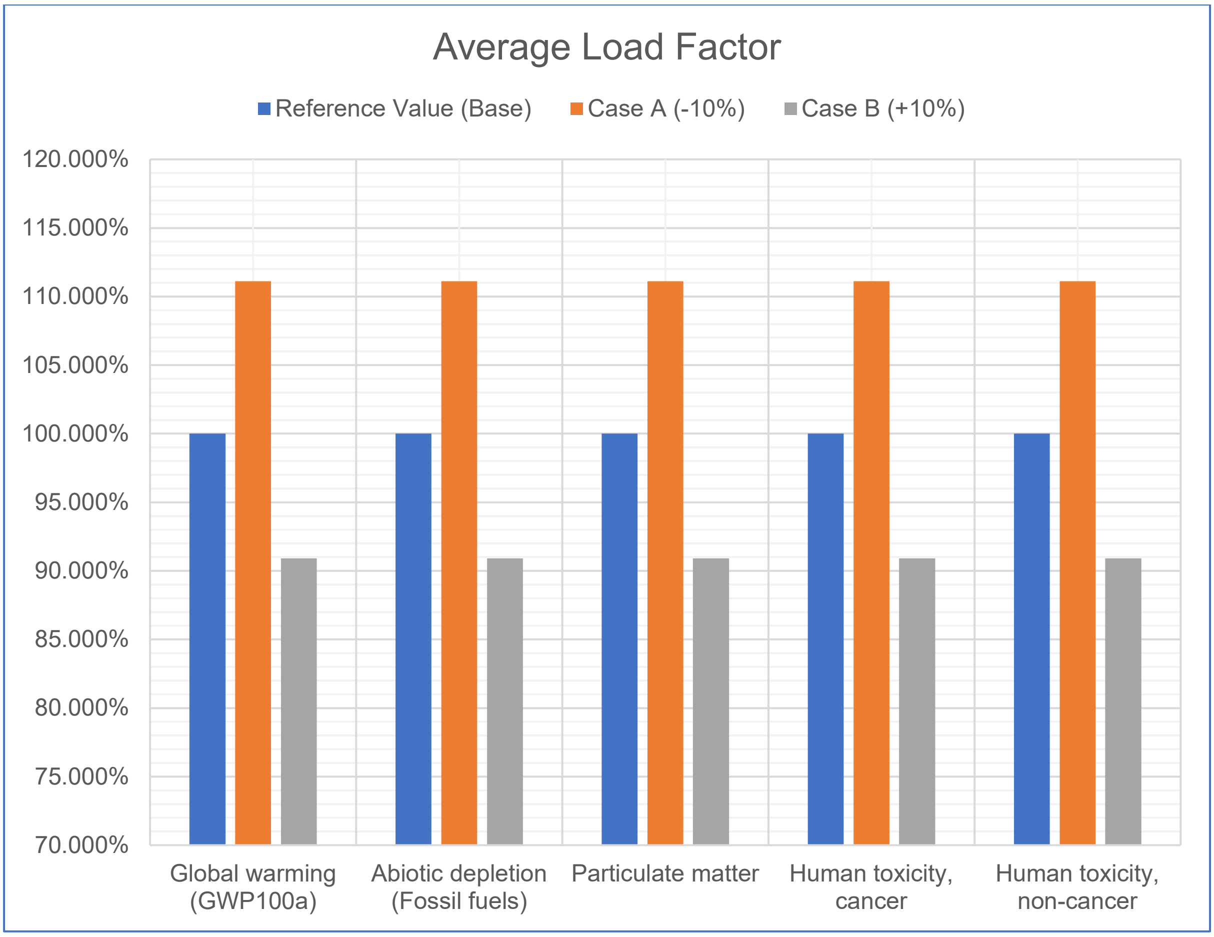


**Figure G.119: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Average Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.309141 | 0.26243079 | 9 | -7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.6990341 | 3.1671063 | 9 | -7 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.90E-05 | 4.40E-05 | 6 | -5 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.25E-09 | 2.16E-09 | 2 | -2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.19E-08 | 2.01E-08 | 5 | -4 |

**Table G.120: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Fraction Load Factor)**

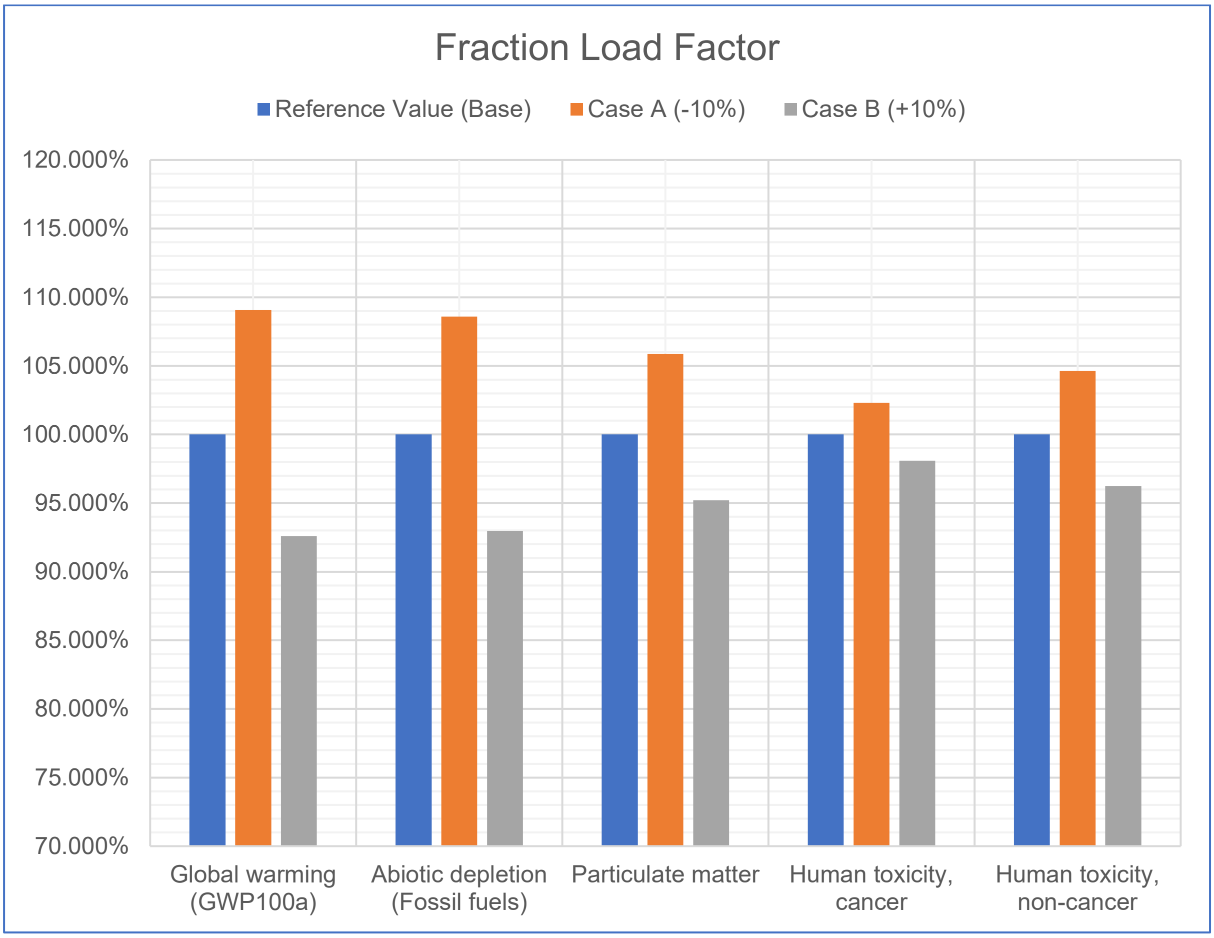


**Figure G.120: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Fraction Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.28047867 | 0.2864221 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.3663362 | 3.4466114 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.50E-05 | 4.75E-05 | -3 | 3 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.06E-09 | 2.34E-09 | -6 | 6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.01E-08 | 2.17E-08 | -4 | 4 |

**Table G.121: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Vehicle Manufacture Parameter)**

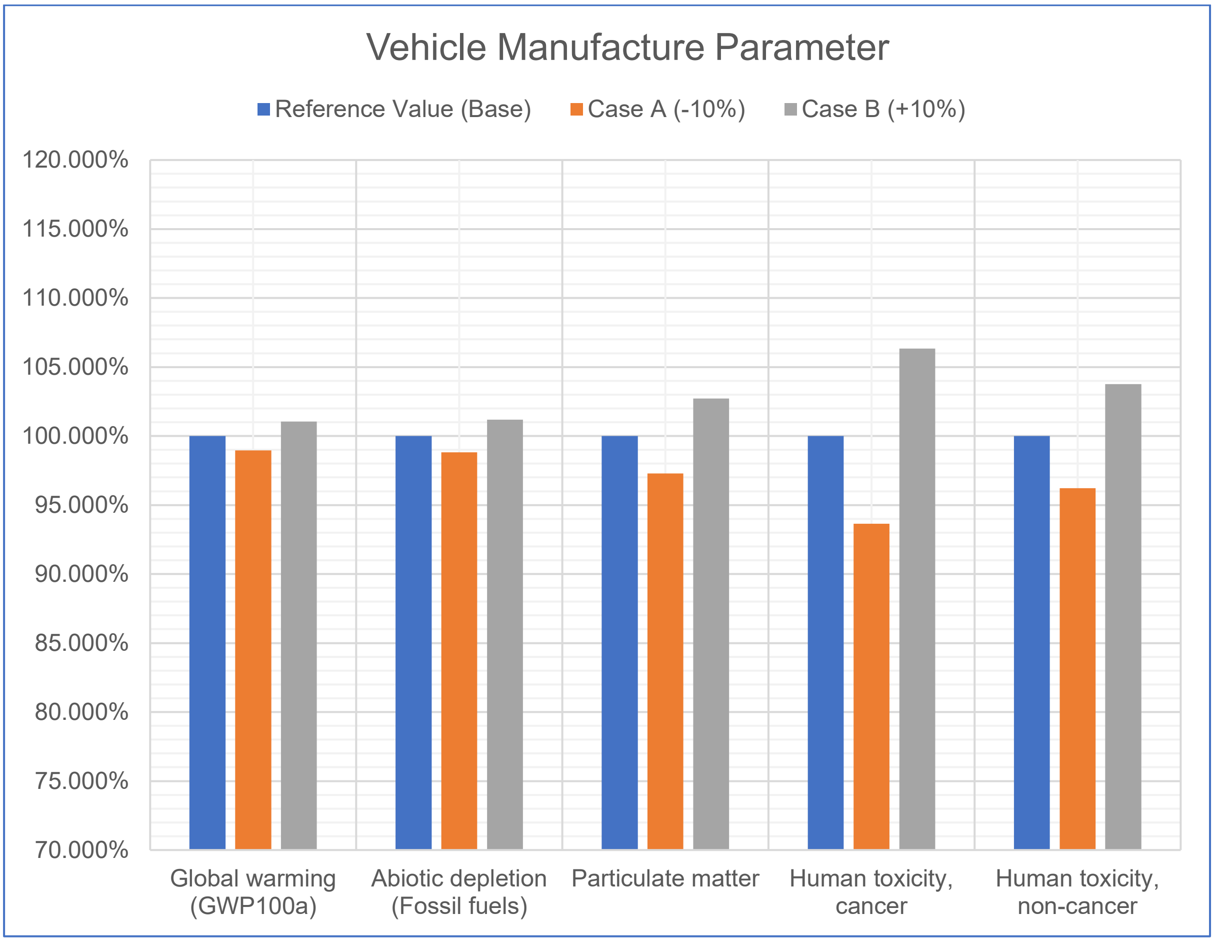


**Figure G.121: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.26048136 | 0.30641941 | -8 | 8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.1445166 | 3.6684311 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.40E-05 | 4.85E-05 | -5 | 5 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.18E-09 | 2.22E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.02E-08 | 2.16E-08 | -3 | 3 |

**Table G.122: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Electricity Mix Production Parameter)**

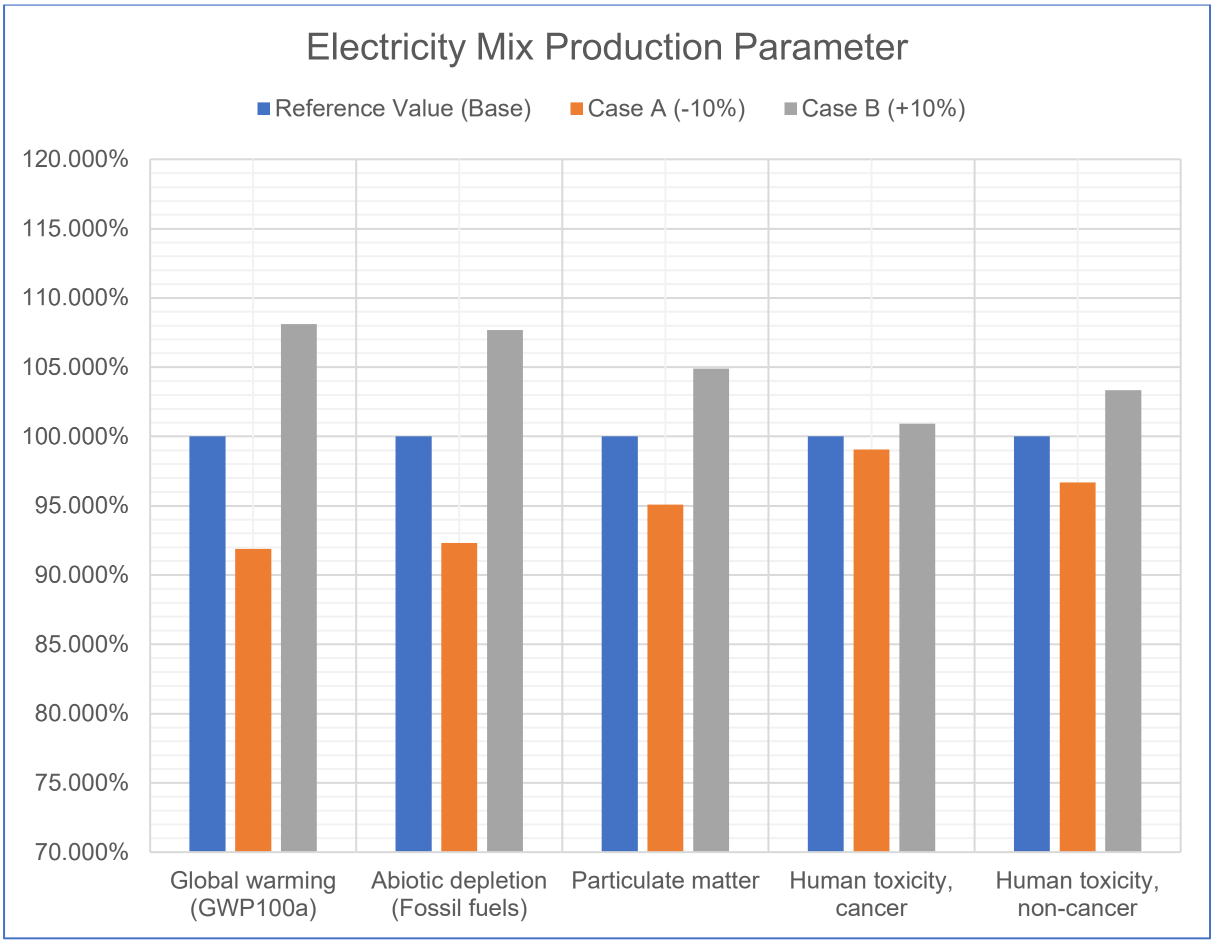
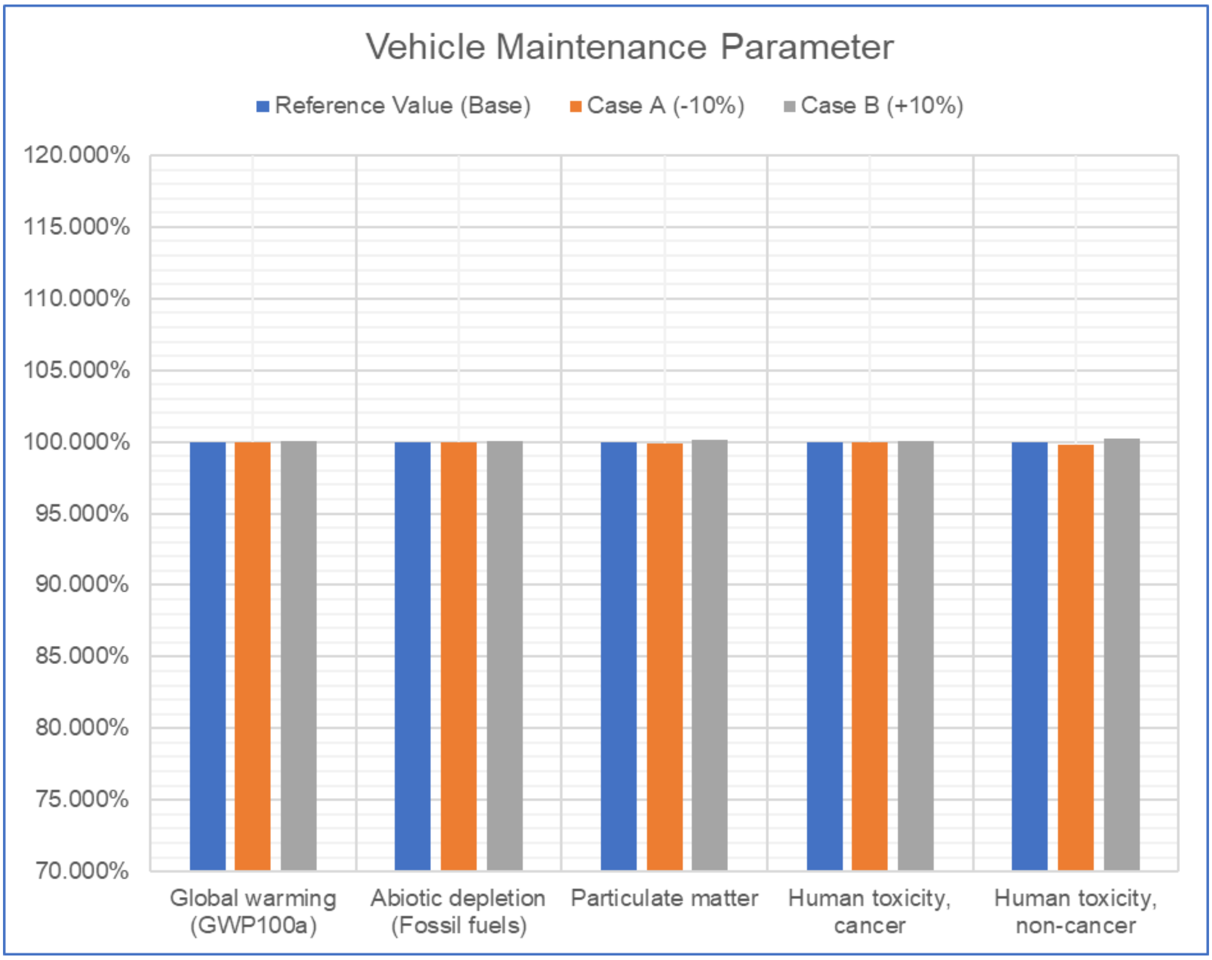


**Figure G.122: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Electricity Mix Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.28138146 | 0.28551931 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.370419 | 3.4425286 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.54E-05 | 4.71E-05 | -2 | 2 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.16E-09 | 2.23E-09 | -2 | 2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.05E-08 | 2.13E-08 | -2 | 2 |

**Table G.123: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Vehicle Maintenance Parameter)**



| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.28345038 | 0.28326754 | 0.28363323 | -0.06 | 0.06 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.4064738 | 3.4053231 | 3.4076245 | -0.03 | 0.03 |
| **Particulate Matter (kg/pkm)** | 4.63E-05 | 4.62E-05 | 4.63E-05 | -0.14 | 0.14 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.20E-09 | 2.20E-09 | 2.20E-09 | -0.04 | 0.04 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.09E-08 | 2.09E-08 | 2.10E-08 | -0.22 | 0.22 |

**Table G.124: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Vehicle Disposal Parameter)**

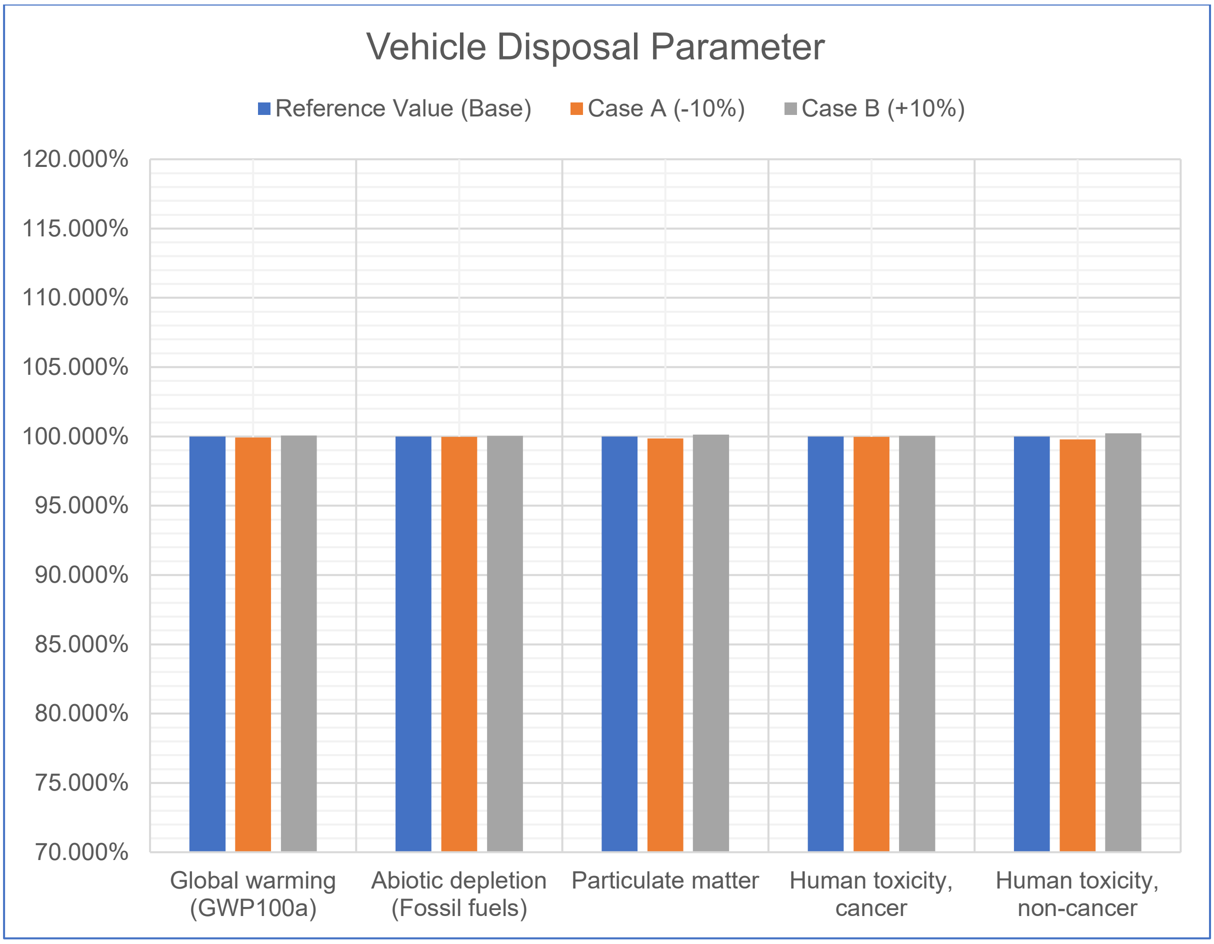


**Figure G.124: Sensitivity Analysis for LCA of Battery Electric Rigid Trucks (Vehicle Disposal Parameter)**

## Low Sulphur Diesel (LSD) Articulated Trucks

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.13737879 | 0.1132278 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.6377875 | 1.3535347 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 8.36E-05 | 6.87E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.76E-10 | 2.60E-10 | 3 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.72E-09 | 1.58E-09 | 5 | -4 |

**Table G.125: Sensitivity Analysis for LCA of Articulated Trucks (Kilometres Travelled Parameter)**

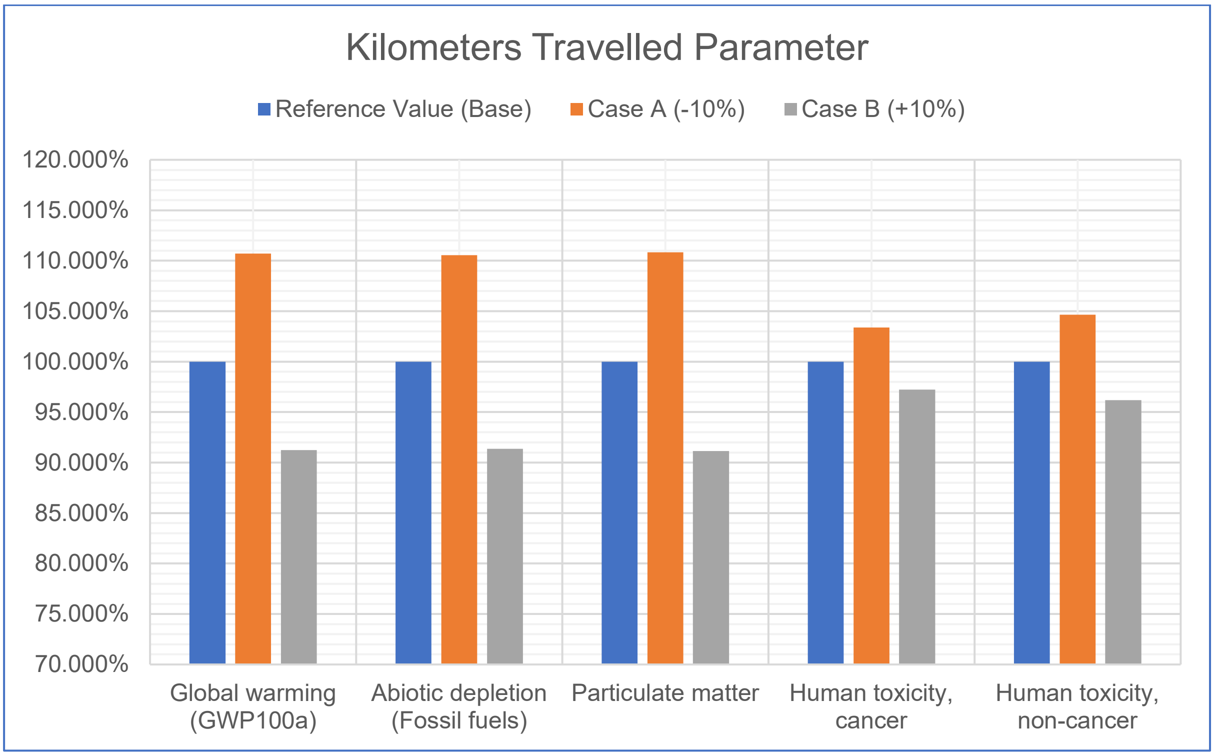


**Figure G.125: Sensitivity Analysis for LCA of Articulated Trucks (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.11214101 | 0.13605049 | -10 | 10 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.3407433 | 1.6221536 | -9 | 9 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 6.81E-05 | 8.28E-05 | -10 | 10 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.59E-10 | 2.76E-10 | -3 | 3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.57E-09 | 1.71E-09 | -4 | 4 |

**Table G.126: Sensitivity Analysis for LCA of LSD Articulated Trucks (Fuel Consumption Parameter)**

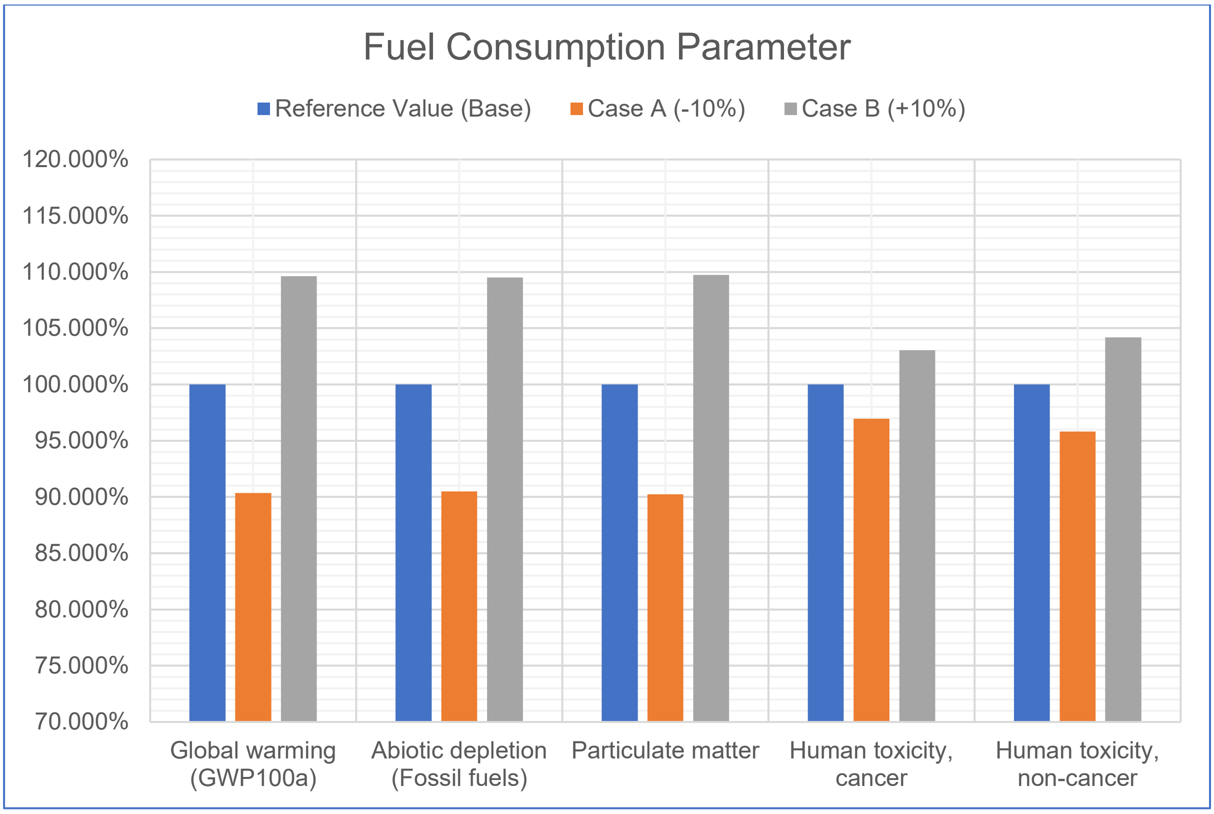


**Figure G.126: Sensitivity Analysis for LCA of LSD Articulated Trucks (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.13788416 | 0.11281431 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.6460538 | 1.3467713 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 8.38E-05 | 6.86E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.97E-10 | 2.43E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.82E-09 | 1.49E-09 | 11 | -9 |

**Table G.127: Sensitivity Analysis for LCA of LSD Articulated Trucks (Average Load Factor)**

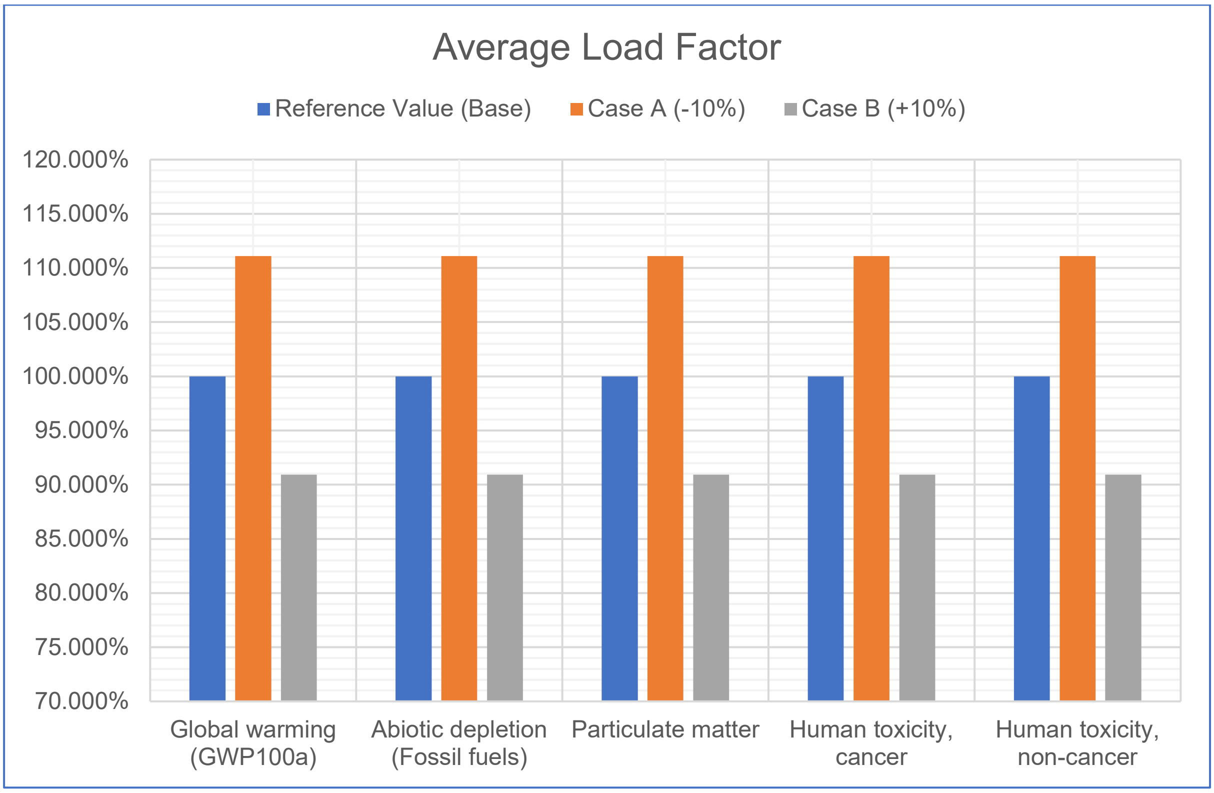


**Figure G.127: Sensitivity Analysis for LCA of LSD Articulated Trucks (Average Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.13737879 | 0.1132278 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.6377875 | 1.3535347 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 8.36E-05 | 6.87E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.76E-10 | 2.60E-10 | 3 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.72E-09 | 1.58E-09 | 5 | -4 |

**Table G.128: Sensitivity Analysis for LCA of LSD Articulated Trucks (Fraction Load Factor)**

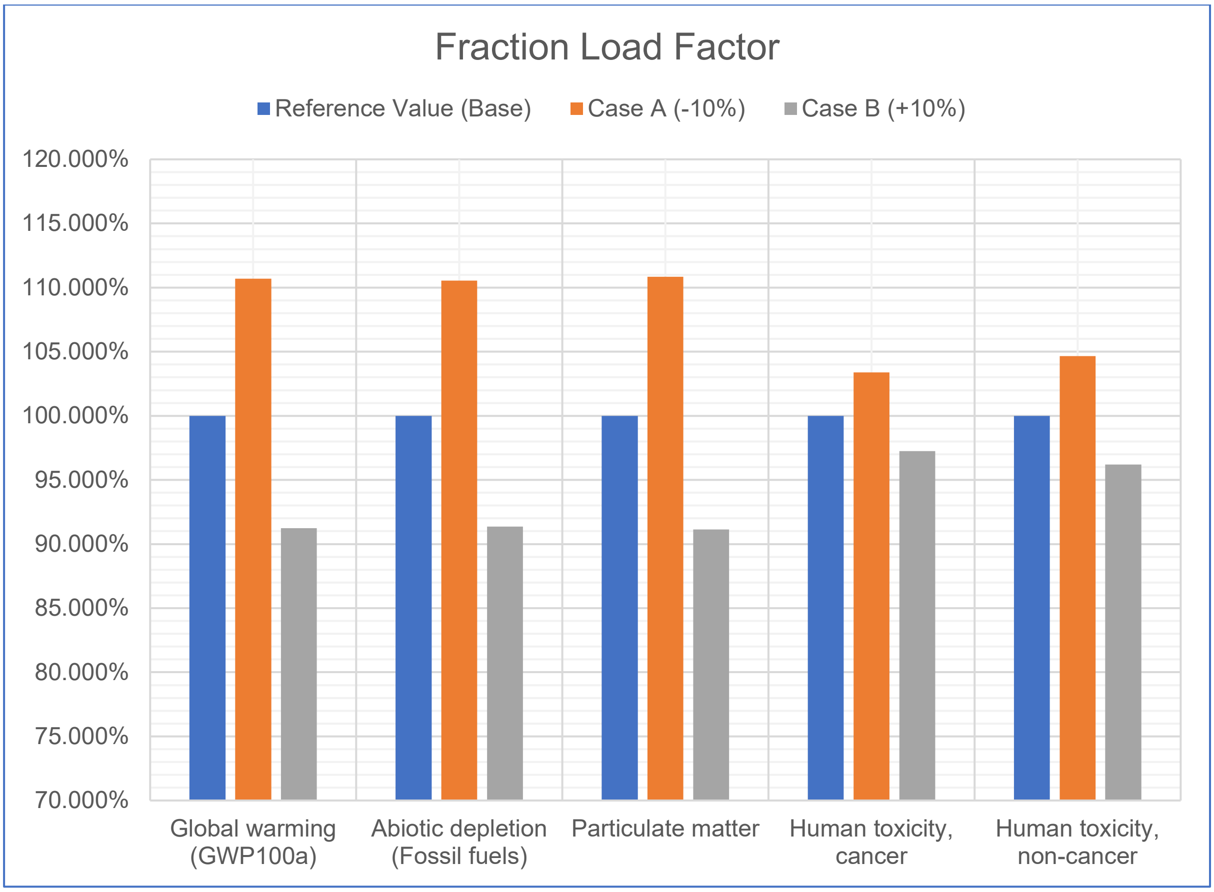


**Table G.128: Sensitivity Analysis for LCA of LSD Articulated Trucks (Fraction Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.12378917 | 0.12440232 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.4772256 | 1.4856713 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 7.53E-05 | 7.56E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.50E-10 | 2.84E-10 | -6 | 6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.56E-09 | 1.72E-09 | -5 | 5 |

**Table G.129: Sensitivity Analysis for LCA of LSD Articulated Trucks (Vehicle Manufacture Parameter)**

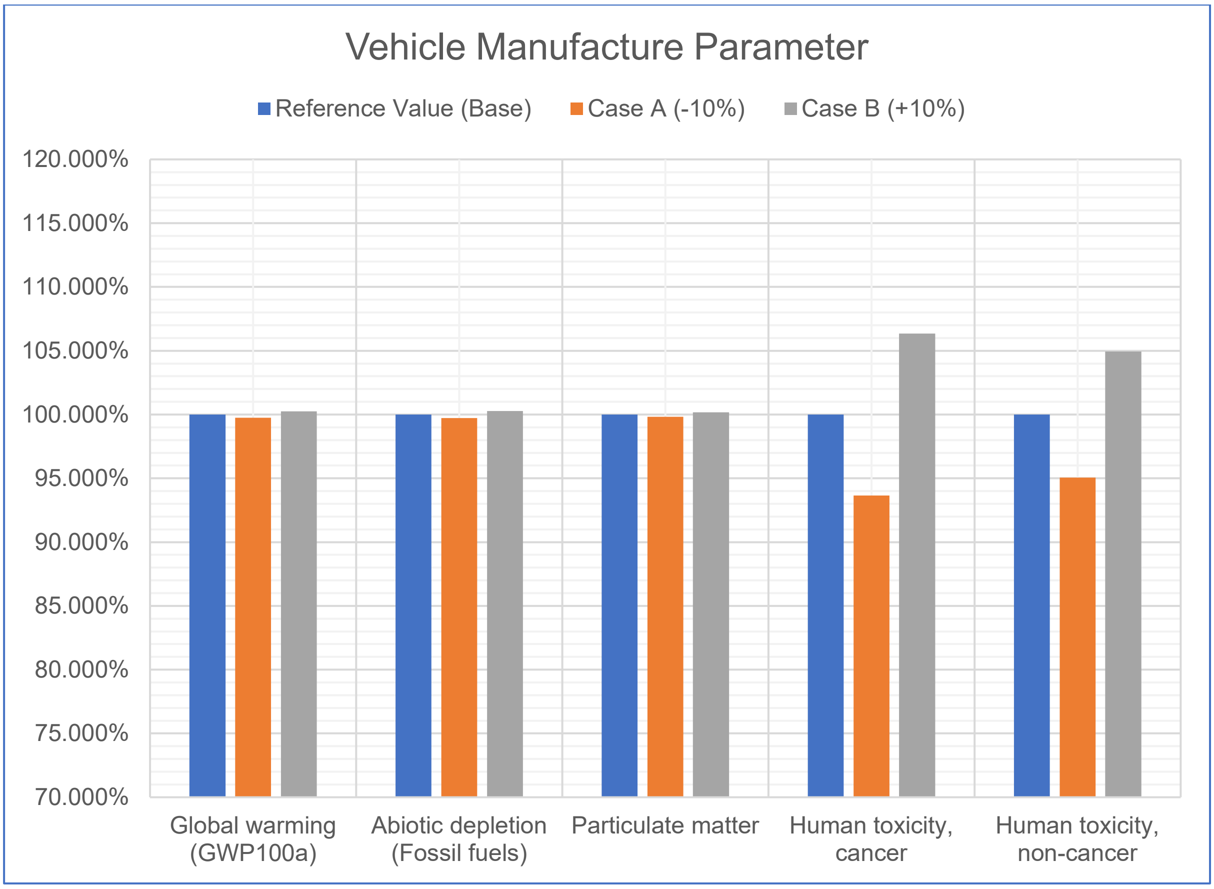


**Figure G.129: Sensitivity Analysis for LCA of LSD Articulated Trucks (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.12398899 | 0.1242025 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.4460105 | 1.5168864 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 7.54E-05 | 7.55E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.67E-10 | 2.68E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.64E-09 | 1.64E-09 | 0 | 0 |

**Table G.130: Sensitivity Analysis for LCA of LSD Articulated Trucks (Crude Oil Extraction Parameter)**

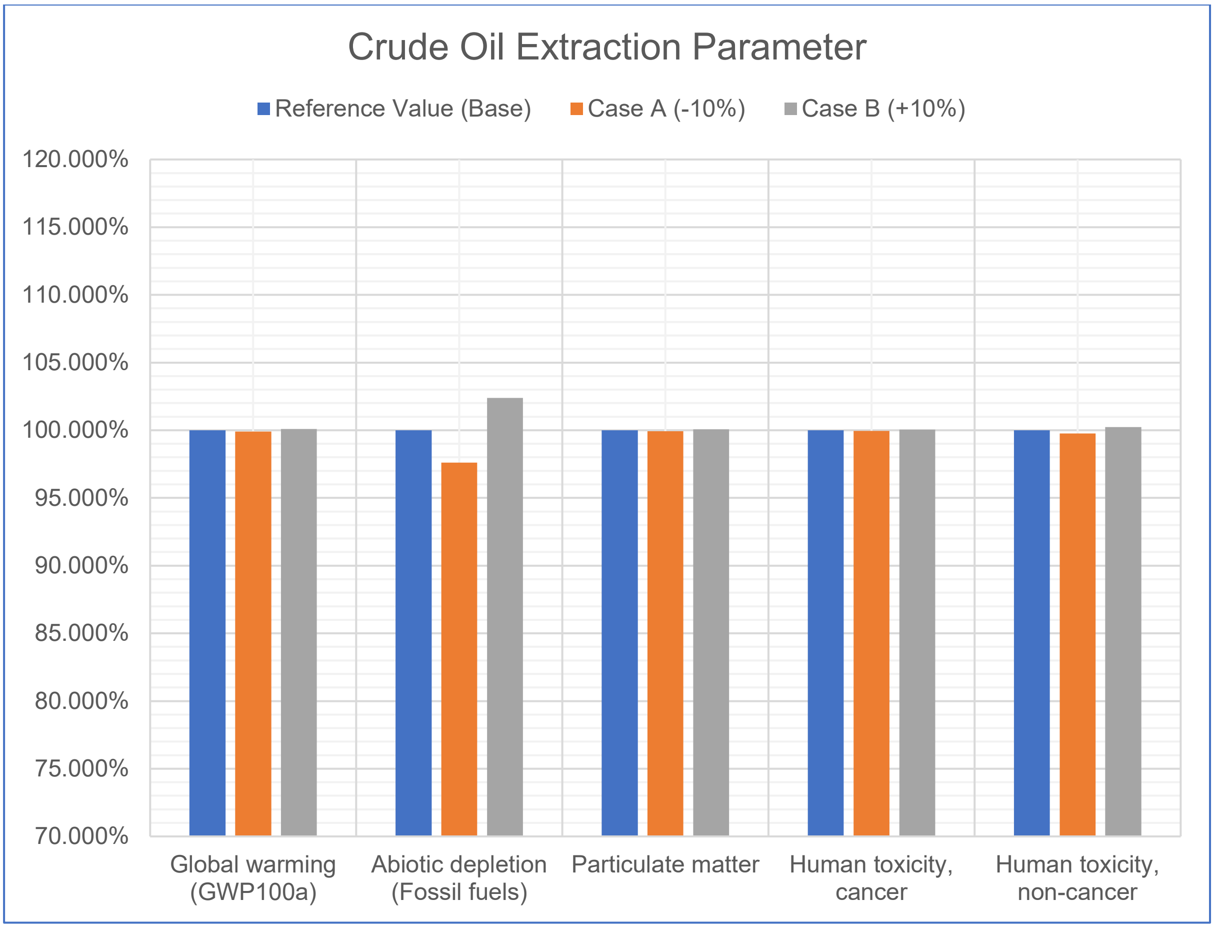


**Figure G.130: Sensitivity Analysis for LCA of LSD Articulated Trucks (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.12324263 | 0.12494886 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.359518 | 1.6033789 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 7.48E-05 | 7.61E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.62E-10 | 2.73E-10 | -2 | 2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.60E-09 | 1.68E-09 | -2 | 2 |

**Table G.131: Sensitivity Analysis for LCA of LSD Articulated Trucks (Crude Oil Refining Parameter)**

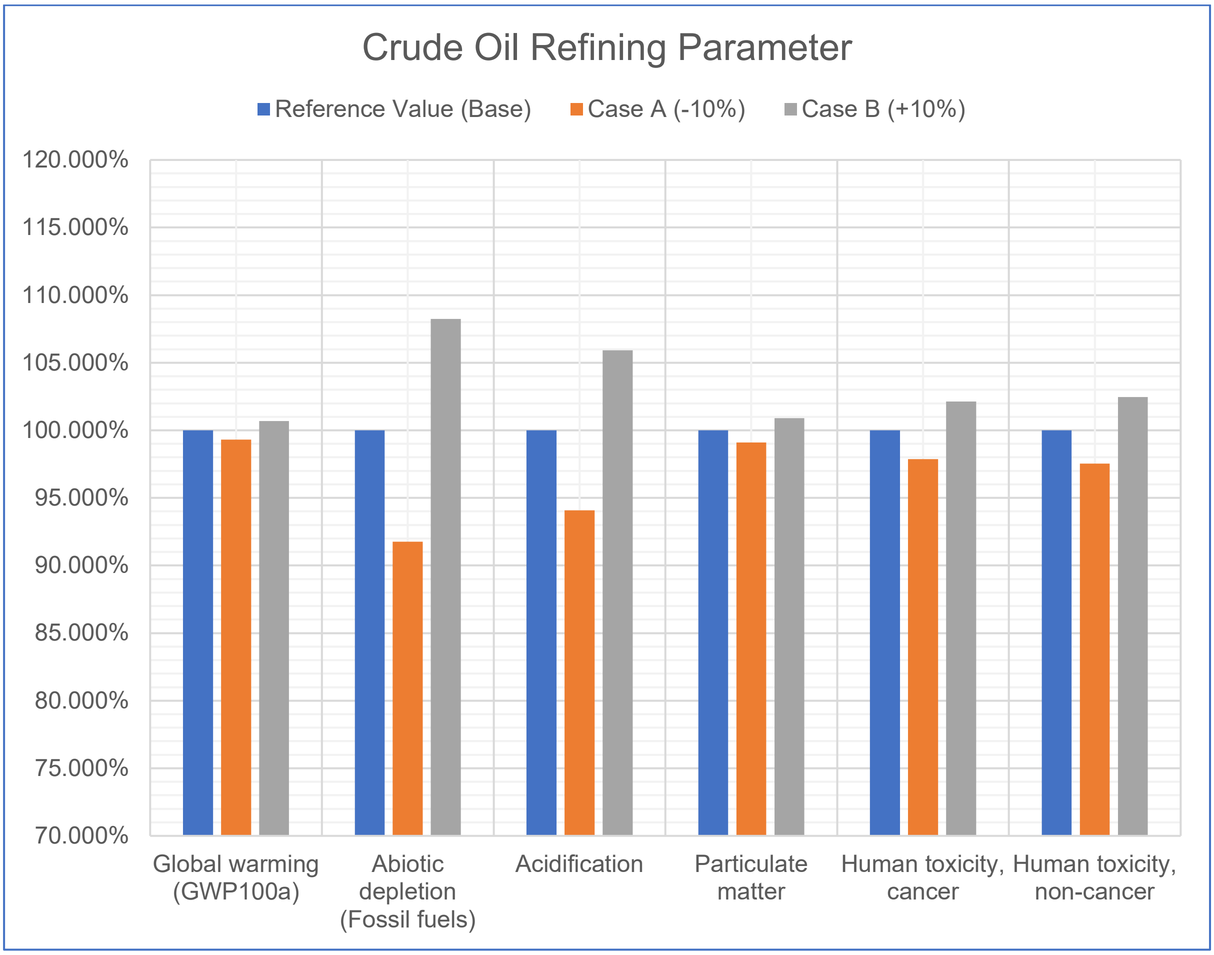


**Figure G.131: Sensitivity Analysis for LCA of LSD Articulated Trucks (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.12395589 | 0.1242356 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.4782423 | 1.4846546 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 7.54E-05 | 7.55E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.66E-10 | 2.69E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.63E-09 | 1.65E-09 | -1 | 1 |

**Table G.132: Sensitivity Analysis for LCA of LSD Articulated Trucks (Vehicle Maintenance Parameter)**

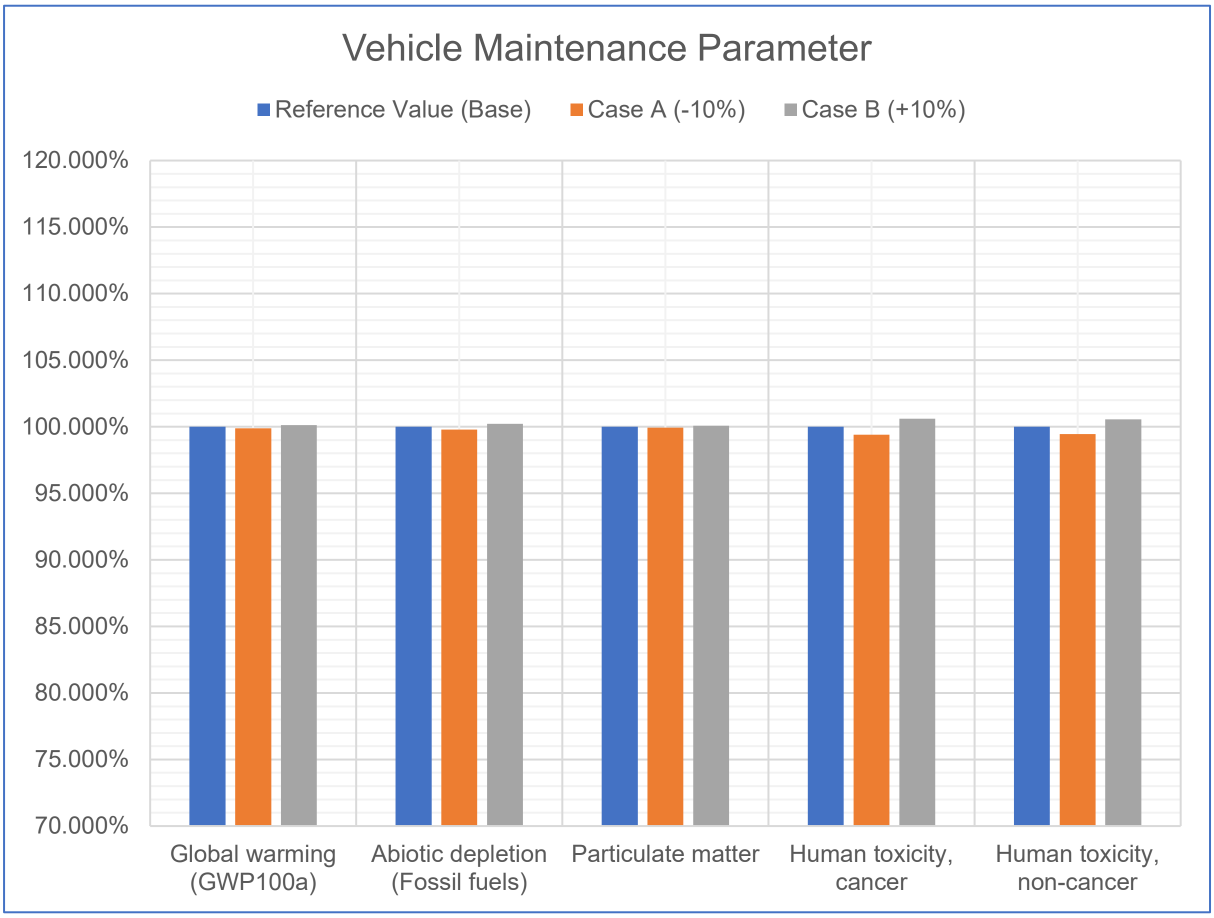


**Figure G.132: Sensitivity Analysis for LCA of LSD Articulated Trucks (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.12409575 | 0.12408734 | 0.12410415 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.4814485 | 1.4814378 | 1.4814591 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 7.54E-05 | 7.54E-05 | 7.54E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.67E-10 | 2.67E-10 | 2.67E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.64E-09 | 1.63E-09 | 1.65E-09 | -0.33 | 0.33 |

**Table G.133: Sensitivity Analysis for LCA of LSD Articulated Trucks (Vehicle Disposal Parameter)**

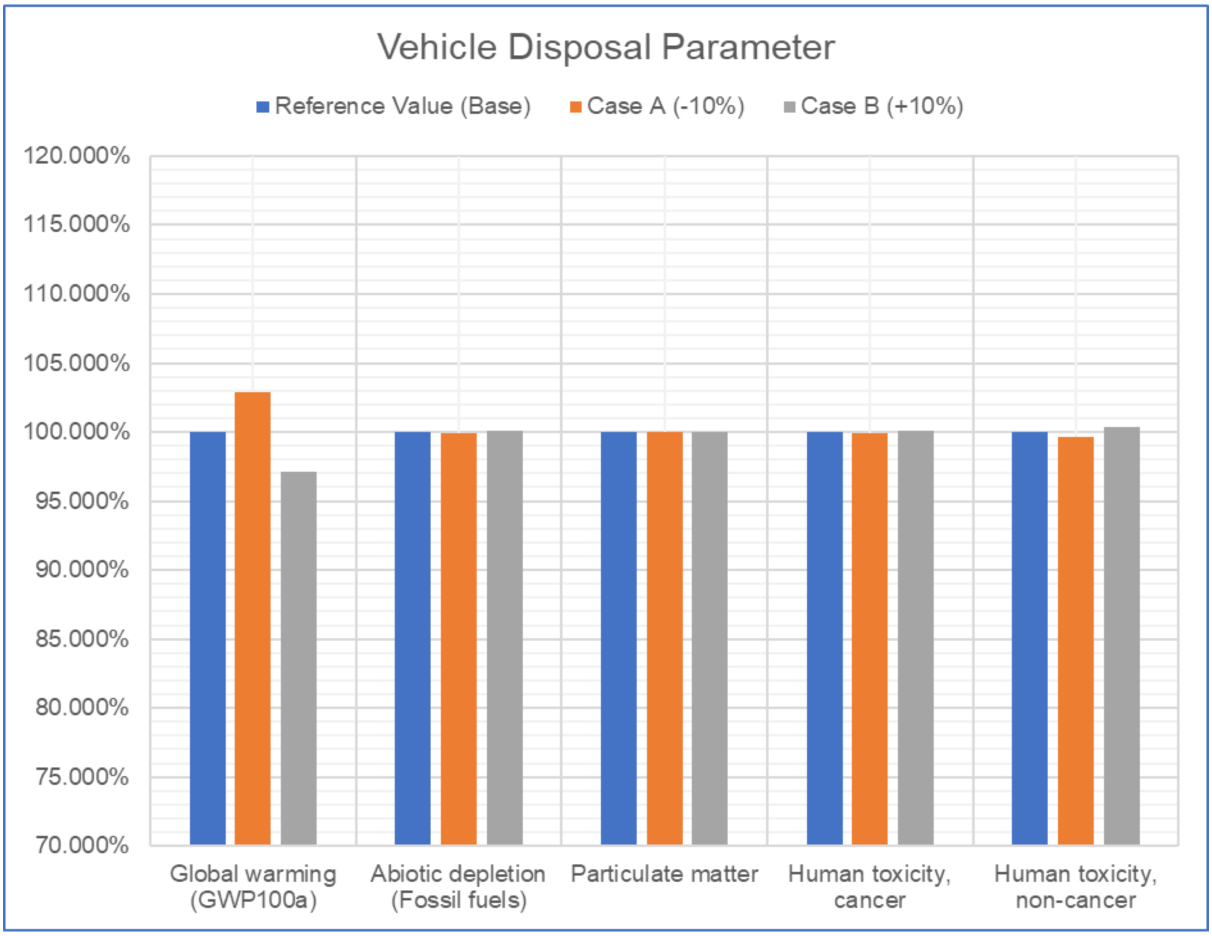


**Figure G.133: Sensitivity Analysis for LCA of LSD Articulated Trucks (Vehicle Disposal Parameter)**

### Hybrid Electric Articulated Trucks

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.15590236 | 0.12755648 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.8558152 | 1.5183943 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 9.54E-05 | 7.80E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 3.12E-10 | 2.55E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.95E-09 | 1.60E-09 | 11 | -9 |

**Table G.134: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Average Load Factor)**

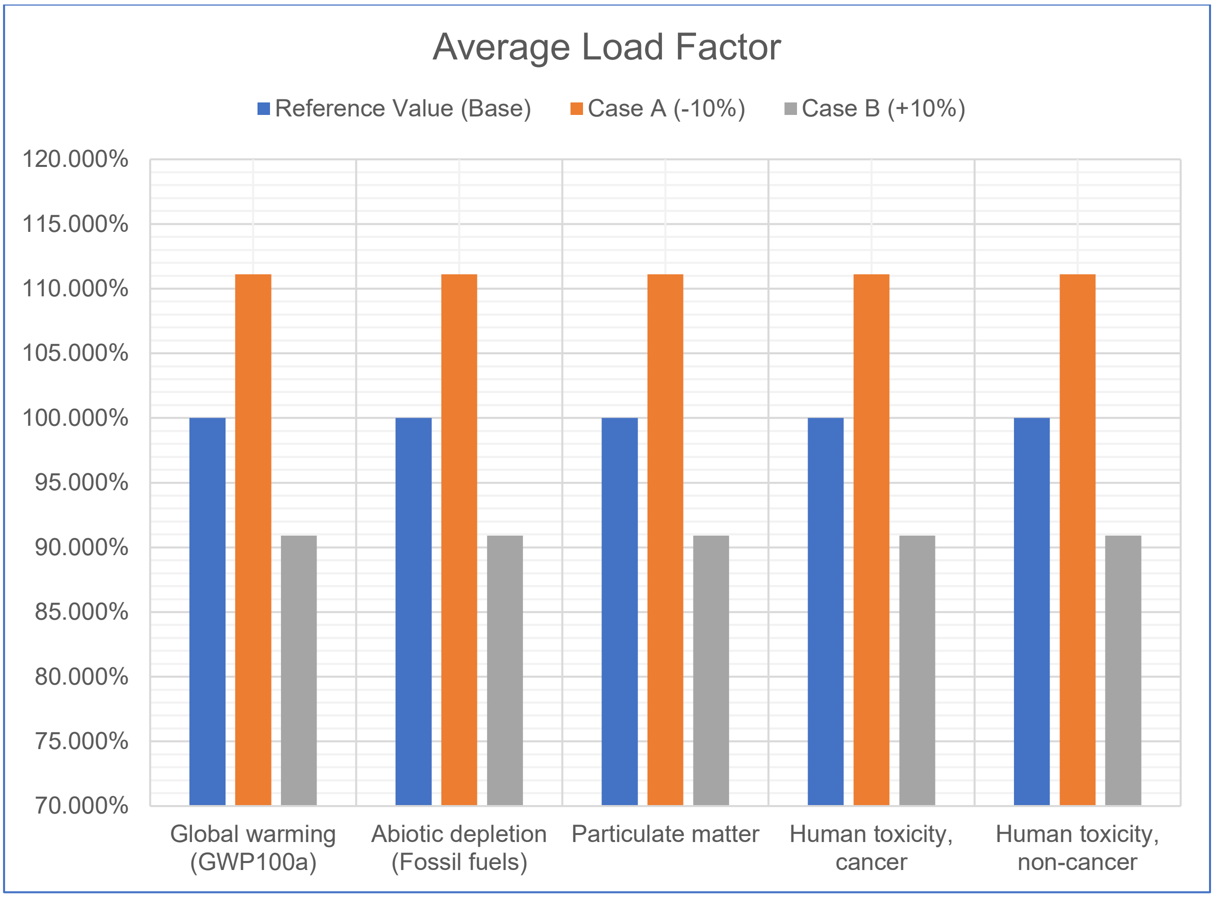


**Figure G.134: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Average Load Factor)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.15541452 | 0.12795562 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.8479549 | 1.5248255 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 9.51E-05 | 7.82E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.91E-10 | 2.72E-10 | 4 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.84E-09 | 1.68E-09 | 5 | -4 |

**Table G.135: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Fraction Load Factor)**

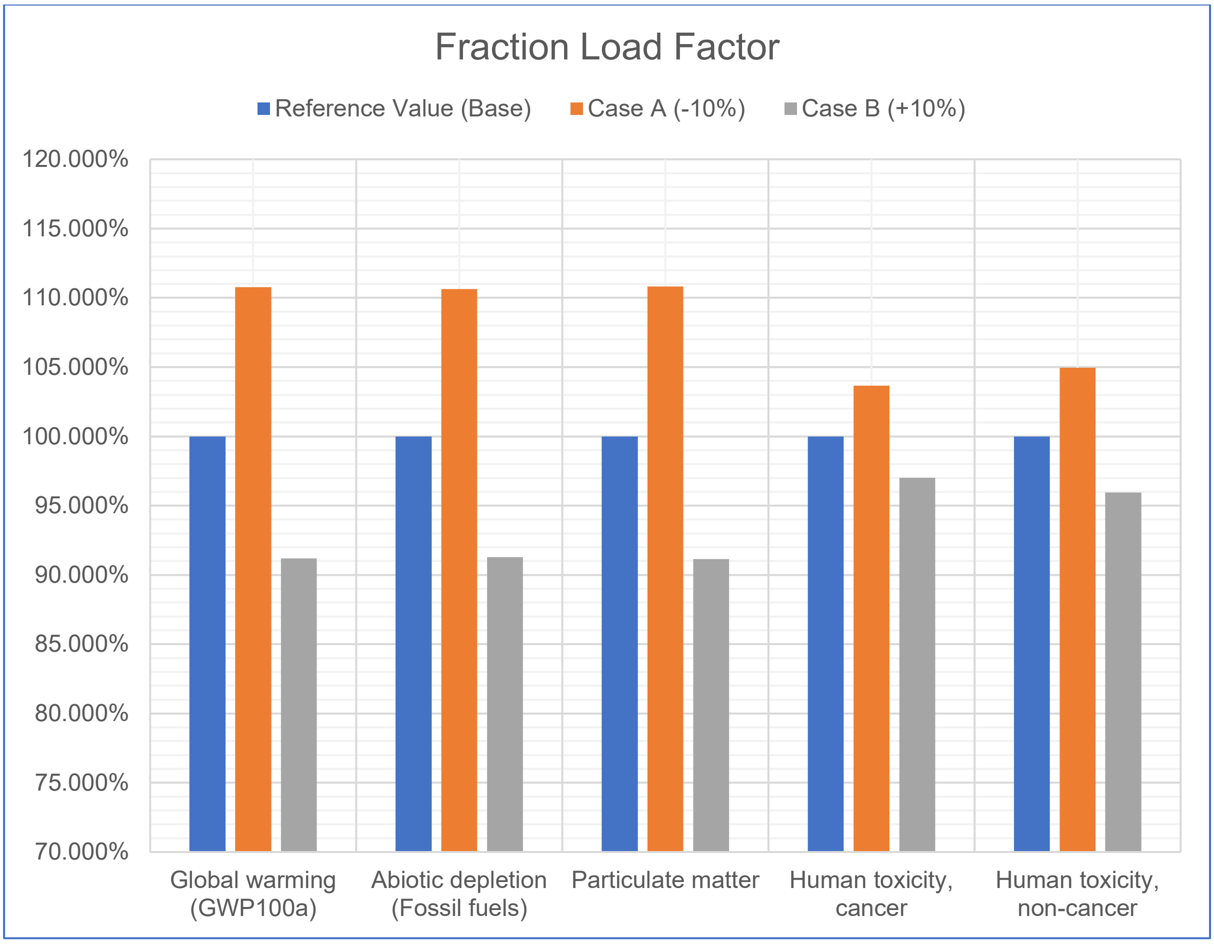


**Figure G.135: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Fraction Load Factor)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.15541452 | 0.12795562 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.8479549 | 1.5248255 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 9.51E-05 | 7.82E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.91E-10 | 2.72E-10 | 4 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.84E-09 | 1.68E-09 | 5 | -4 |

**Table G.136: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Kilometres Travelled Parameter)**

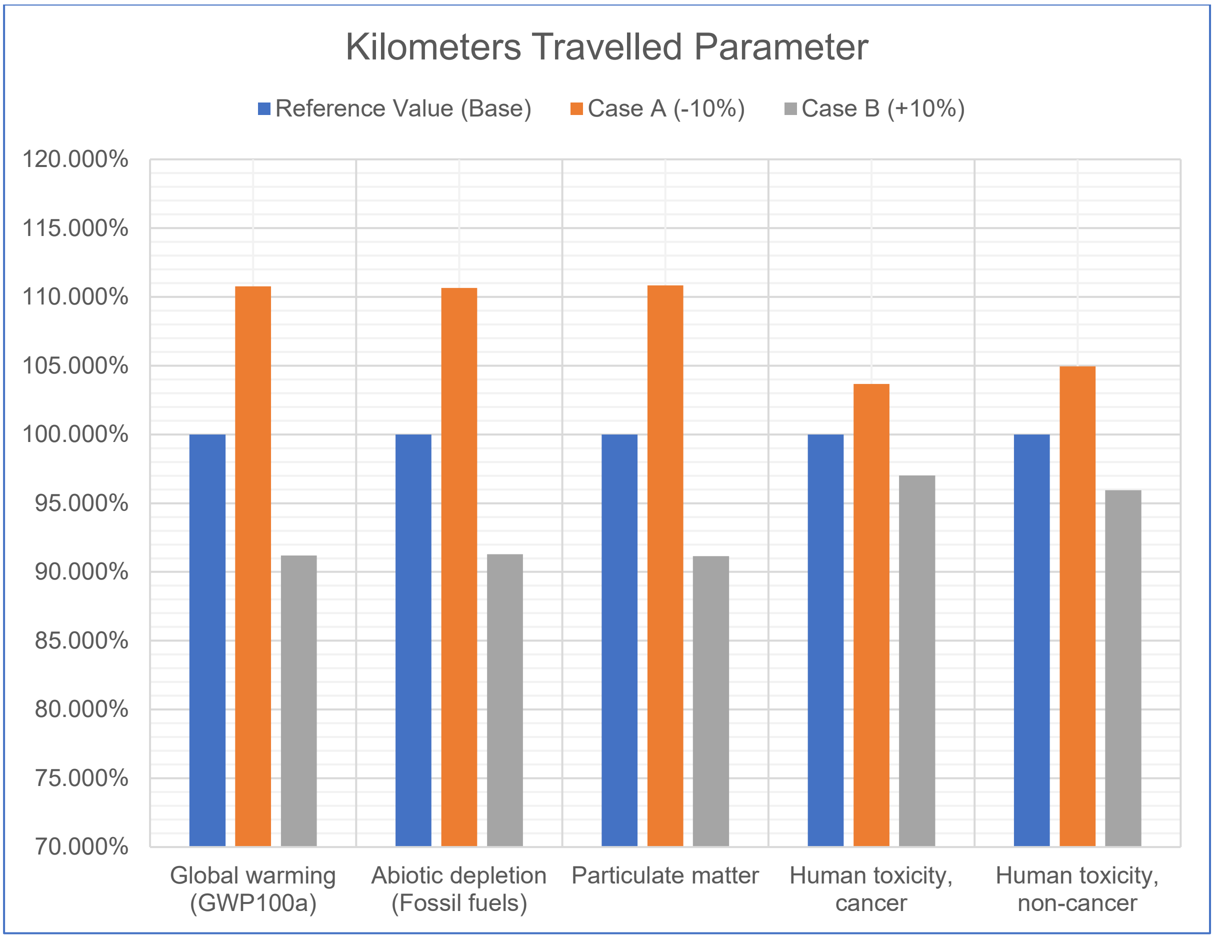


**Figure G.136: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.14006587 | 0.14055838 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.6667908 | 1.6736766 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 8.57E-05 | 8.59E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.66E-10 | 2.95E-10 | -5 | 5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.70E-09 | 1.81E-09 | -3 | 3 |

**Table G.137: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Vehicle Manufacture Parameter)**

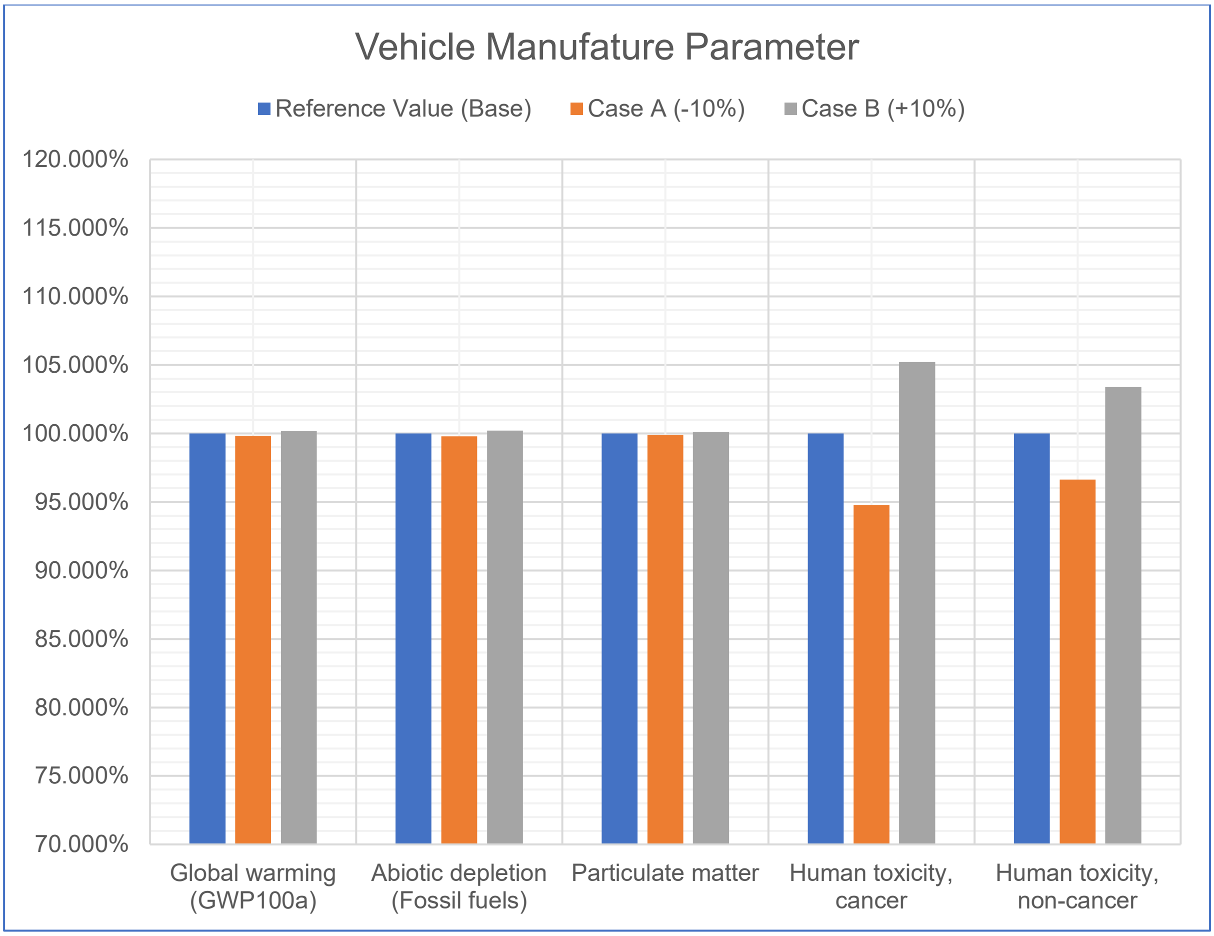


**Figure G.137: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.14012789 | 0.14049635 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.6666144 | 1.673853 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 8.57E-05 | 8.59E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.76E-10 | 2.85E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.72E-09 | 1.79E-09 | -2 | 2 |

**Table G.138: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Vehicle Maintenance Parameter)**

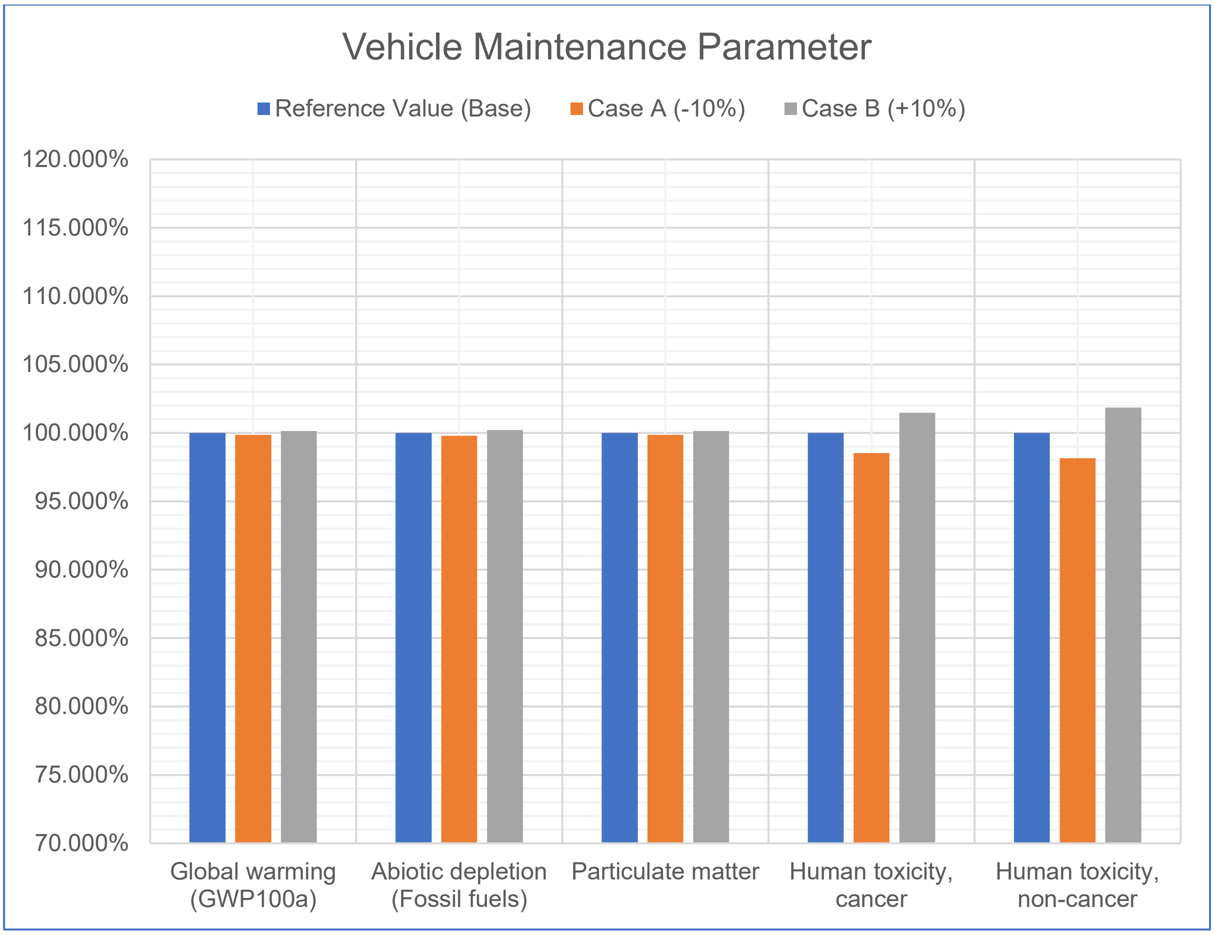


**Figure G.138: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.13934233 | 0.14128192 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.5316271 | 1.8088403 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 8.51E-05 | 8.66E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.74E-10 | 2.87E-10 | -2 | 2 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.71E-09 | 1.80E-09 | -3 | 3 |

**Table G.139: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Crude Oil Refining Parameter)**

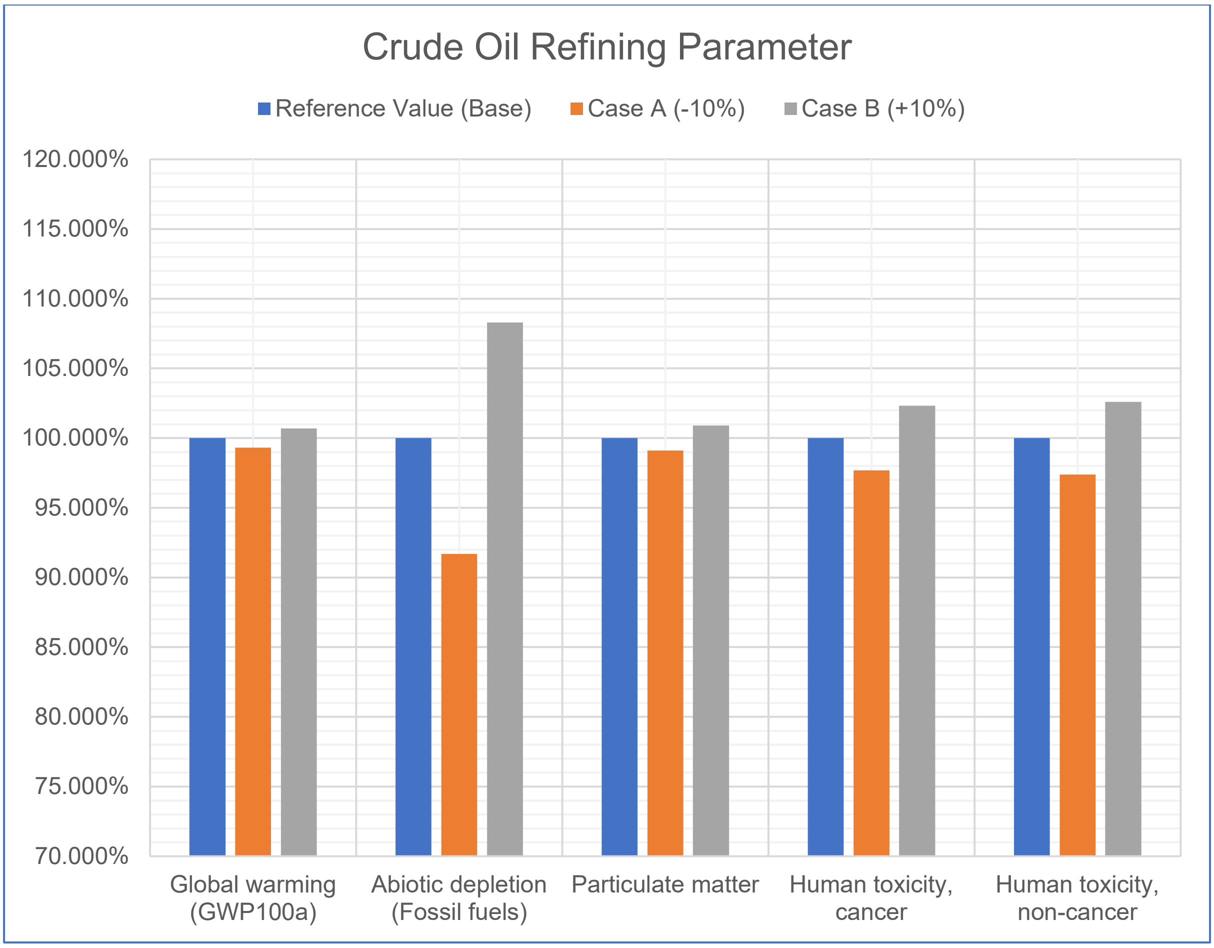


**Figure G.139: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.14030355 | 0.1403207 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.6702216 | 1.6702458 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 8.58E-05 | 8.58E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.80E-10 | 2.81E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.75E-09 | 1.76E-09 | -0.31 | 0.31 |

**Table G.140: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Vehicle Disposal Parameter)**

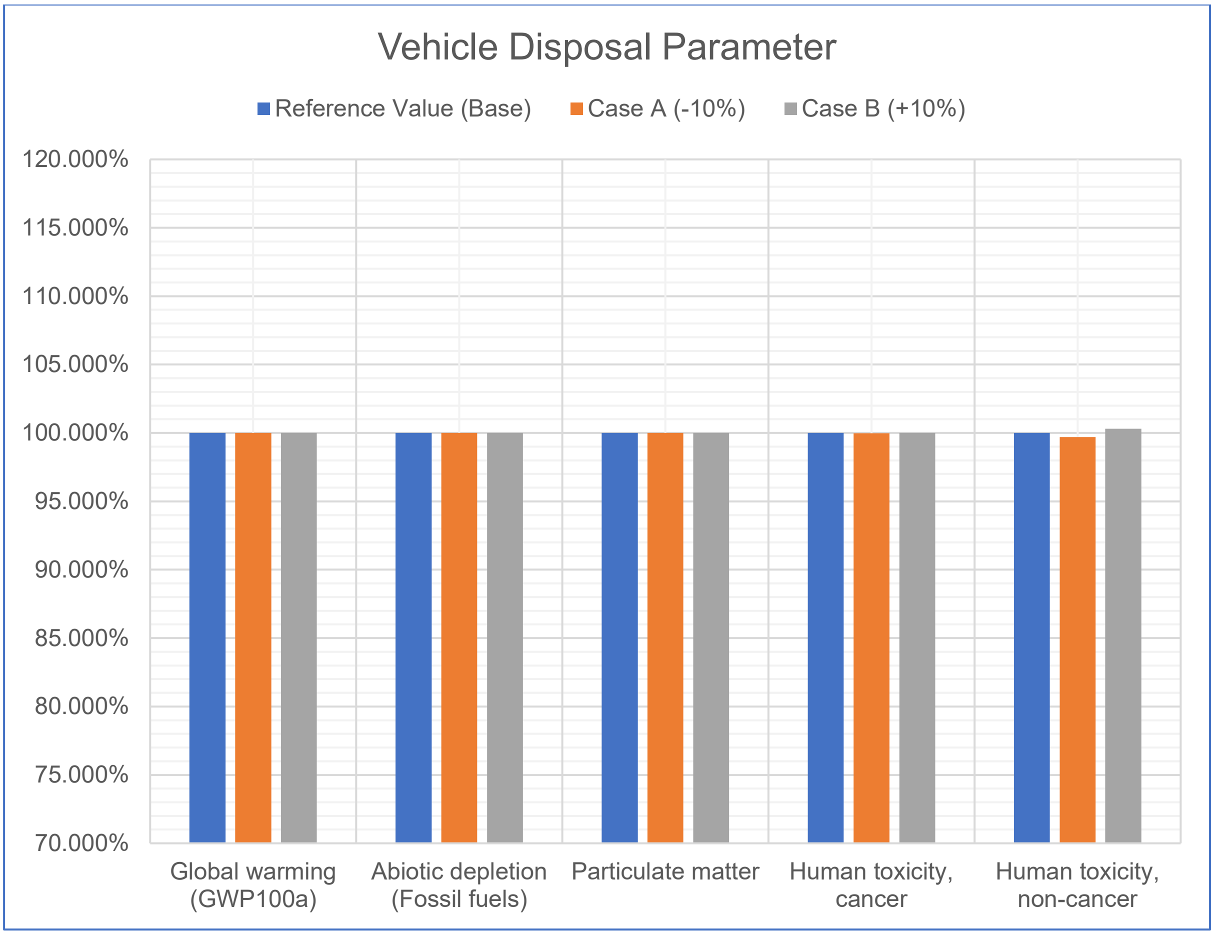


**Figure G.140: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Vehicle Disposal Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.14031212 | 0.14019077 | 0.14043348 | -0.1 | 0.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.6702337 | 1.629949 | 1.7105184 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 8.58E-05 | 8.58E-05 | 8.59E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 2.80E-10 | 2.80E-10 | 2.81E-10 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.75E-09 | 1.75E-09 | 1.76E-09 | 0 | 0 |

**Table G.141: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Crude Oil Extraction Parameter)**

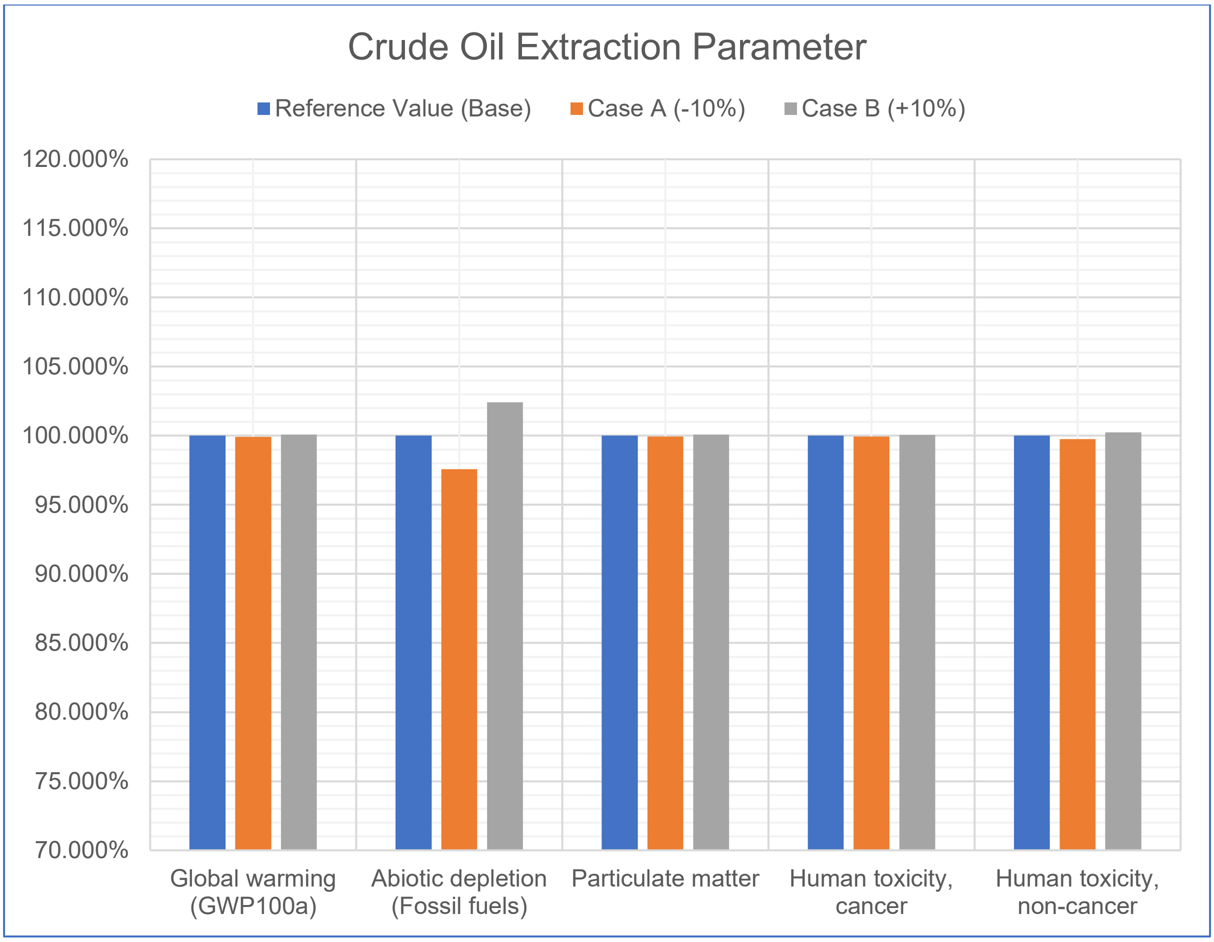


**Figure G.141: Sensitivity Analysis for LCA of Hybrid Articulated Trucks (Crude Oil Extraction Parameter)**

### Battery Electric Articulated Trucks

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.073240527 | 0.081378363 | 0.066582297 | 11.1 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.85665157 | 0.95183508 | 0.77877416 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 9.15E-06 | 1.02E-05 | 8.32E-06 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 3.23E-10 | 3.59E-10 | 2.93E-10 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 3.54E-09 | 3.93E-09 | 3.22E-09 | 11 | -9 |

**Table G.142: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Average Load Factor)**

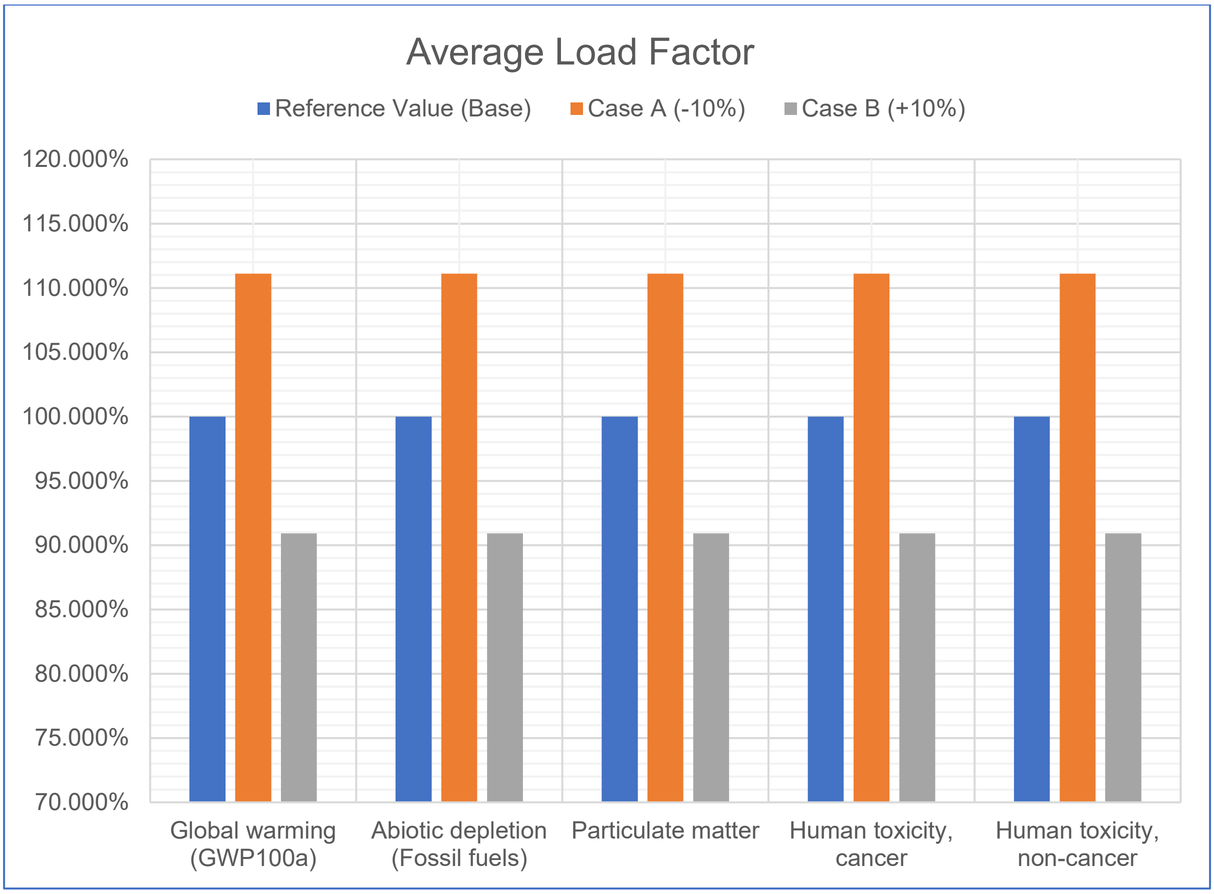


**Figure G.142: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Average Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.073240527 | 0.080872992 | 0.066995783 | 10.4 | -8.53 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.85665157 | 0.94356877 | 0.7855375 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 9.15E-06 | 9.95E-06 | 8.49E-06 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 3.23E-10 | 3.38E-10 | 3.10E-10 | 5 | -4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 3.54E-09 | 3.83E-09 | 3.30E-09 | 8 | -7 |

**Table G.143: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Fraction Load Factor)**

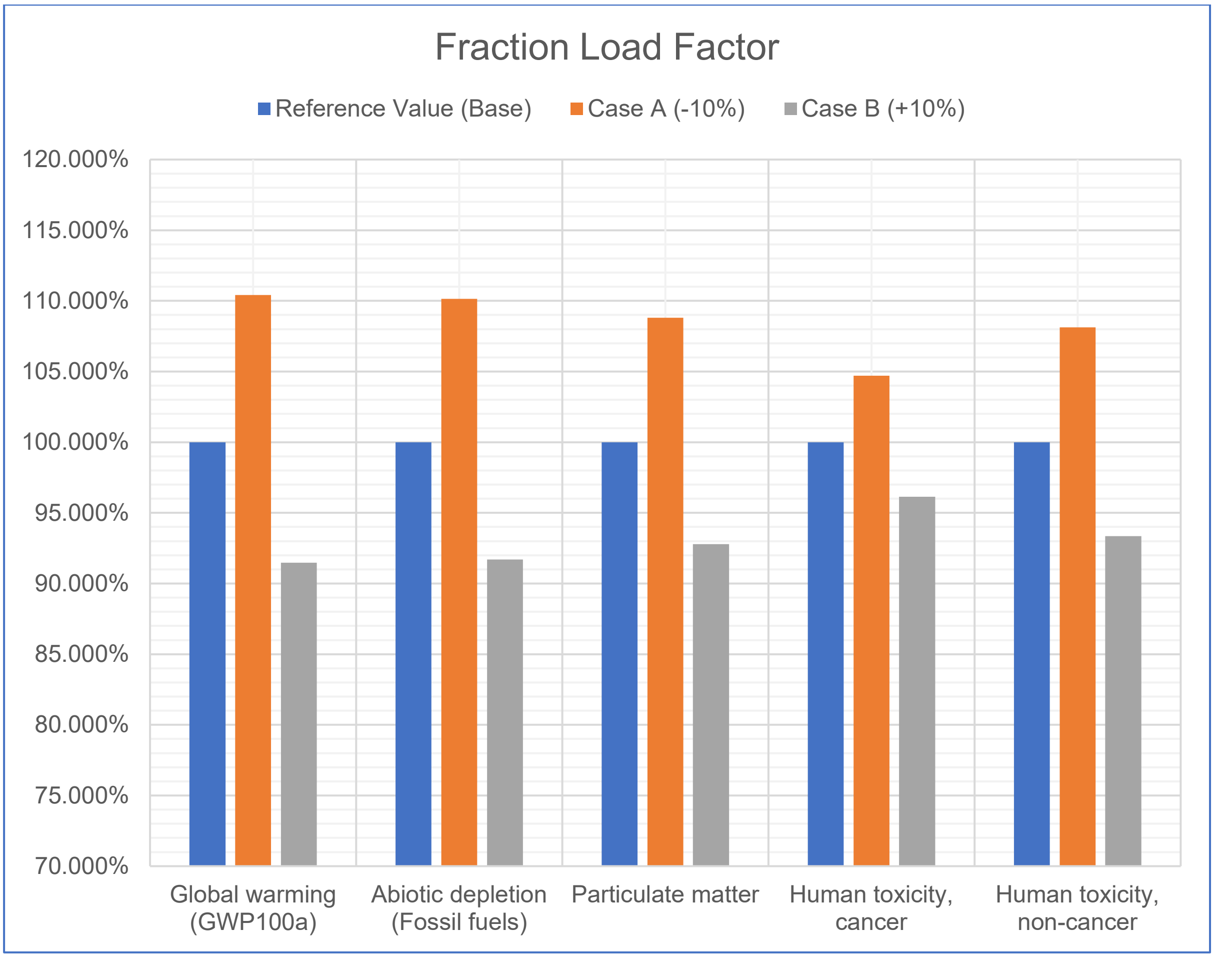


**Figure G.143: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Fraction Load Factor)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.073240527 | 0.080872992 | 0.066995783 | 10.4 | -8.53 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.85665157 | 0.94356877 | 0.7855375 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 9.15E-06 | 9.95E-06 | 8.49E-06 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 3.23E-10 | 3.38E-10 | 3.10E-10 | 5 | -4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 3.54E-09 | 3.83E-09 | 3.30E-09 | 8 | -7 |

**Table G.144: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Kilometres Travelled Parameter)**

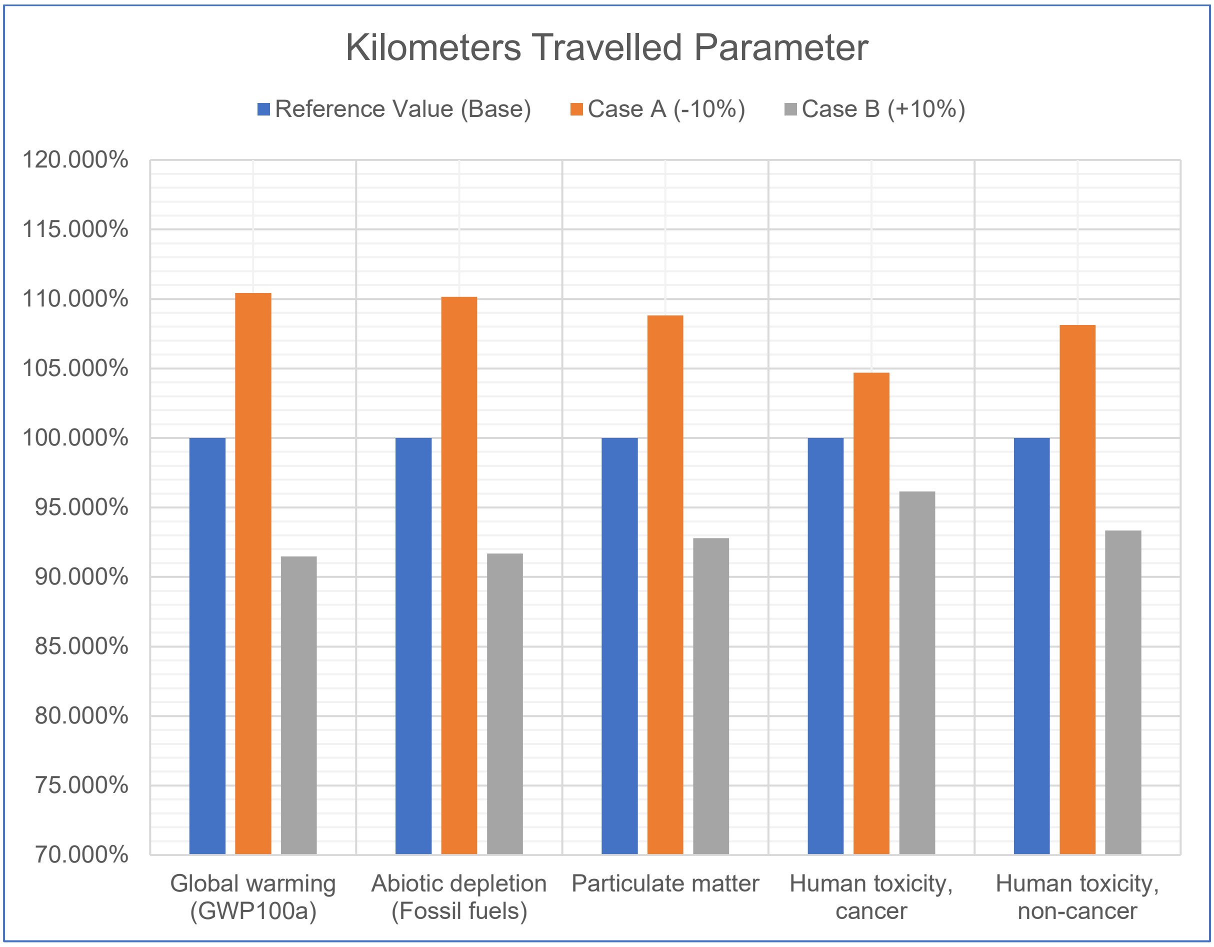


**Figure G.144: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Kilometres Travelled Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.073240527 | 0.072933954 | 0.0735471 | -0.4 | 0.42 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.85665157 | 0.85242871 | 0.86087444 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 9.15E-06 | 9.02E-06 | 9.28E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 3.23E-10 | 3.06E-10 | 3.40E-10 | -5 | 5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 3.54E-09 | 3.46E-09 | 3.62E-09 | -2 | 2 |

**Table G.145: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Vehicle Manufacture Parameter)**

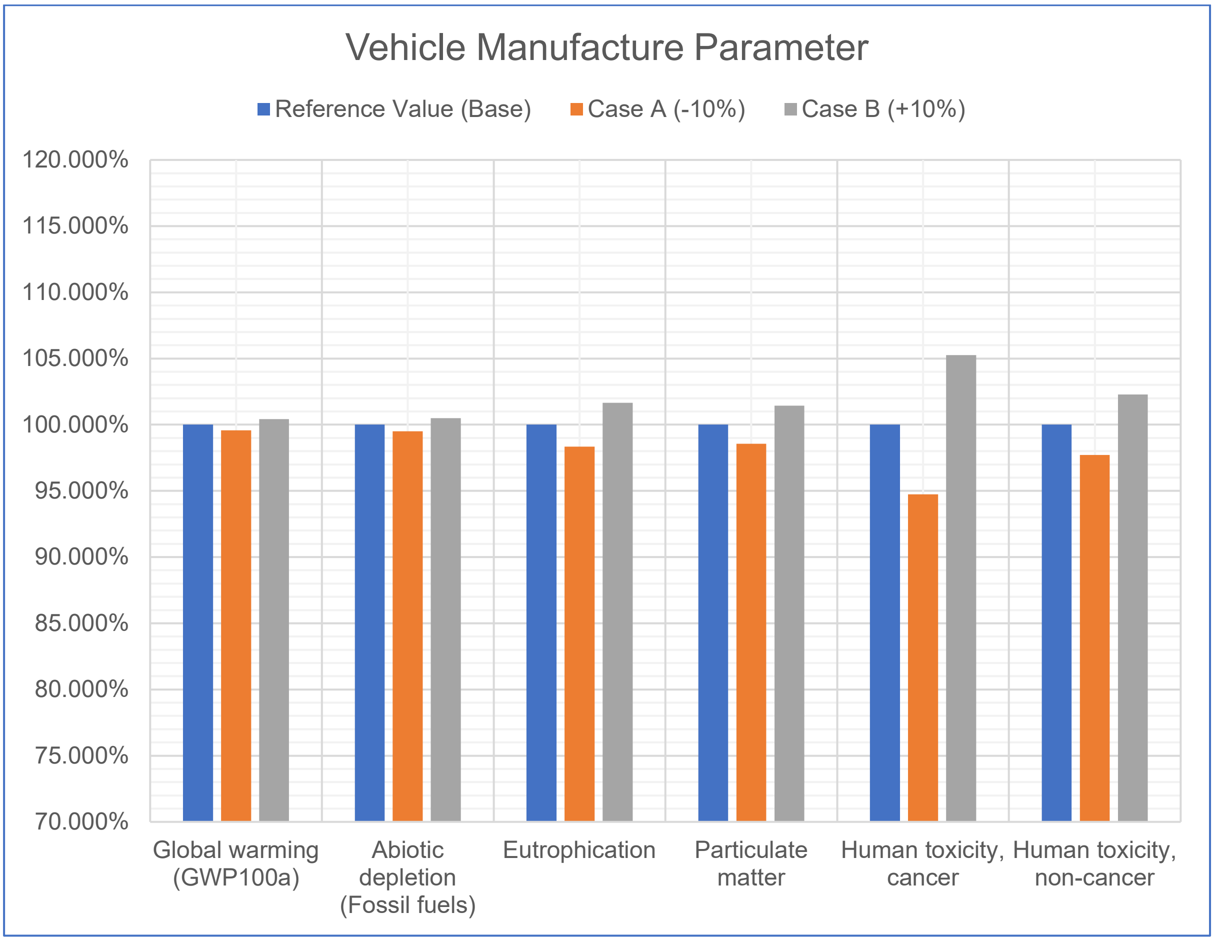


**Figure G.145: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.073240527 | 0.073100669 | 0.073380385 | -0.2 | 0.19 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.85665157 | 0.85344542 | 0.85985773 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 9.15E-06 | 9.09E-06 | 9.20E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 3.23E-10 | 3.21E-10 | 3.24E-10 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 3.54E-09 | 3.53E-09 | 3.55E-09 | 0 | 0 |

**Table G.146: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Vehicle Maintenance Parameter)**

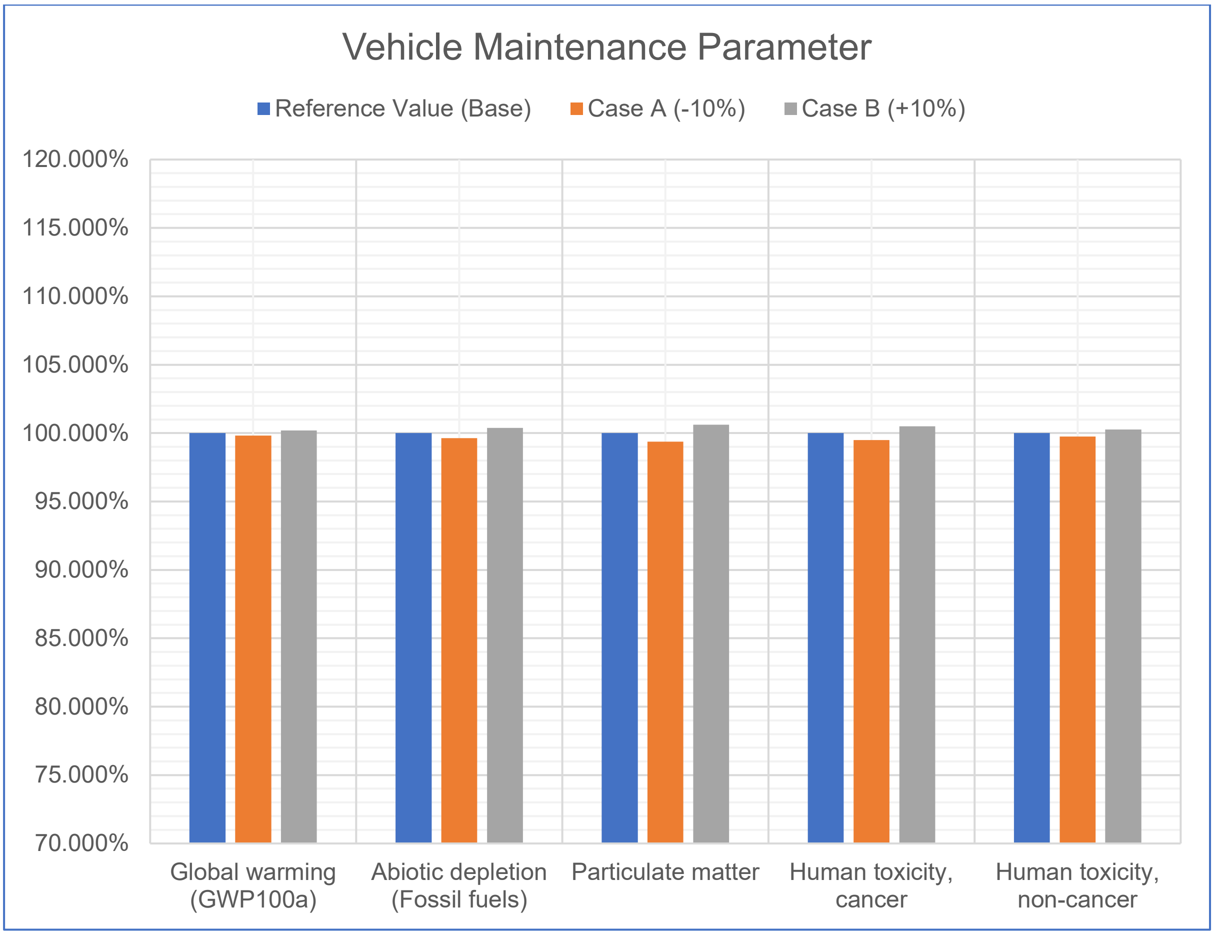


**Figure G.146: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.073240527 | 0.073232123 | 0.07324893 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.85665157 | 0.85664091 | 0.85666223 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 9.15E-06 | 9.15E-06 | 9.15E-06 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 3.23E-10 | 3.23E-10 | 3.23E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 3.54E-09 | 3.53E-09 | 3.54E-09 | -0.15 | 0.15 |

**Table G.147: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Vehicle Disposal Parameter)**

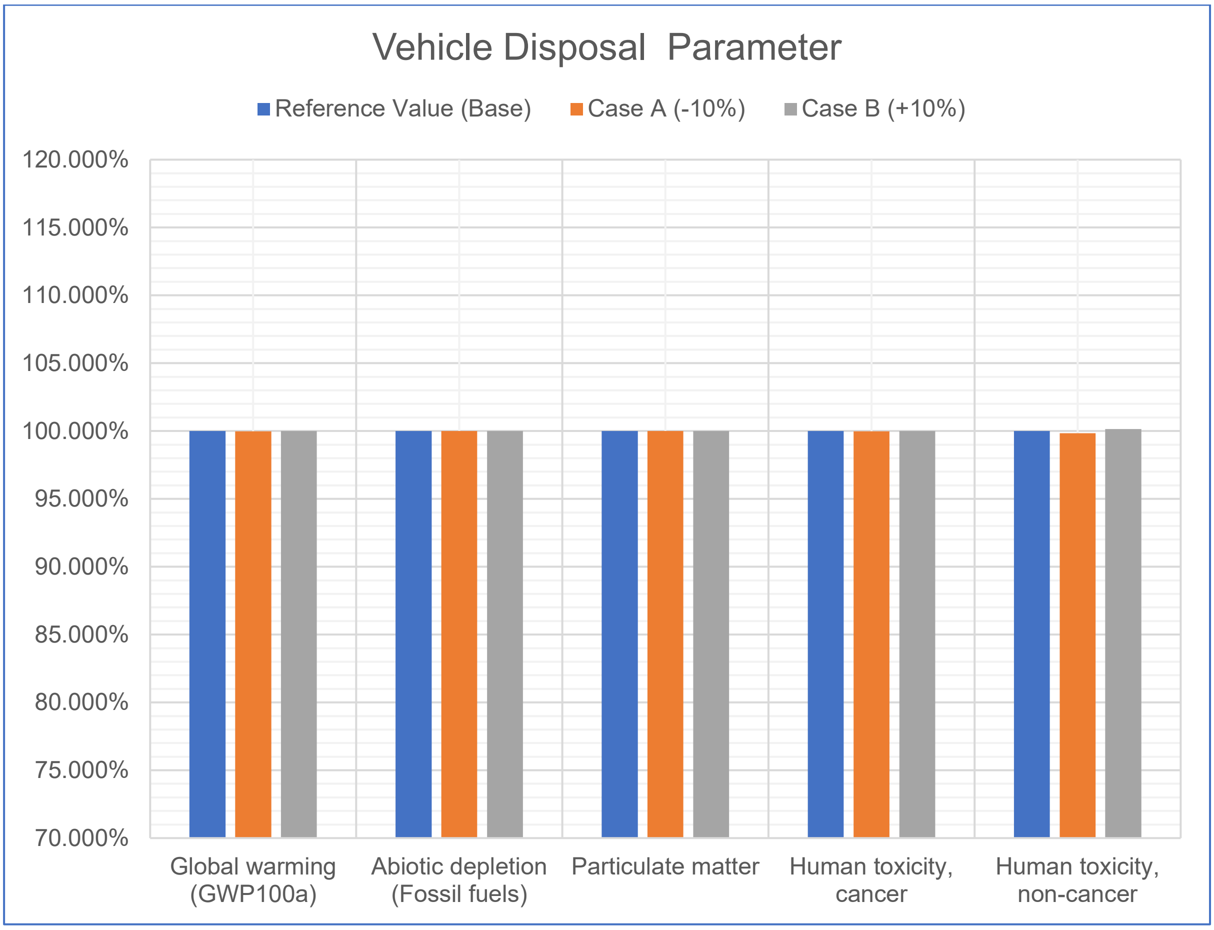


**Figure G.147: Sensitivity Analysis for LCA of Battery Electric Articulated Trucks (Vehicle Disposal Parameter)**

# APPENDIX H: SENSITIVITY ANALYSIS FOR LCA OF BIOFUEL VEHICLES

## E10 Vehicles

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.23434551 | 0.25625534 | 0.21641928 | 9 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.6052408 | 3.0459796 | 9 | -8 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 6.19E-05 | 5.29E-05 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.60E-09 | 1.57E-09 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.51E-09 | 7.96E-09 | 4 | -3 |

**Table H.1: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Kilometres Travelled Parameter)**

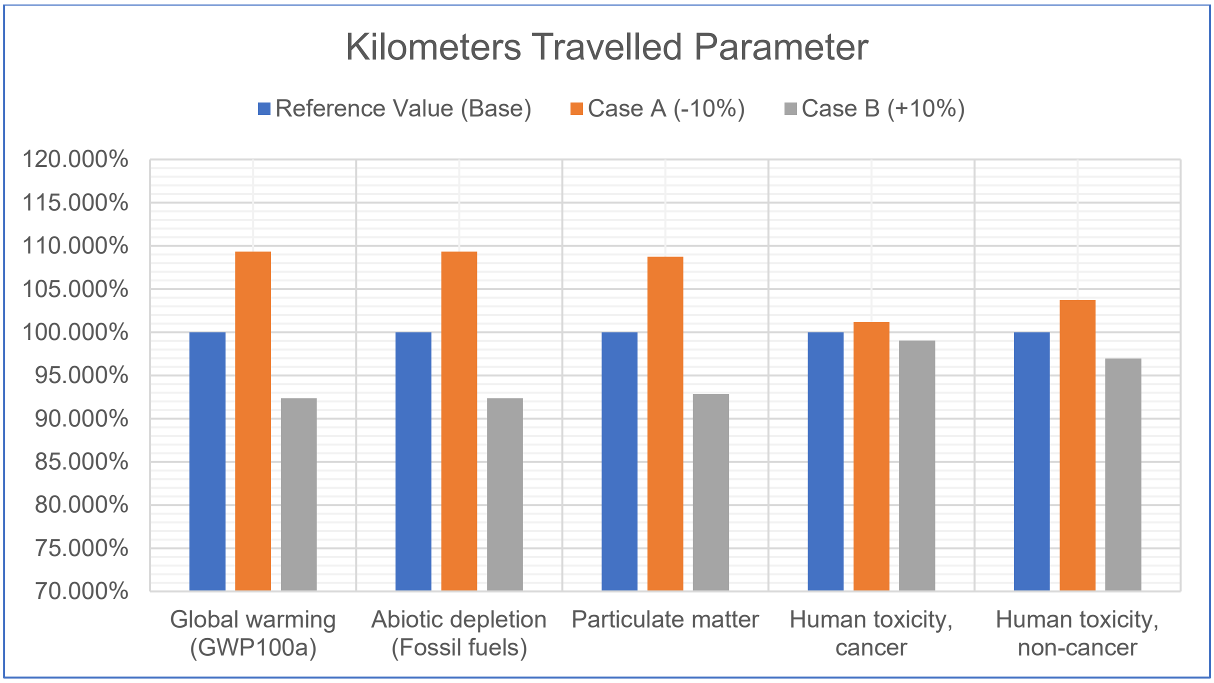


**Figure H.1: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.21462666 | 0.25406436 | -8 | 8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.0208128 | 3.5744814 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.25E-05 | 6.14E-05 | -8 | 8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.56E-09 | 1.60E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 7.93E-09 | 8.48E-09 | -3 | 3 |

**Table H.2: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Fuel Consumption Parameter)**

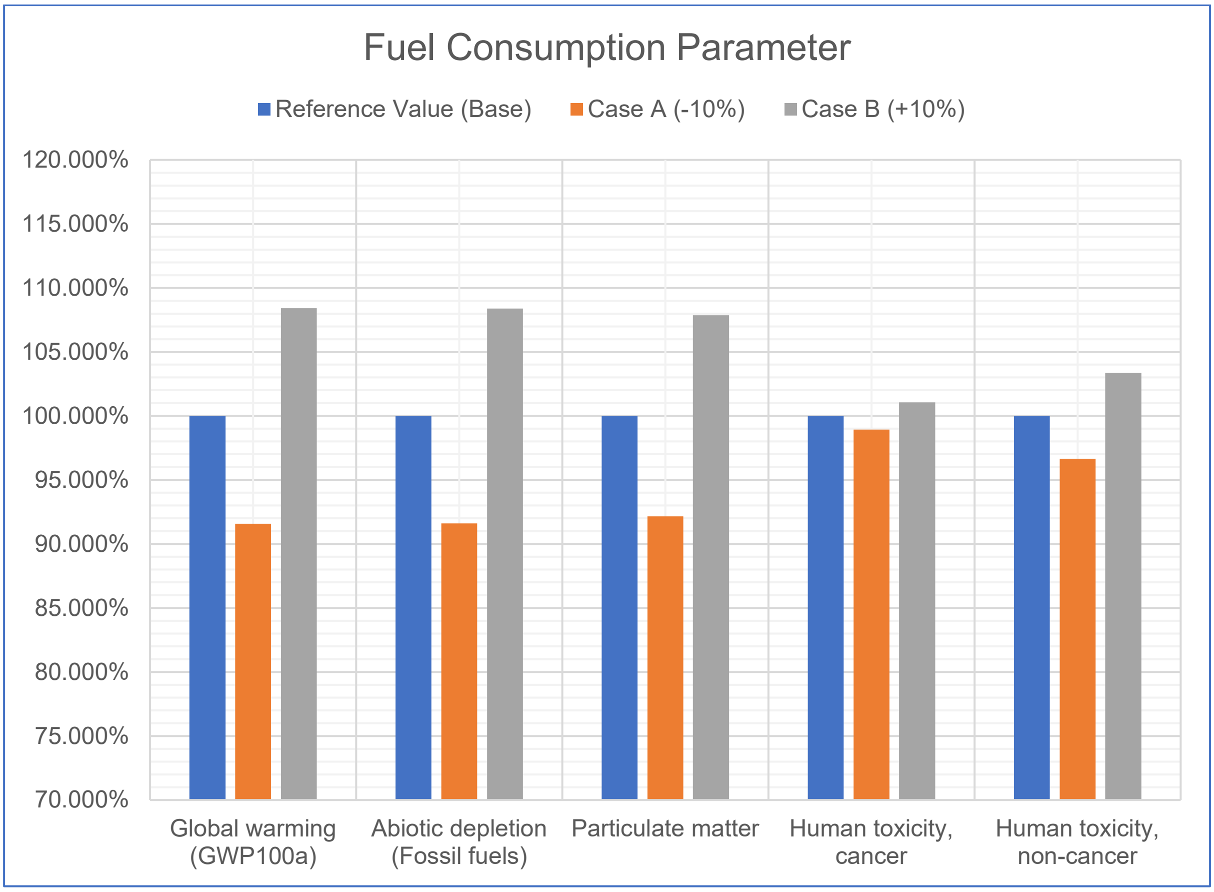


**Figure H.2: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.2603839 | 0.21304137 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.6640523 | 2.997861 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 6.33E-05 | 5.18E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.76E-09 | 1.44E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 9.12E-09 | 7.46E-09 | 11 | -9 |

**Table H.3: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Occupancy Rate Parameter)**

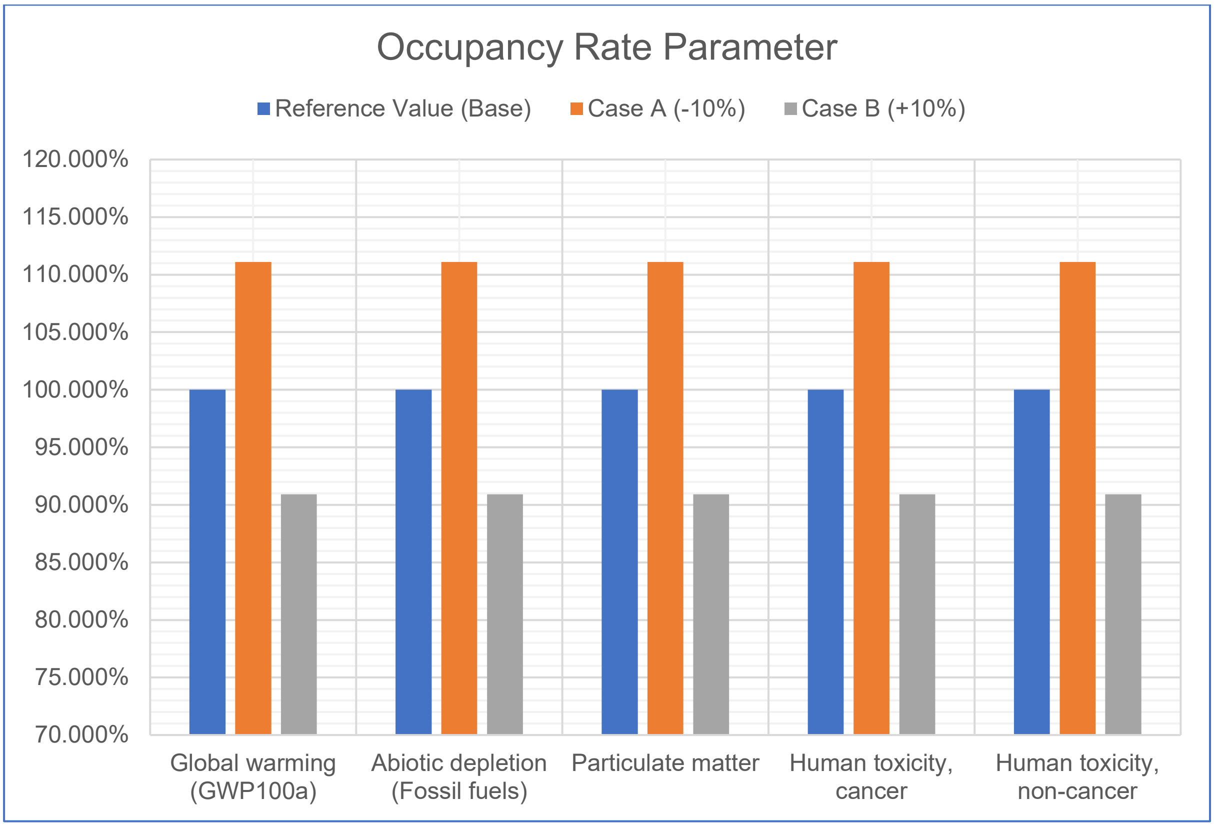


**Figure H.3: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23144458 | 0.23724644 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2572116 | 3.3380826 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.60E-05 | 5.80E-05 | -2 | 2 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.44E-09 | 1.72E-09 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 7.77E-09 | 8.65E-09 | -5 | 5 |

**Table H.4: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

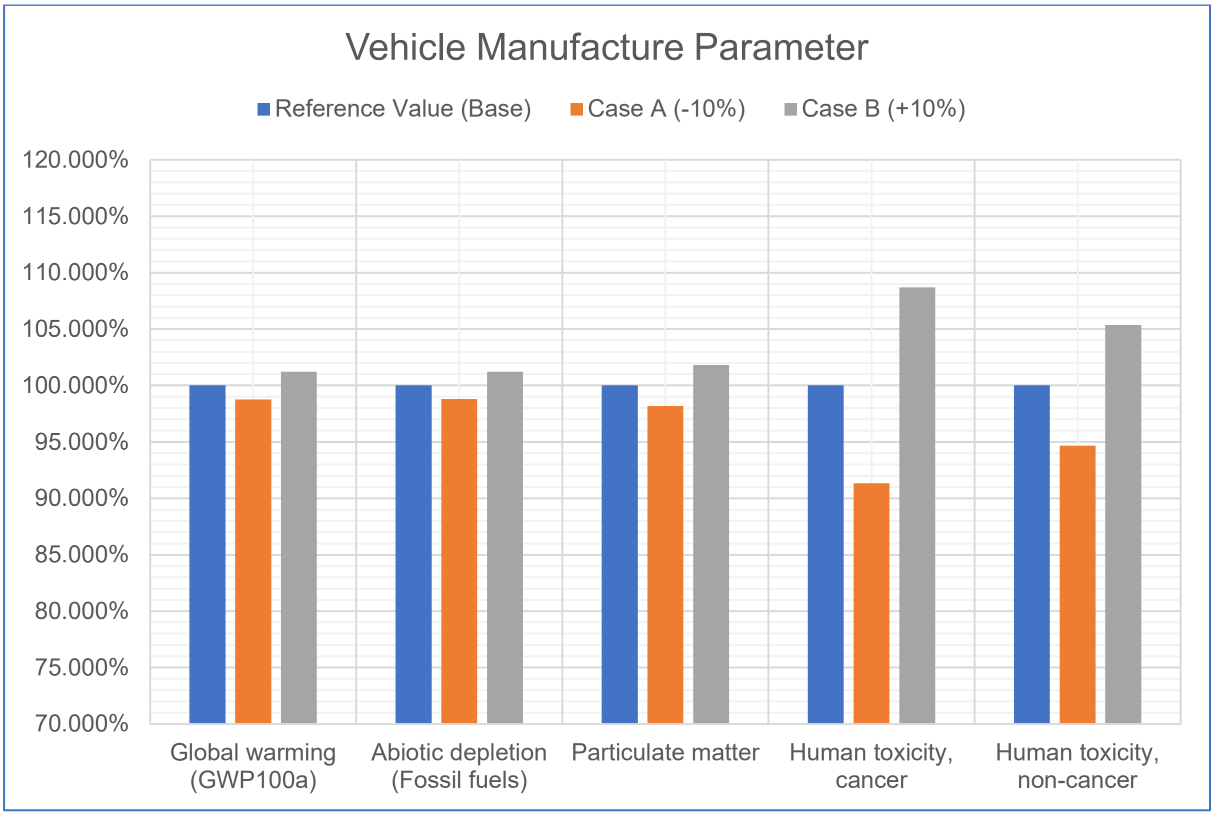


**Figure H.4: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23418743 | 0.23450358 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2451732 | 3.350121 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.69E-05 | 5.71E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.20E-09 | 8.21E-09 | 0 | 0 |

**Table H.5: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

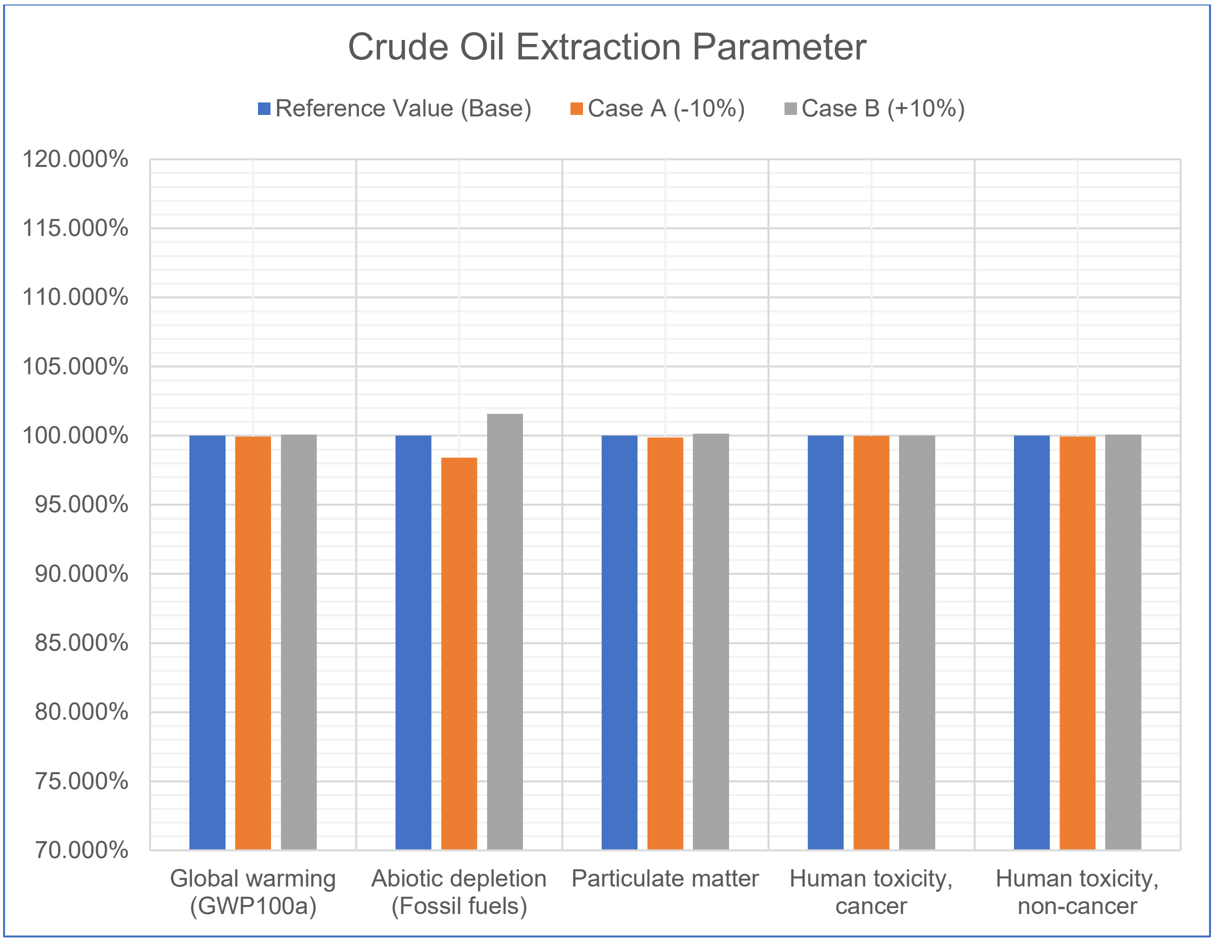


**Figure H.5: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23402653 | 0.23466449 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2430352 | 3.352259 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.68E-05 | 5.72E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.20E-09 | 8.22E-09 | 0 | 0 |

**Table H.6: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Crude Oil Refining Parameter)**

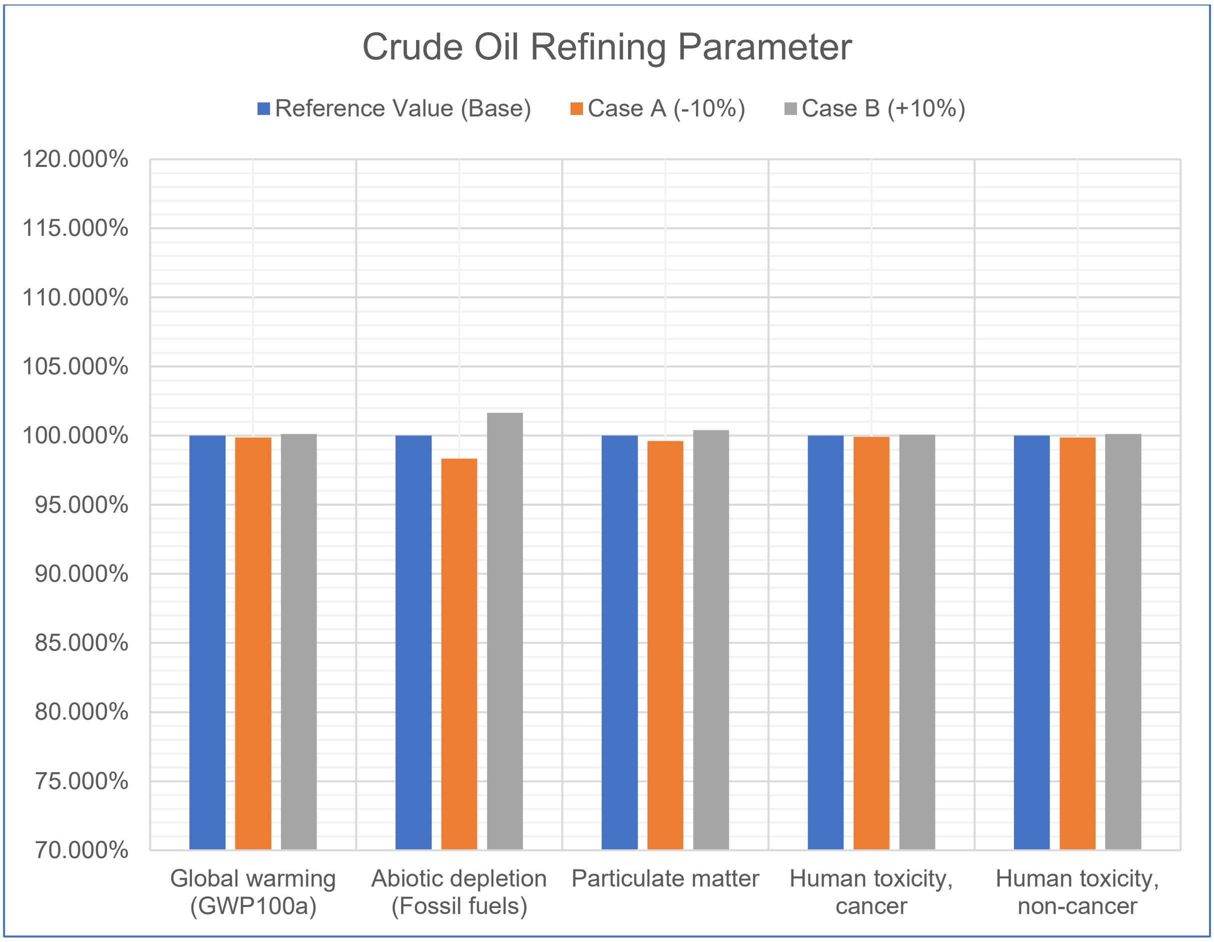


**Figure H.6: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23447925 | 0.23421177 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2916887 | 3.3036055 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.67E-05 | 5.73E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.10E-09 | 8.32E-09 | -1 | 1 |

**Table H.7: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Ethanol Production Parameter)**

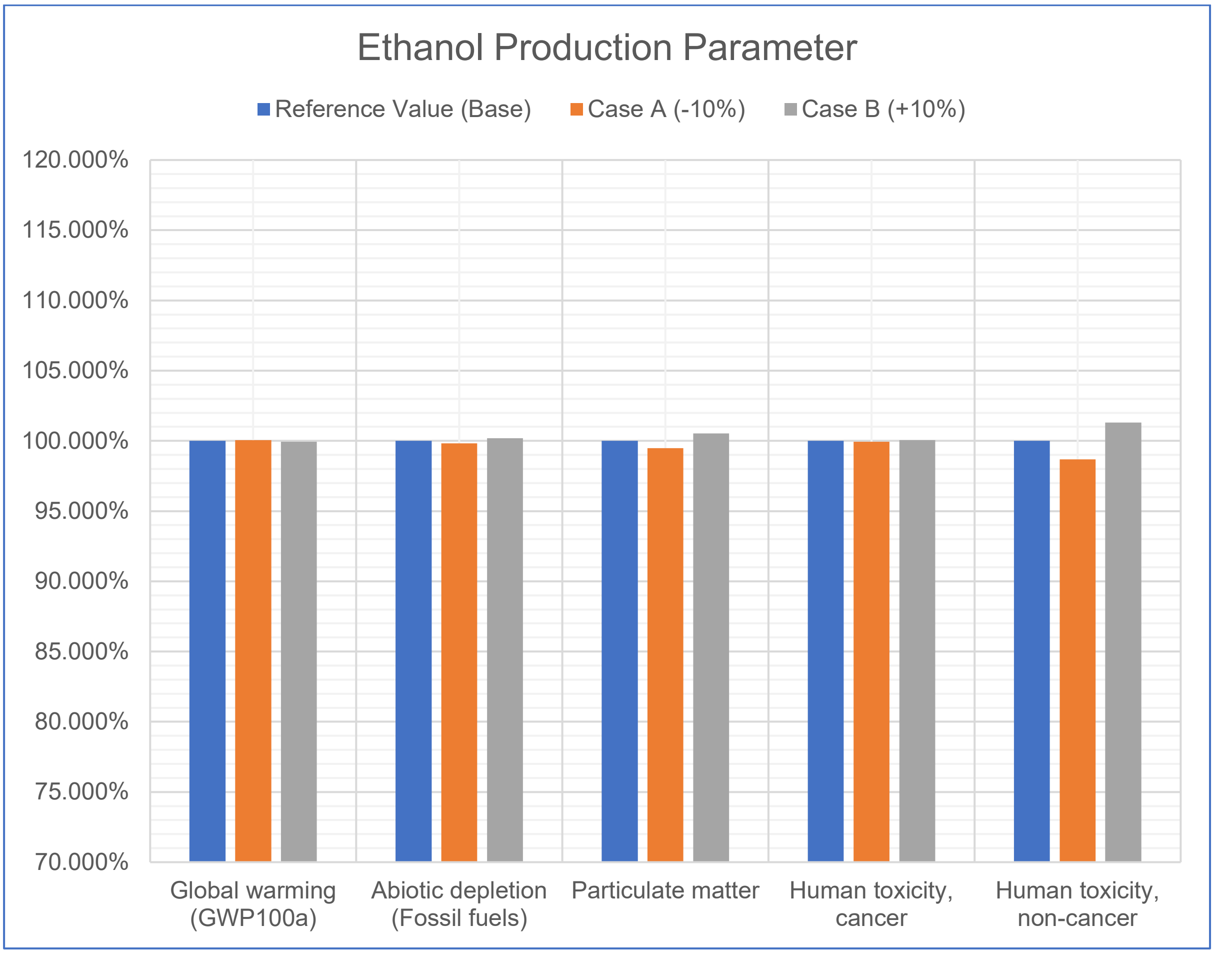


**Figure H.7: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Ethanol Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23444486 | 0.23424616 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2916887 | 3.3036055 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.67E-05 | 5.73E-05 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.10E-09 | 8.32E-09 | -1 | 1 |

**Table H.8: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Ethanol Processing Parameter)**

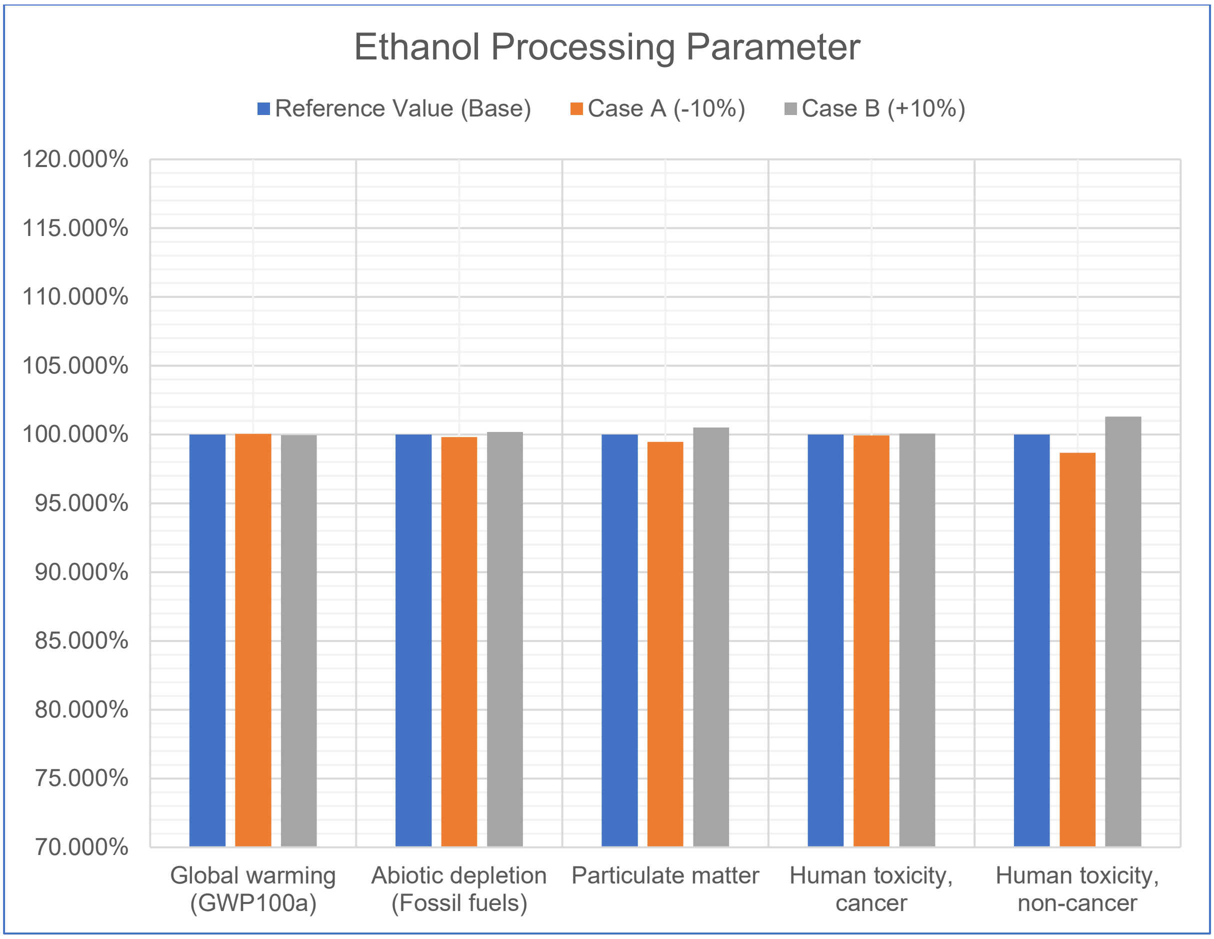


**Figure H.8: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Ethanol Processing Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23374308 | 0.23494794 | -0.26 | 0.26 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2863231 | 3.3089711 | -0.34 | 0.34 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.68E-05 | 5.72E-05 | -0.31 | 0.31 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | -0.20 | 0.20 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.17E-09 | 8.25E-09 | -0.50 | 0.50 |

**Table H.9: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

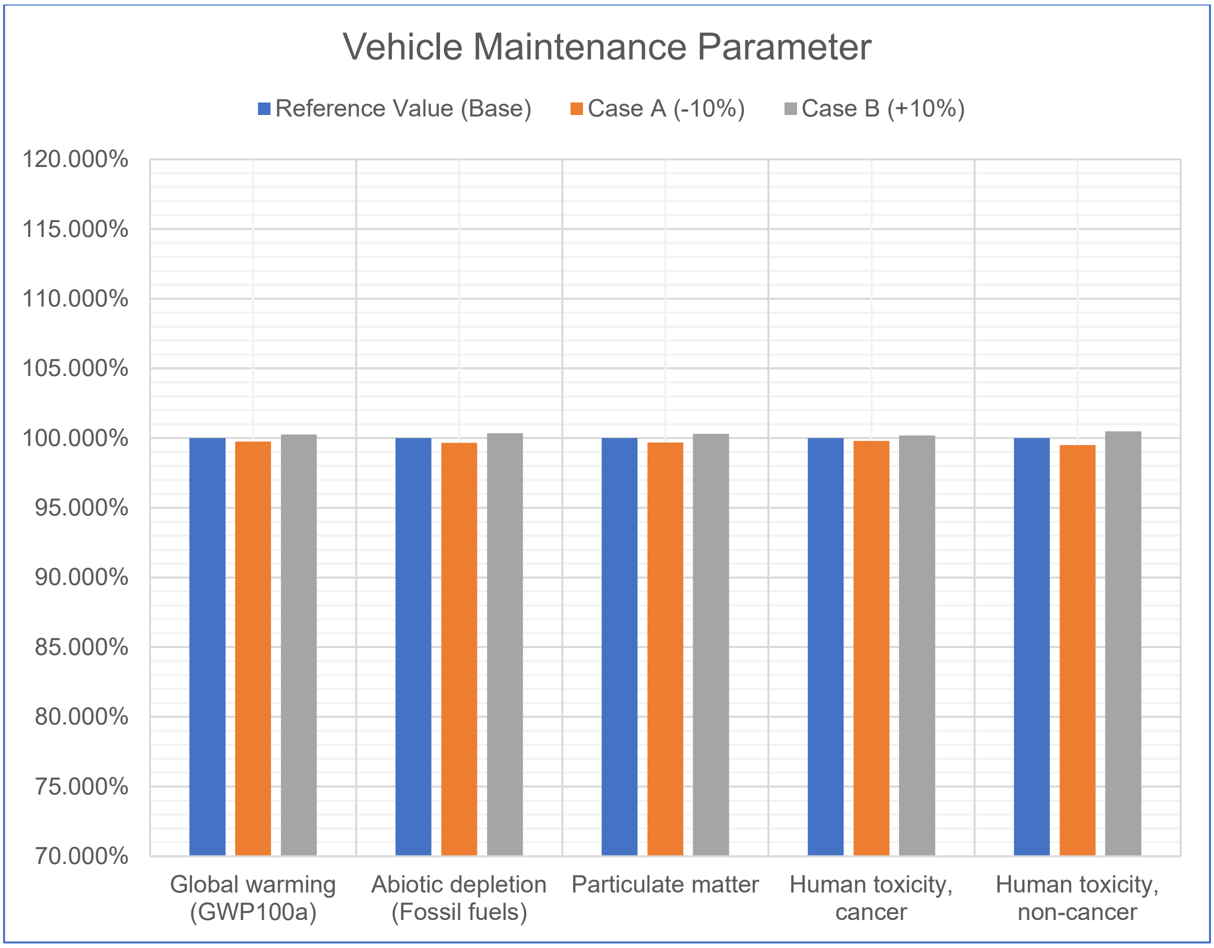


**Figure H.9: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.23434551 | 0.23413317 | 0.23455785 | -0.09 | 0.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 3.2976471 | 3.2964762 | 3.298818 | -0.04 | 0.04 |
| **Particulate Matter (kg/pkm)** | 5.70E-05 | 5.70E-05 | 5.70E-05 | -0.04 | 0.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | -0.06 | 0.06 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 8.21E-09 | 8.14E-09 | 8.27E-09 | -0.81 | 0.81 |

**Table H.10: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Vehicle Disposal Parameter)**

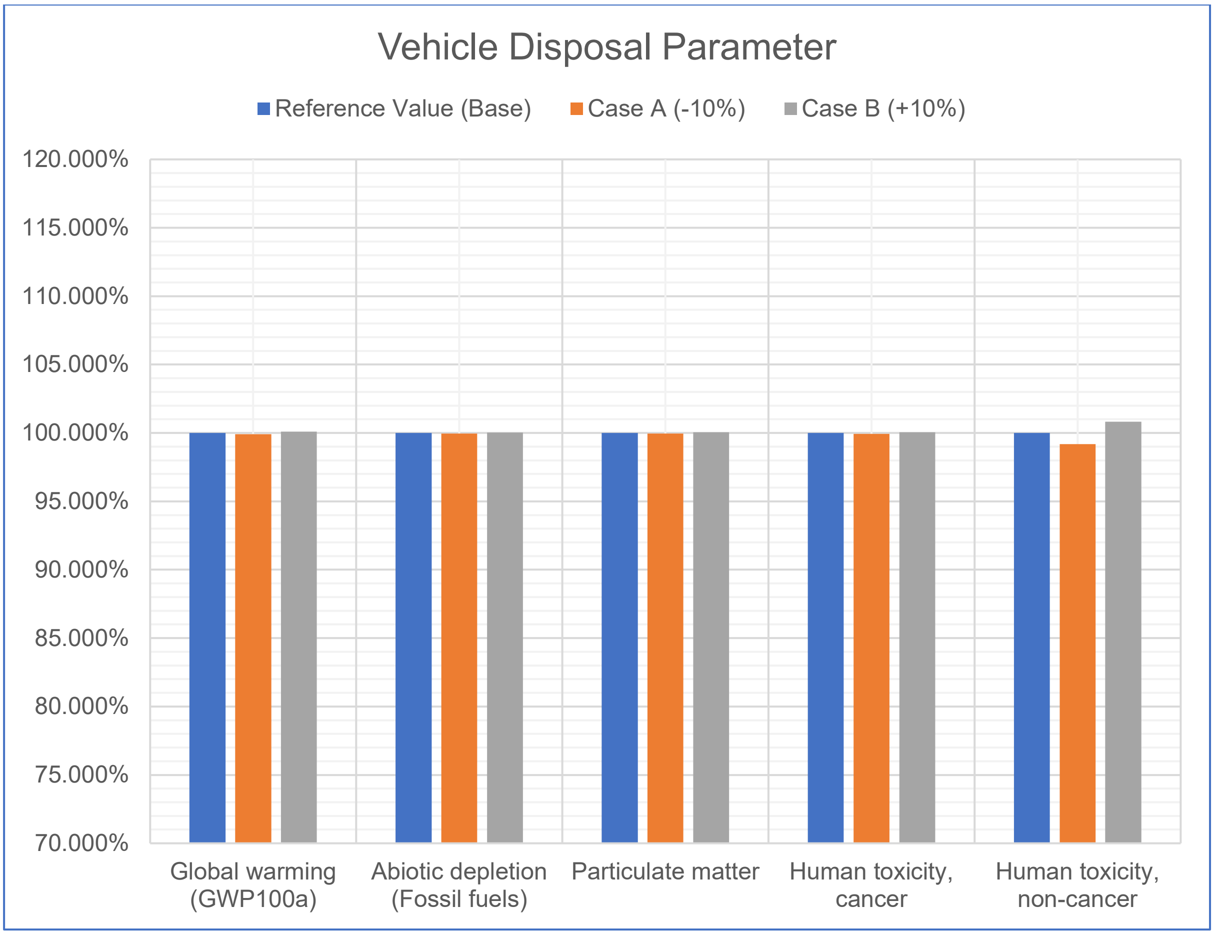


**Figure H.10: Sensitivity Analysis for LCA of $E_{10}$ Passenger Vehicles (Vehicle Disposal Parameter)**

## $E_{25}$ Passenger Vehicles

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.19876198 | 0.16937926 | 9 | -7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 3.2615292 | 2.764761 | 9 | -7 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 6.31E-05 | 5.38E-05 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.60E-09 | 1.57E-09 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 1.06E-08 | 9.63E-09 | 5 | -4 |

**Table H.11: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Kilometres Travelled Parameter)**

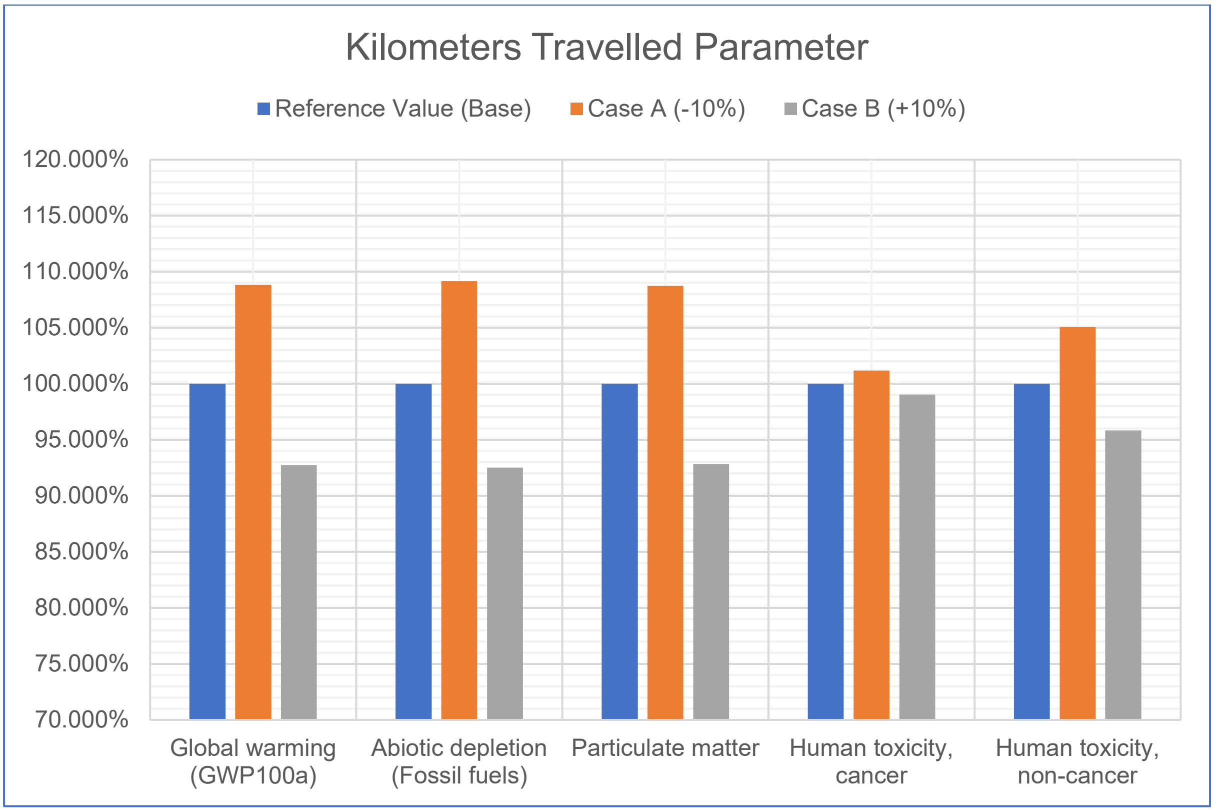


**Figure H.11: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.16805704 | 0.19714593 | -8 | 8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.7424064 | 3.234207 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.34E-05 | 6.25E-05 | -8 | 8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.57E-09 | 1.60E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 9.59E-09 | 1.05E-08 | -5 | 5 |

**Table H.12: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Fuel Consumption Parameter)**

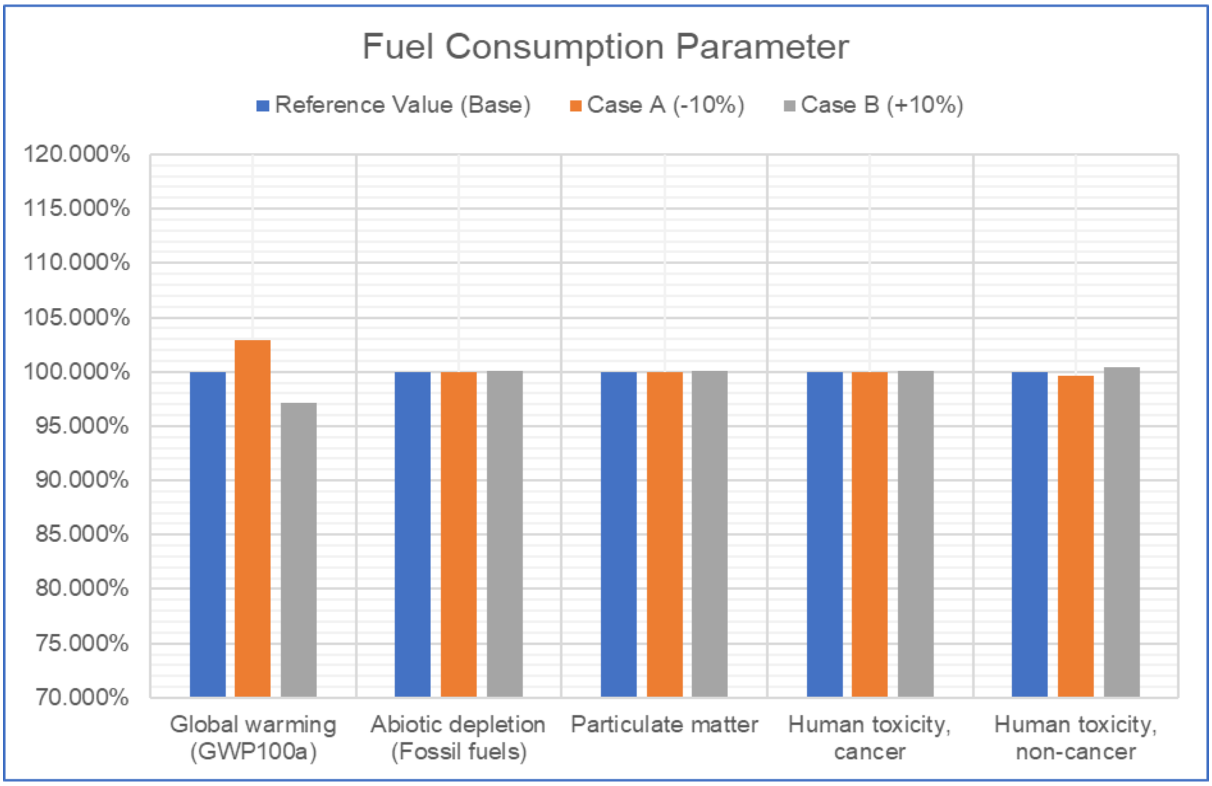


**Figure H.12: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.20289054 | 0.16600135 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 3.3203408 | 2.7166425 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 6.44E-05 | 5.27E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.76E-09 | 1.44E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 1.12E-08 | 9.14E-09 | 11 | -9 |

**Table H.13: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Occupancy Rate Parameter)**

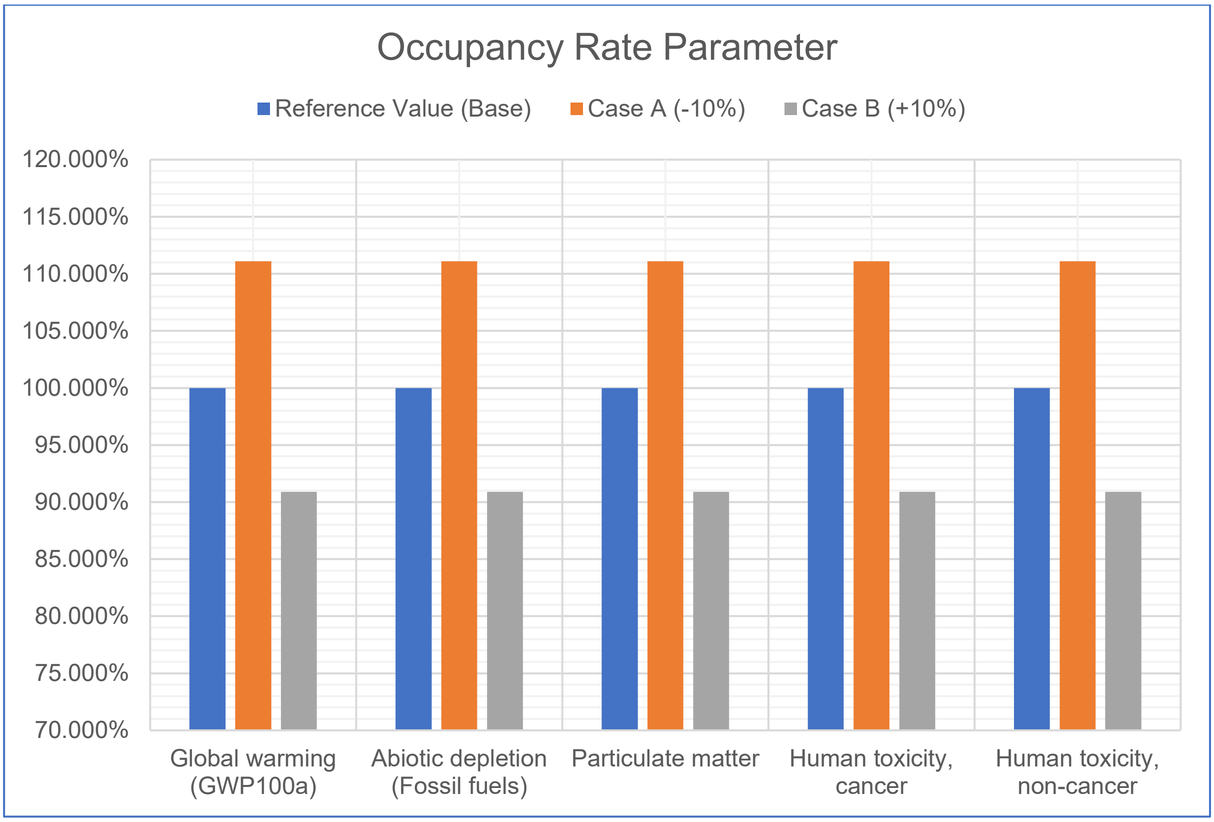


**Figure H.13: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Occupancy Rate Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.17970055 | 0.18550241 | -2 | 2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9478712 | 3.0287422 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.69E-05 | 5.90E-05 | -2 | 2 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.45E-09 | 1.72E-09 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 9.61E-09 | 1.05E-08 | -4 | 4 |

**Table H.14: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

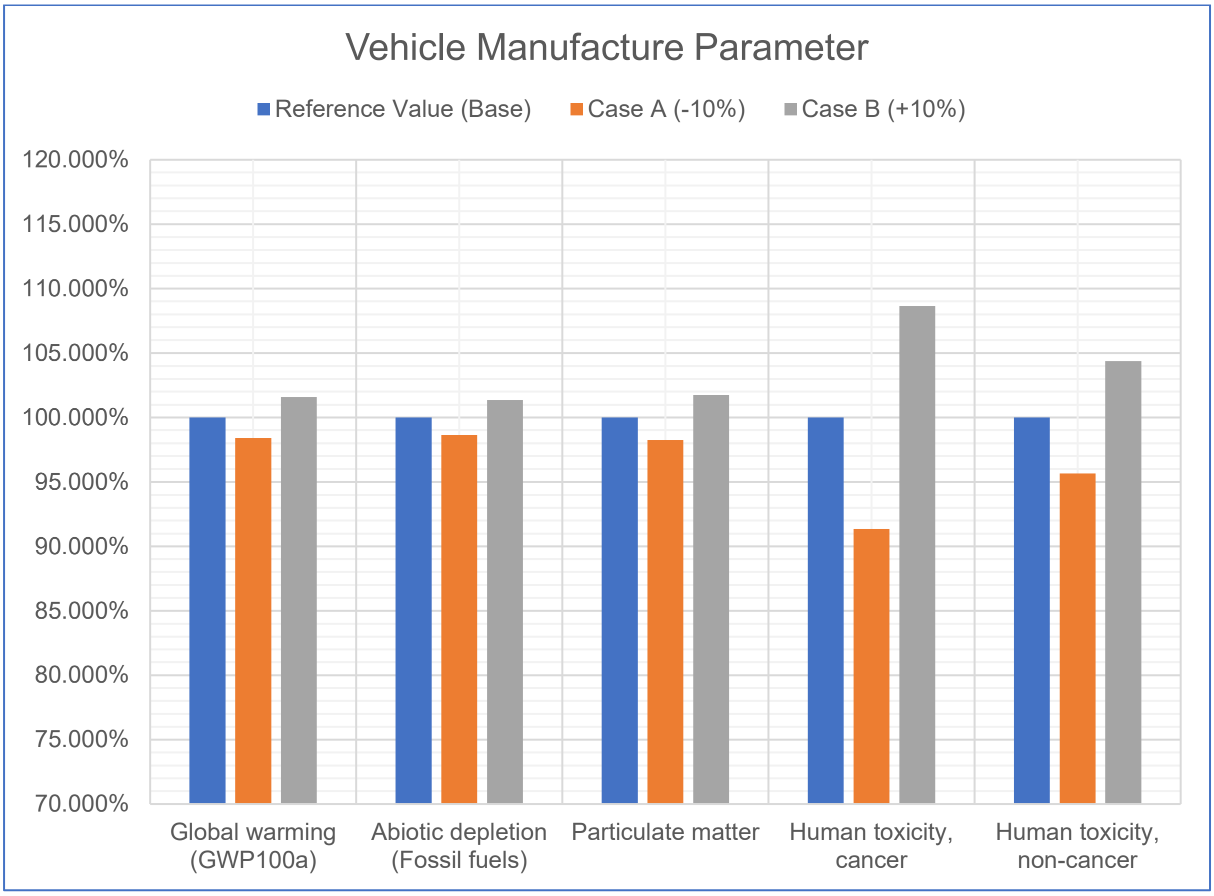


**Figure H.14: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.1824687 | 0.18273427 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9442282 | 3.0323853 | -1 | 1 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.79E-05 | 5.80E-05 | 0 | 0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | 0 | 0 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 1.00E-08 | 1.01E-08 | 0 | 0 |

**Table H.15: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

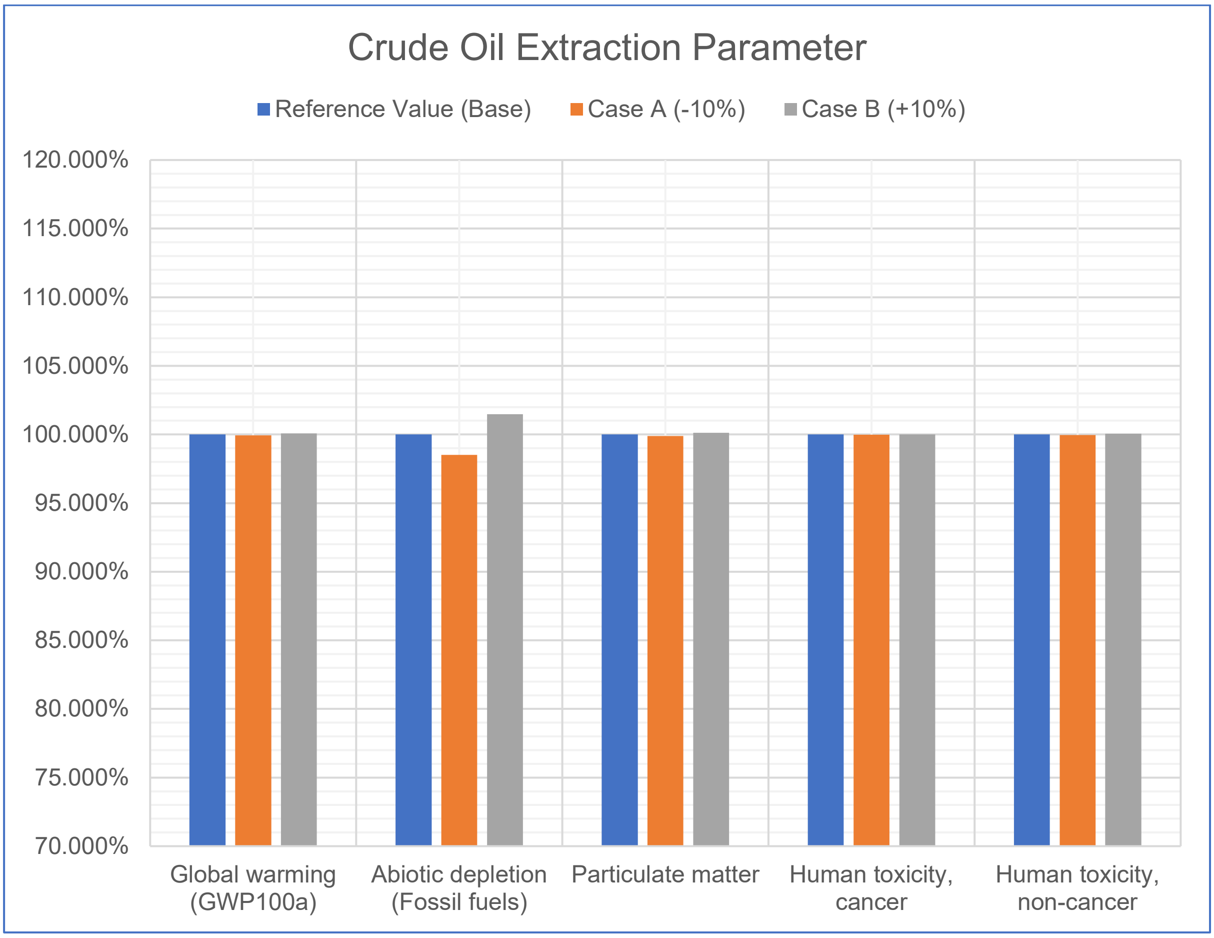


**Figure H.15: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.18233354 | 0.18286943 | -0.15 | 0.15 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9424322 | 3.0341812 | -1.54 | 1.54 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.78E-05 | 5.82E-05 | -0.33 | 0.33 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | -0.07 | 0.07 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 1.00E-08 | 1.01E-08 | -0.09 | 0.09 |

**Table H.16: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Crude Oil Refining Parameter)**

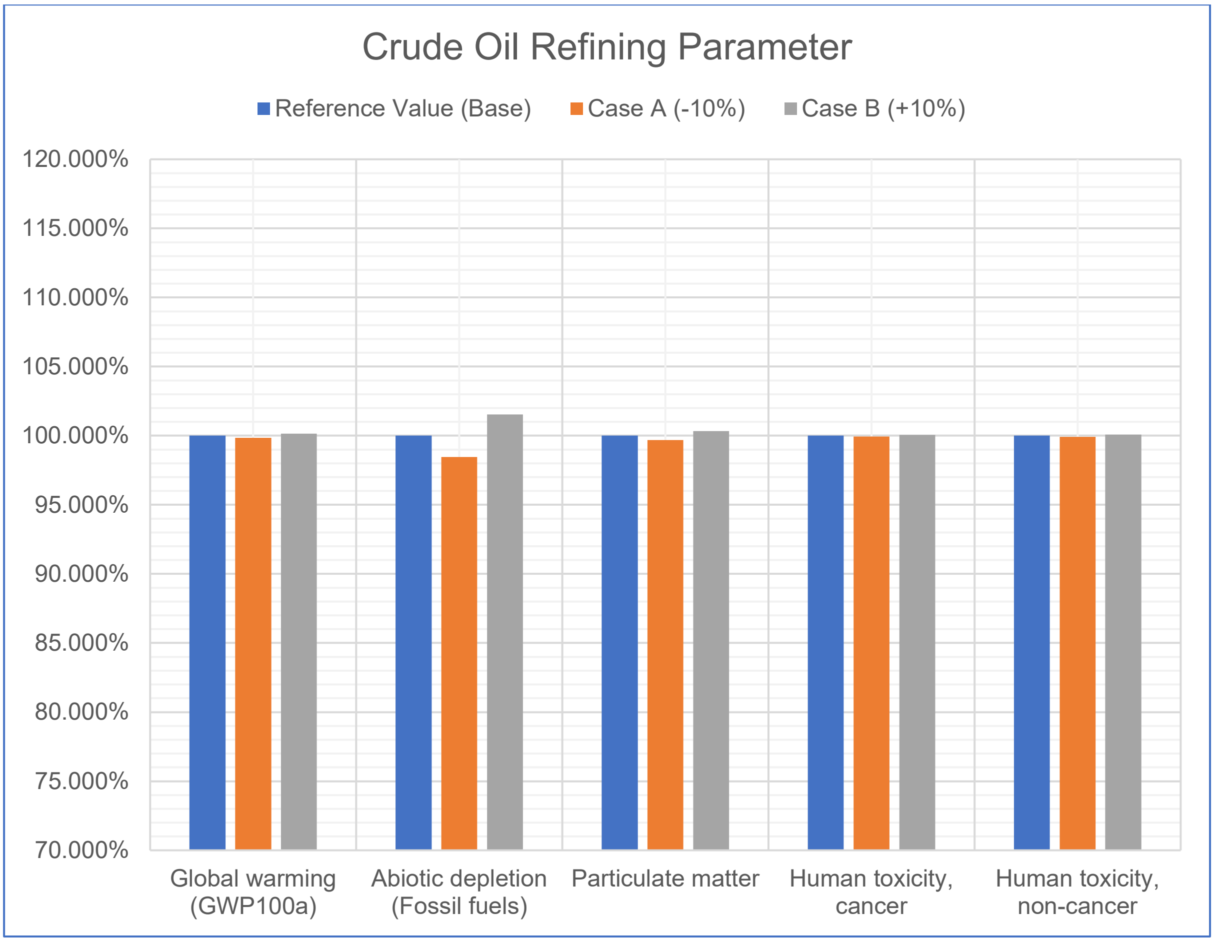


**Figure H.16: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.18293834 | 0.18226462 | 0.18 | -0.18 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9732994 | 3.003314 | -0.50 | 0.50 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.72E-05 | 5.87E-05 | -1.30 | 1.30 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.59E-09 | -0.16 | 0.16 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 9.78E-09 | 1.03E-08 | -2.70 | 2.70 |

**Table H.17: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Ethanol Production Parameter)**

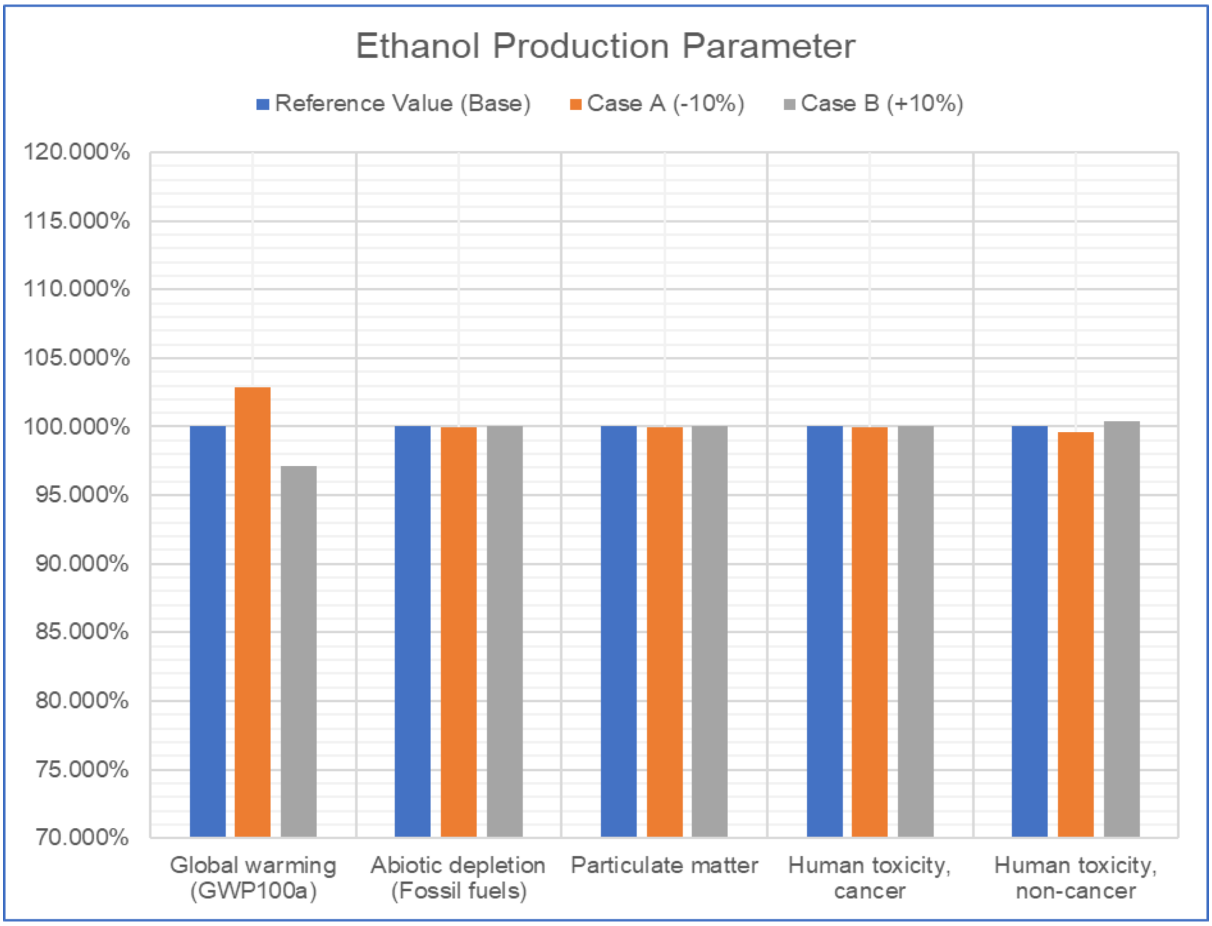


**Figure H.17: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Ethanol Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.1828517 | 0.18235126 | 0.14 | -0.14 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9732994 | 3.003314 | -0.50 | 0.50 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.72E-05 | 5.87E-05 | -1.30 | 1.30 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.59E-09 | -0.16 | 0.16 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 9.78E-09 | 1.03E-08 | -2.70 | 2.70 |

**Table H.18: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Ethanol Processing Parameter)**

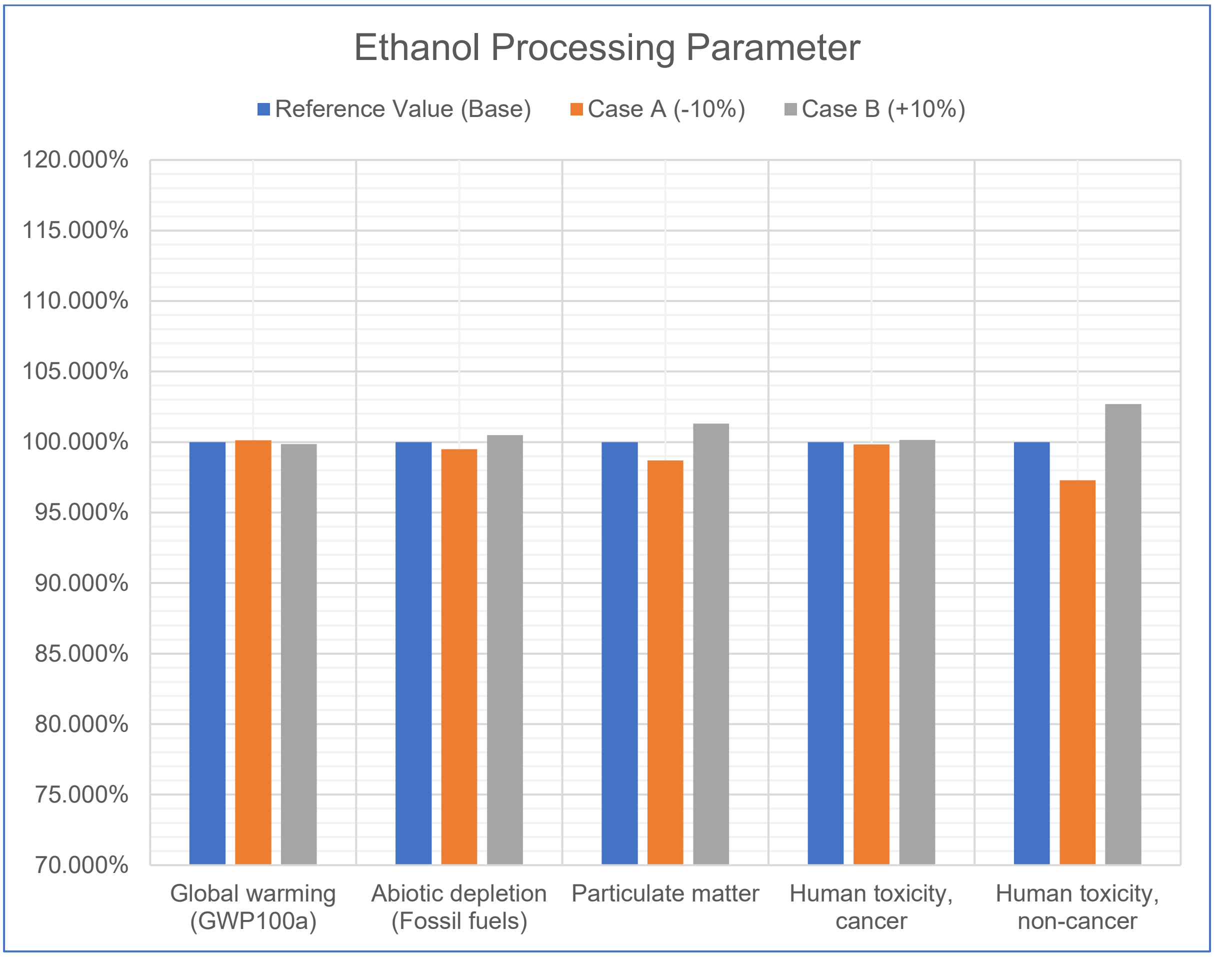


**Figure H.18: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Ethanol Processing Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.18199905 | 0.18320391 | -0.33 | 0.33 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9769827 | 2.9996307 | -0.38 | 0.38 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.78E-05 | 5.81E-05 | -0.30 | 0.30 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.59E-09 | -0.20 | 0.20 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 1.00E-08 | 1.01E-08 | -0.41 | 0.41 |

**Table H.19: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

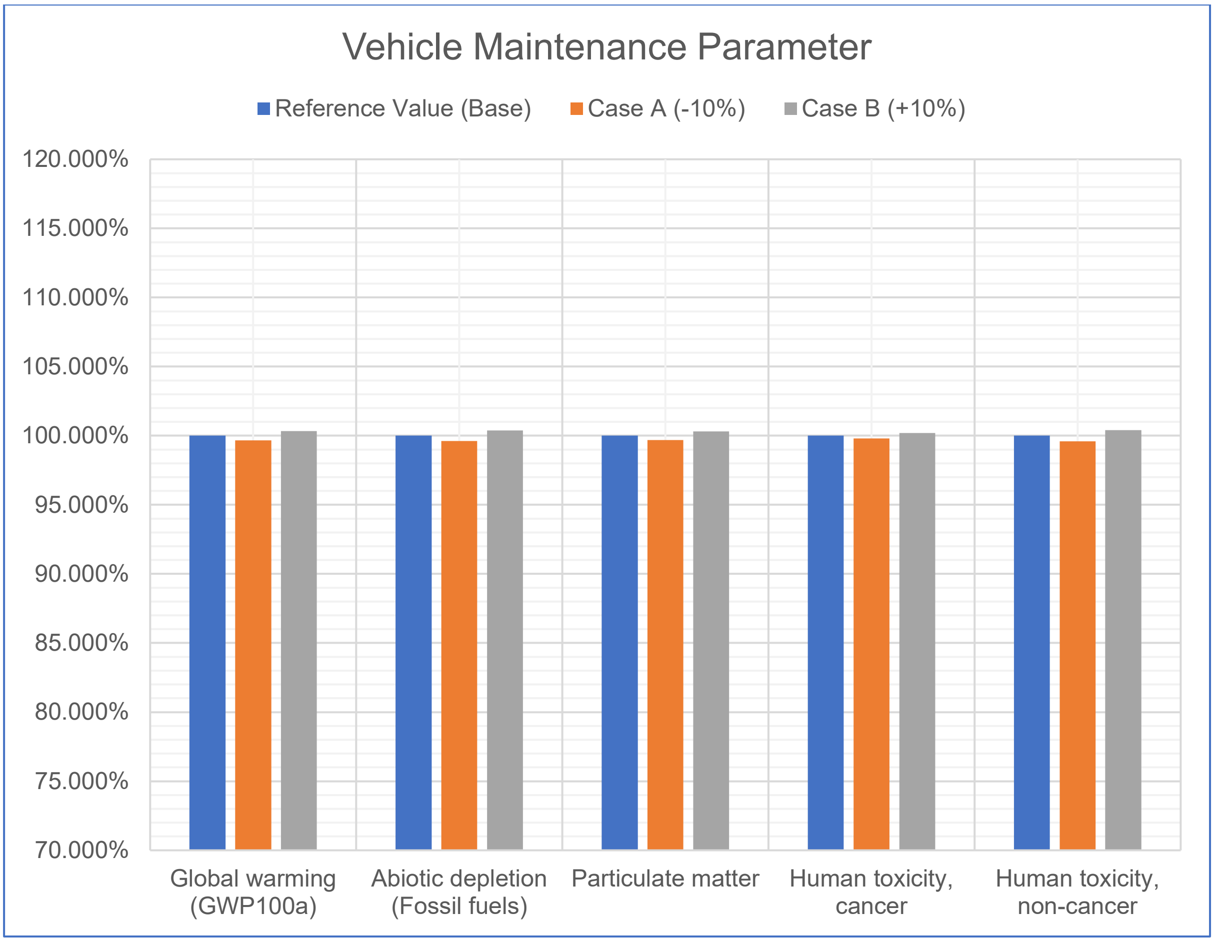


**Figure H.19: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.18260148 | 0.18238914 | 0.18281383 | -0.12 | 0.12 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.9883067 | 2.9871358 | 2.9894776 | -0.04 | 0.04 |
| **Particulate Matter (kg/pkm)** | 5.80E-05 | 5.79E-05 | 5.80E-05 | -0.04 | 0.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.58E-09 | 1.58E-09 | 1.58E-09 | -0.06 | 0.06 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.01E-08 | 9.98E-09 | 1.01E-08 | -0.67 | 0.67 |

**Table H.20: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Vehicle Disposal Parameter)**

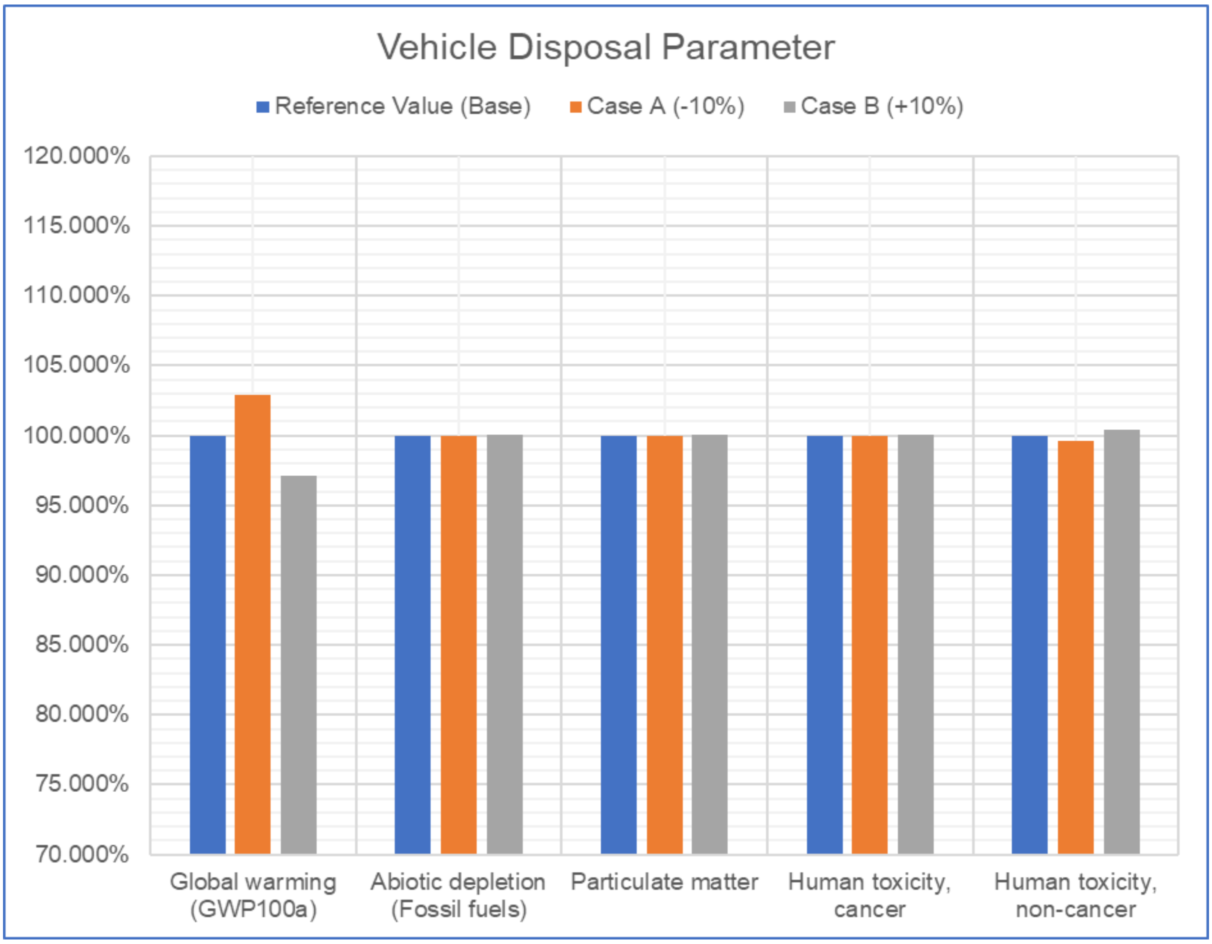


**Figure H.20: Sensitivity Analysis for LCA of $E_{25}$ Passenger Vehicles (Vehicle Disposal Parameter)**

## $E_{40}$ Passenger Vehicles

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.14349817 | 0.12416342 | 8 | -7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.9353878 | 2.497918 | 9 | -7 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 6.43E-05 | 5.48E-05 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.60E-09 | 1.57E-09 | 1 | -1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.26E-08 | 1.13E-08 | 6 | -5 |

**Table H.21: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Kilometres Travelled Parameter)**

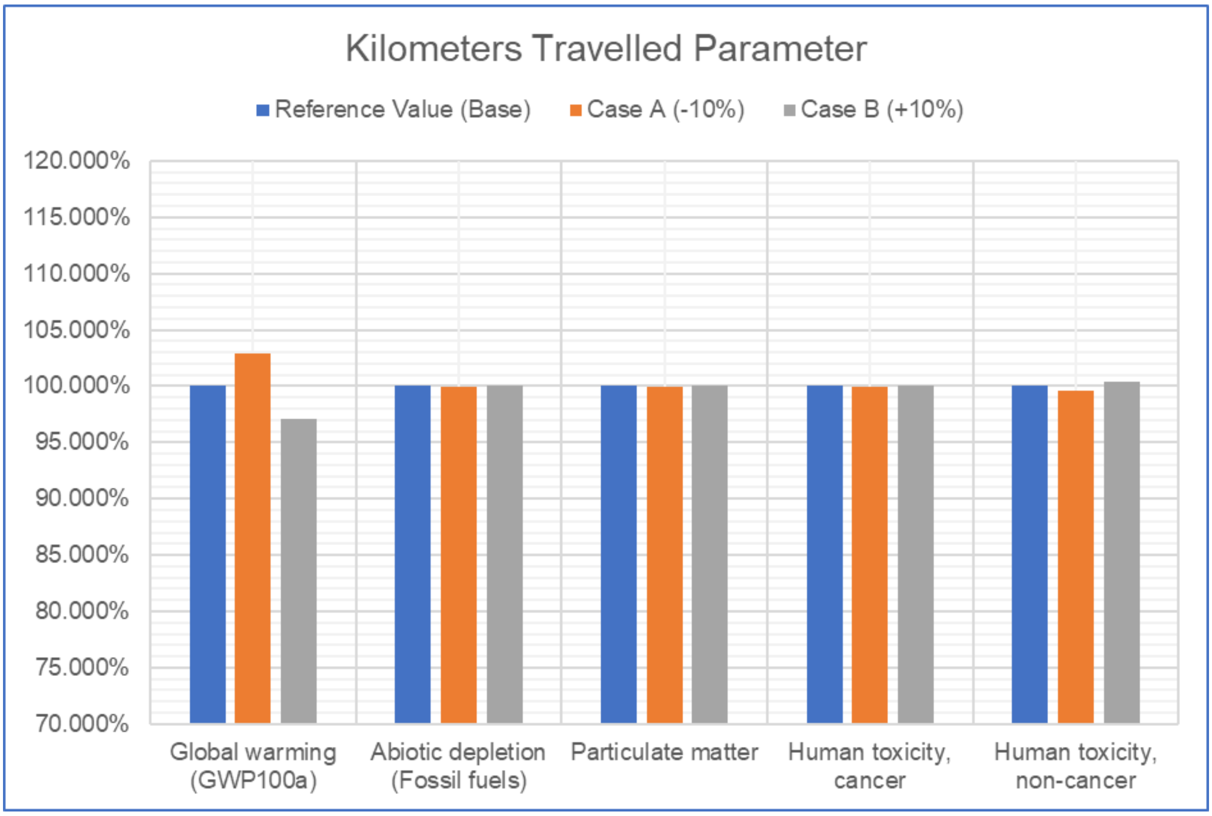


**Figure H.21: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.12329335 | 0.14243476 | -7 | 7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.4782318 | 2.9113269 | -8 | 8 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.44E-05 | 6.38E-05 | -8 | 8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.57E-09 | 1.60E-09 | -1 | 1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.13E-08 | 1.26E-08 | -5 | 5 |

**Table H.22: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Fuel Consumption Parameter)**

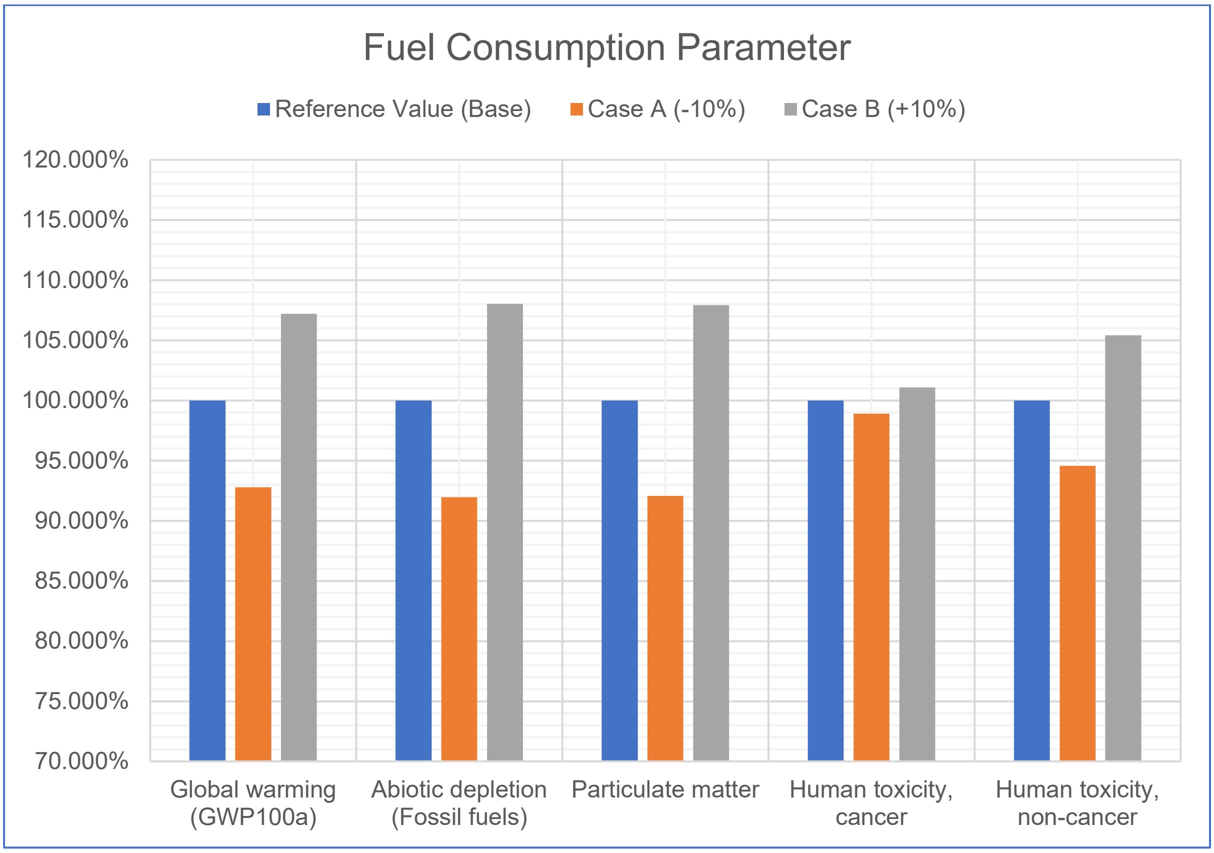


**Figure H.22: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.14762673 | 0.12078551 | 11 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.9941993 | 2.4497994 | 11 | -9 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 6.57E-05 | 5.37E-05 | 11 | -9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.76E-09 | 1.44E-09 | 11 | -9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.33E-08 | 1.08E-08 | 11 | -9 |

**Table H.23: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Occupancy Rate Parameter)**

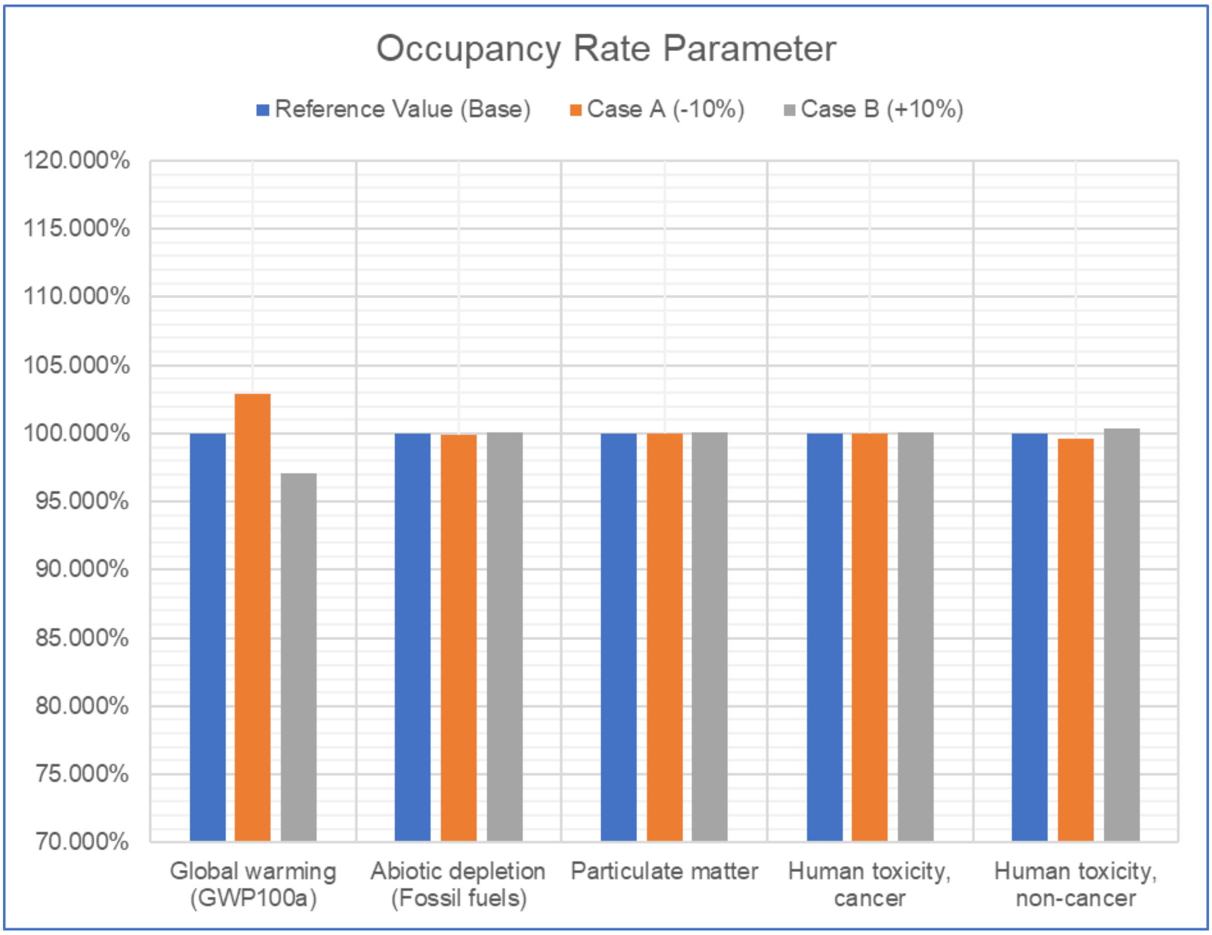


**Figure H.23: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Occupancy Rate Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.12996313 | 0.13576499 | -2 | 2 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.6543439 | 2.7352149 | -2 | 2 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.81E-05 | 6.01E-05 | -2 | 2 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.45E-09 | 1.72E-09 | -9 | 9 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.15E-08 | 1.24E-08 | -4 | 4 |

**Table H.24: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

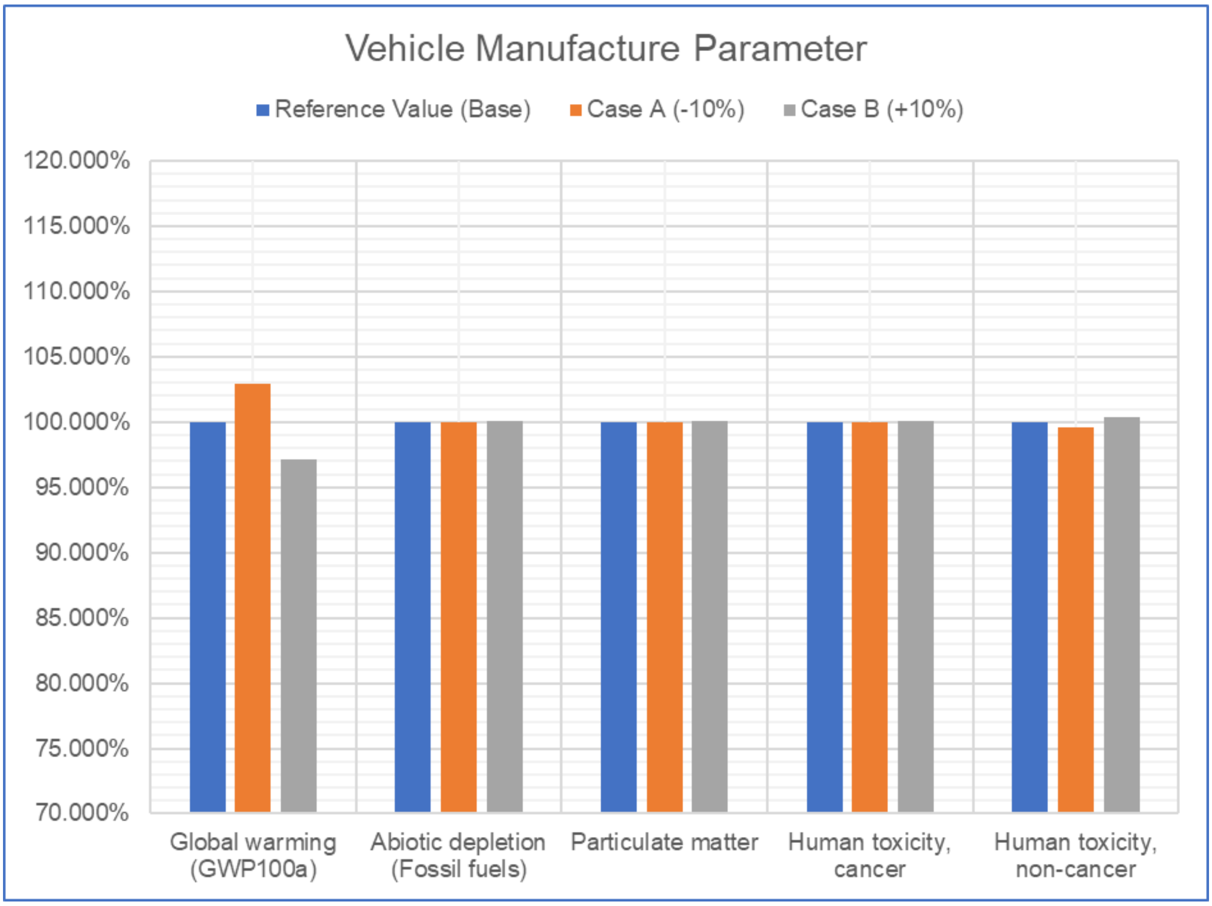


**Figure H.24: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.13275572 | 0.1329724 | -0.08 | 0.08 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.658816 | 2.7307428 | -1.33 | 1.33 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.91E-05 | 5.92E-05 | -0.09 | 0.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.59E-09 | 1.59E-09 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.19E-08 | 1.19E-08 | -0.03 | 0.03 |

**Table H.25: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

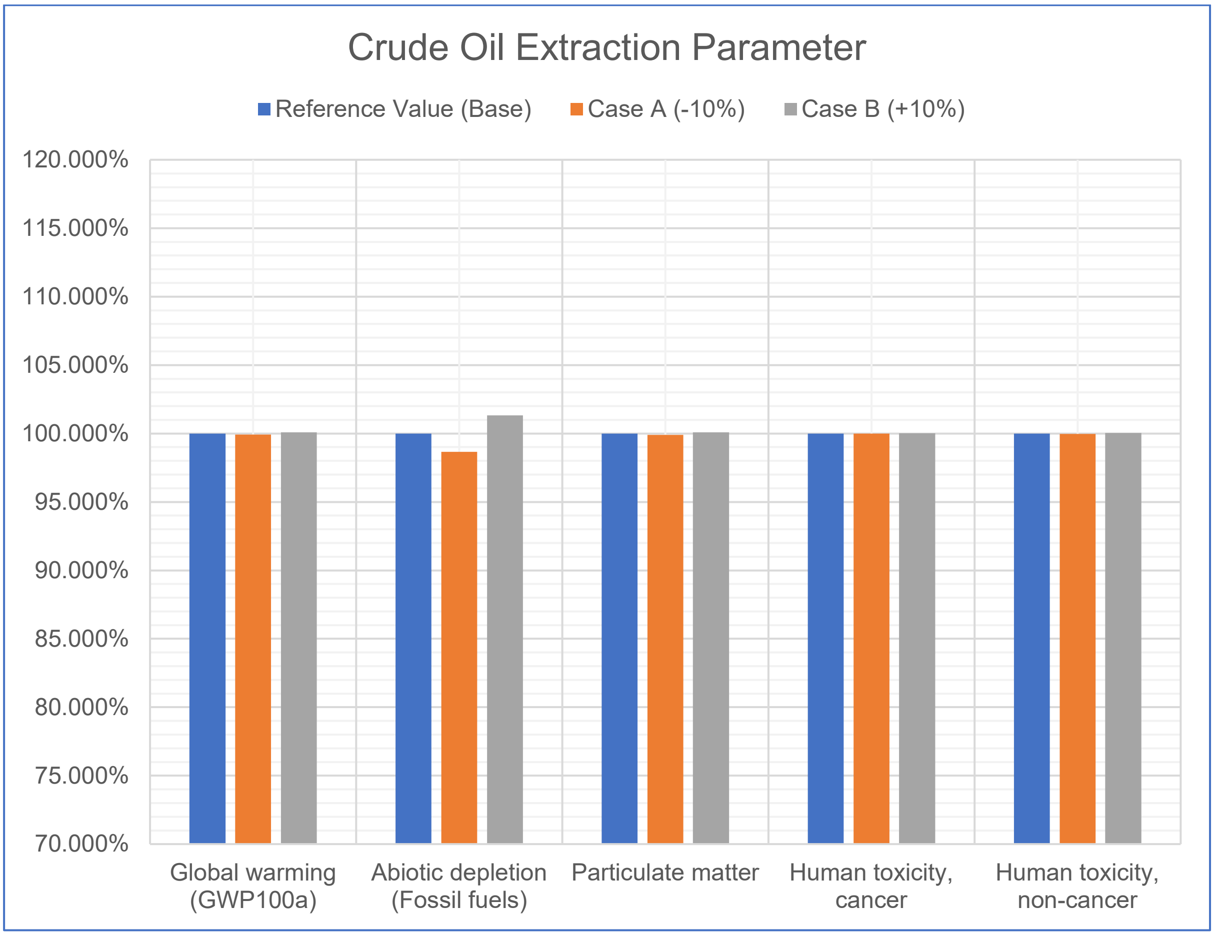


**Figure H.25: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.13264544 | 0.13308268 | -0.16 | 0.16 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.6573507 | 2.7322081 | -1.39 | 1.39 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.90E-05 | 5.93E-05 | -0.26 | 0.26 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.59E-09 | -0.05 | 0.05 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.19E-08 | 1.19E-08 | -0.06 | 0.06 |

**Table H.26: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Crude Oil Refining Parameter)**

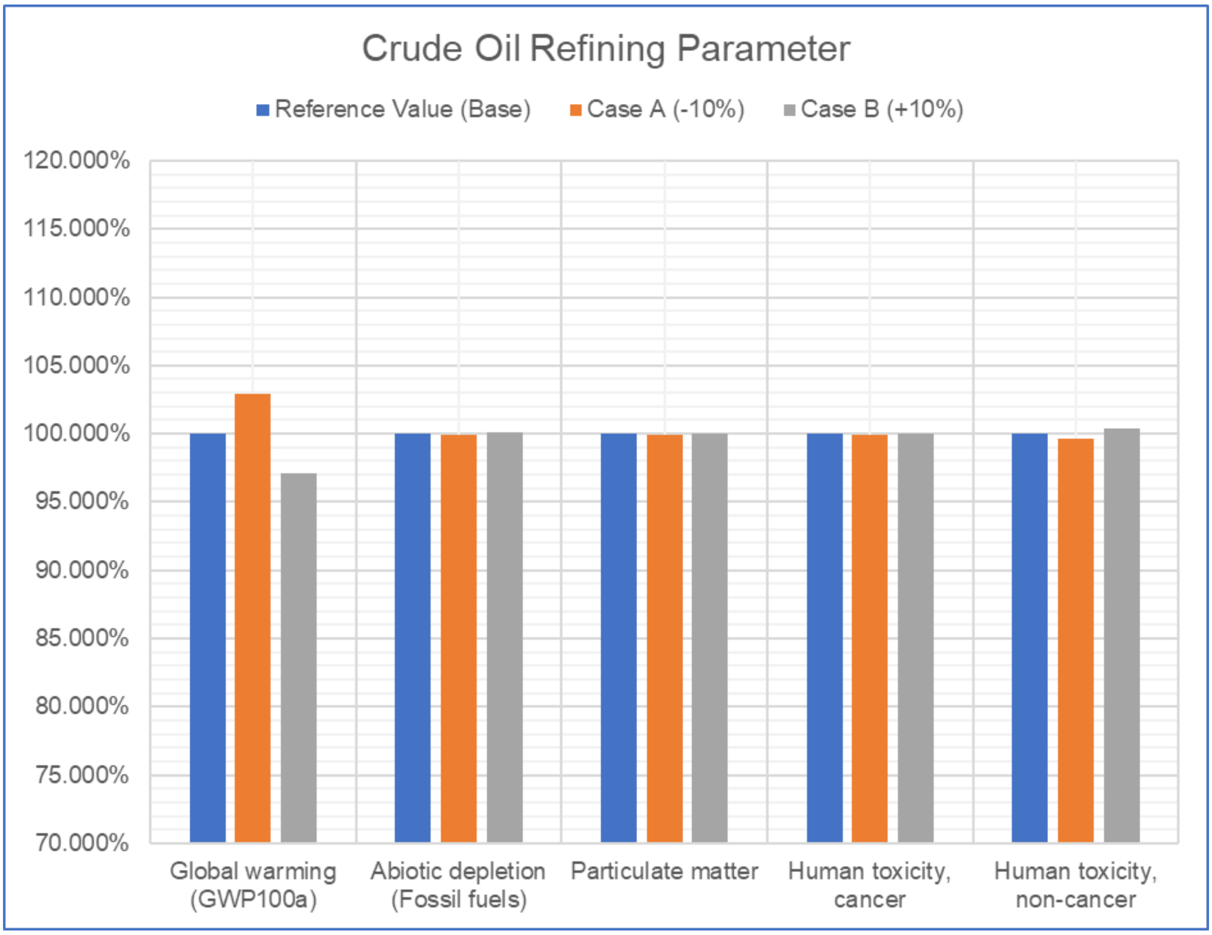


**Figure H.26: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.13340647 | 0.13232164 | 0.41 | -0.41 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.6706143 | 2.7189444 | -0.90 | 0.90 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.79E-05 | 6.03E-05 | -2.05 | 2.05 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.59E-09 | -0.25 | 0.25 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.15E-08 | 1.24E-08 | -3.67 | 3.67 |

**Table H.27: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Ethanol Production Parameter)**

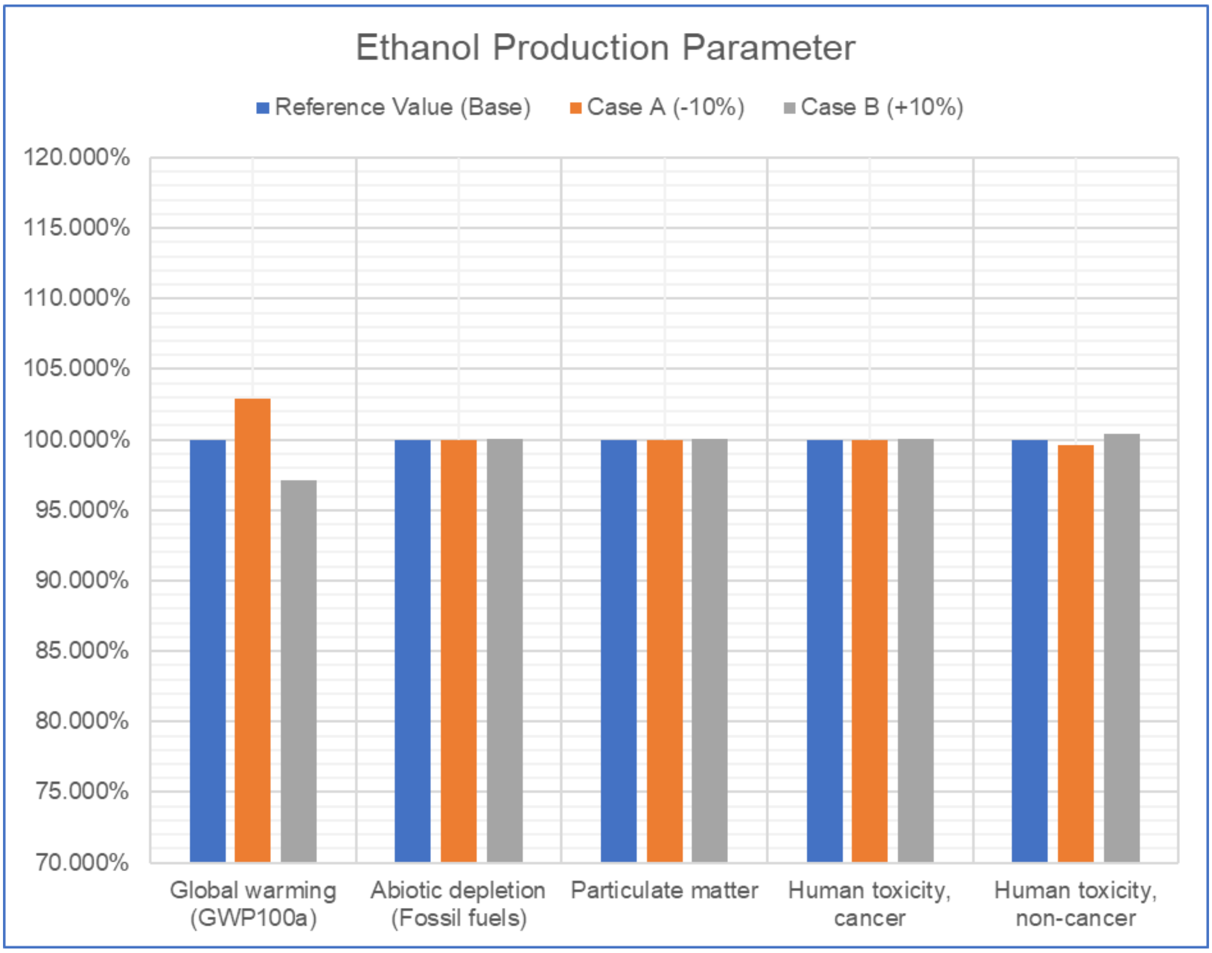


**Figure H.27: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Ethanol Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.13326697 | 0.13246115 | 0.30 | -0.30 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.6706143 | 2.7189444 | -0.90 | 0.90 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.79E-05 | 6.03E-05 | -2.05 | 2.05 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.59E-09 | -0.25 | 0.25 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.15E-08 | 1.24E-08 | -3.67 | 3.67 |

**Table H.28: Sensitivity Analysis for LCA of E40 Passenger Vehicles (Ethanol Processing Parameter)**

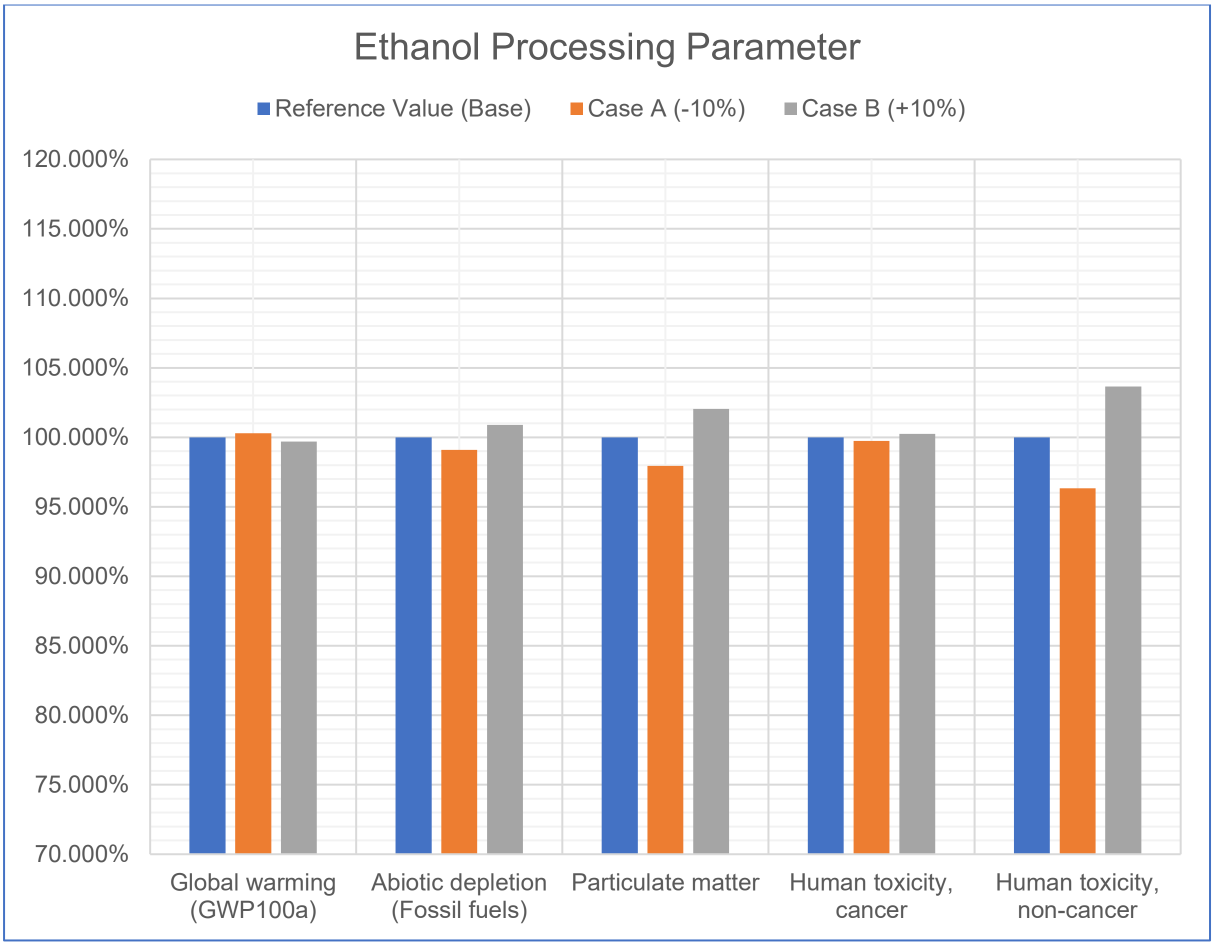


**Figure H.28: Sensitivity Analysis for LCA of E40 Passenger Vehicles (Ethanol Processing Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.13226163 | 0.13346649 | -0.45 | 0.45 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.6834554 | 2.7061034 | -0.42 | 0.42 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.89E-05 | 5.93E-05 | -0.30 | 0.30 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.59E-09 | -0.20 | 0.20 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.19E-08 | 1.20E-08 | -0.34 | 0.34 |

**Table H.29: Sensitivity Analysis for LCA of E$_{40}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

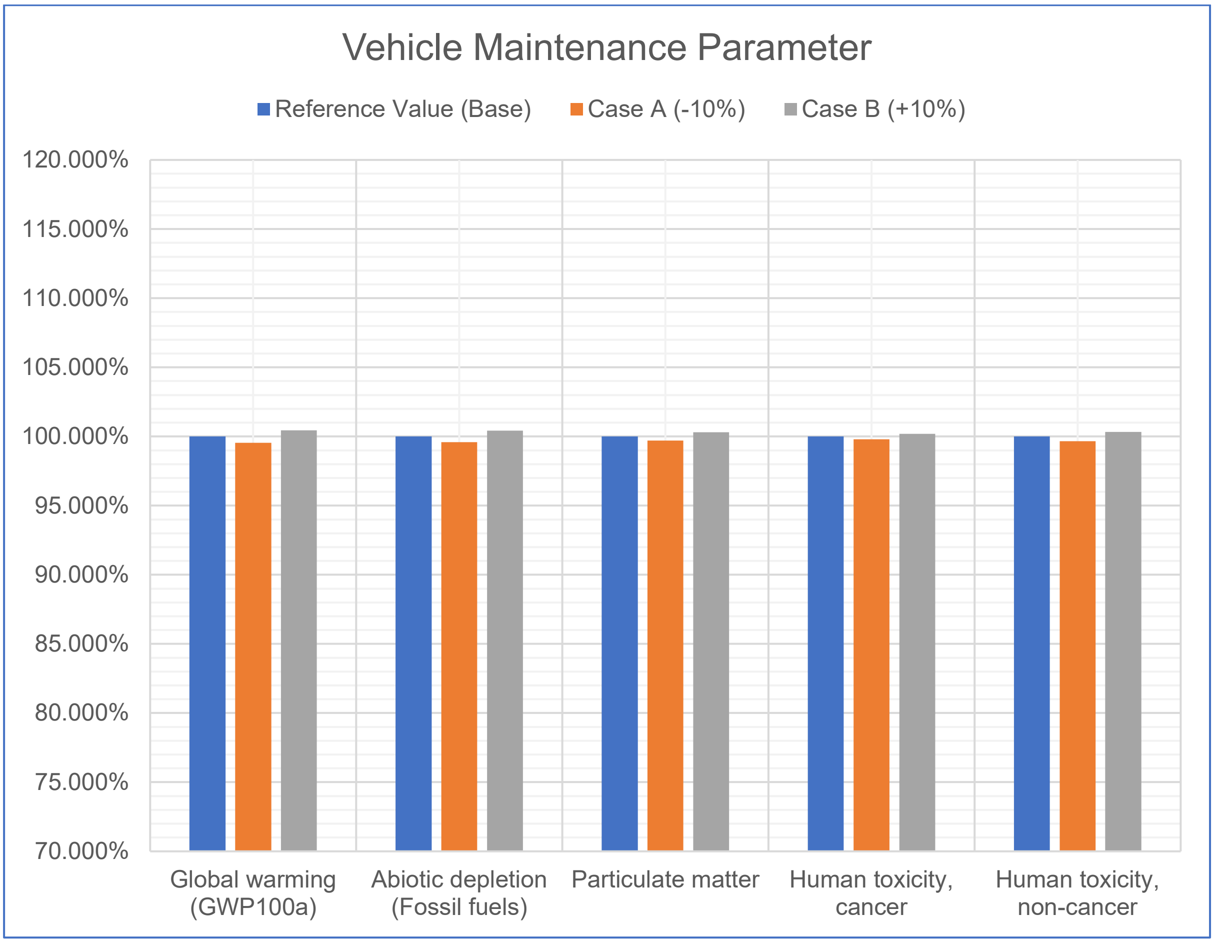


**Figure H.29: Sensitivity Analysis for LCA of E$_{40}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.13286406 | 0.13265172 | 0.1330764 | -0.16 | 0.16 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 2.6947794 | 2.6936085 | 2.6959503 | -0.04 | 0.04 |
| **Particulate Matter (kg/pkm)** | 5.91E-05 | 5.91E-05 | 5.91E-05 | -0.04 | 0.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.59E-09 | -0.06 | 0.06 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.19E-08 | 1.19E-08 | 1.20E-08 | -0.56 | 0.56 |

**Table H.30: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Vehicle Disposal Parameter)**

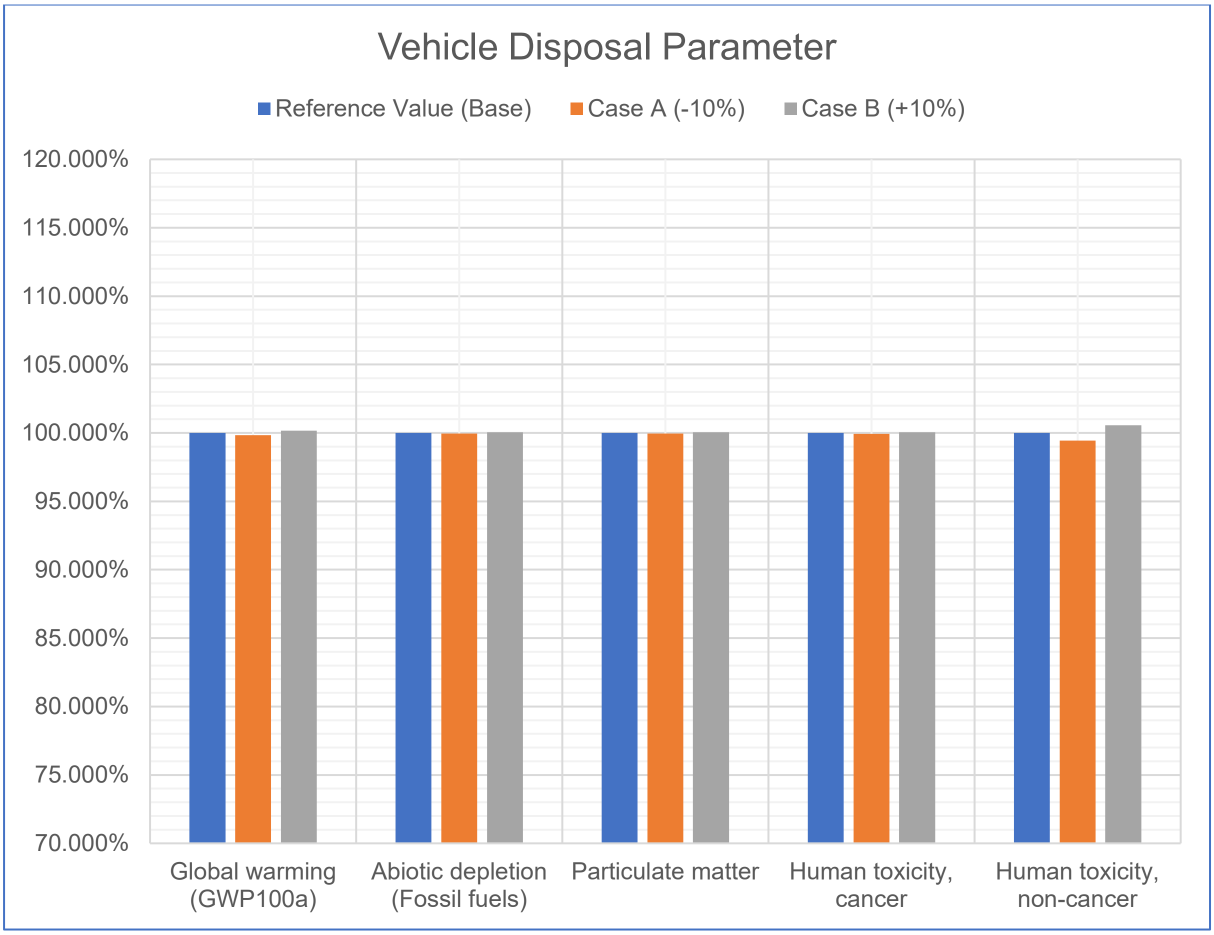


**Figure H.30: Sensitivity Analysis for LCA of $E_{40}$ Passenger Vehicles (Vehicle Disposal Parameter)**

### E85 Passenger Vehicles

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.012310783 | -0.003316637 | 67.18 | -54.96 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.8319447 | 1.595101 | 7.66 | -6.26 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.77E-05 | 5.76E-05 | 8.92 | -7.30 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.61E-09 | 1.57E-09 | 1.23 | -1.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.91E-08 | 1.66E-08 | 7.70 | -6.30 |

**Table H.31: Sensitivity Analysis for LCA of E85 Passenger Vehicles (Kilometres Travelled Parameter)**

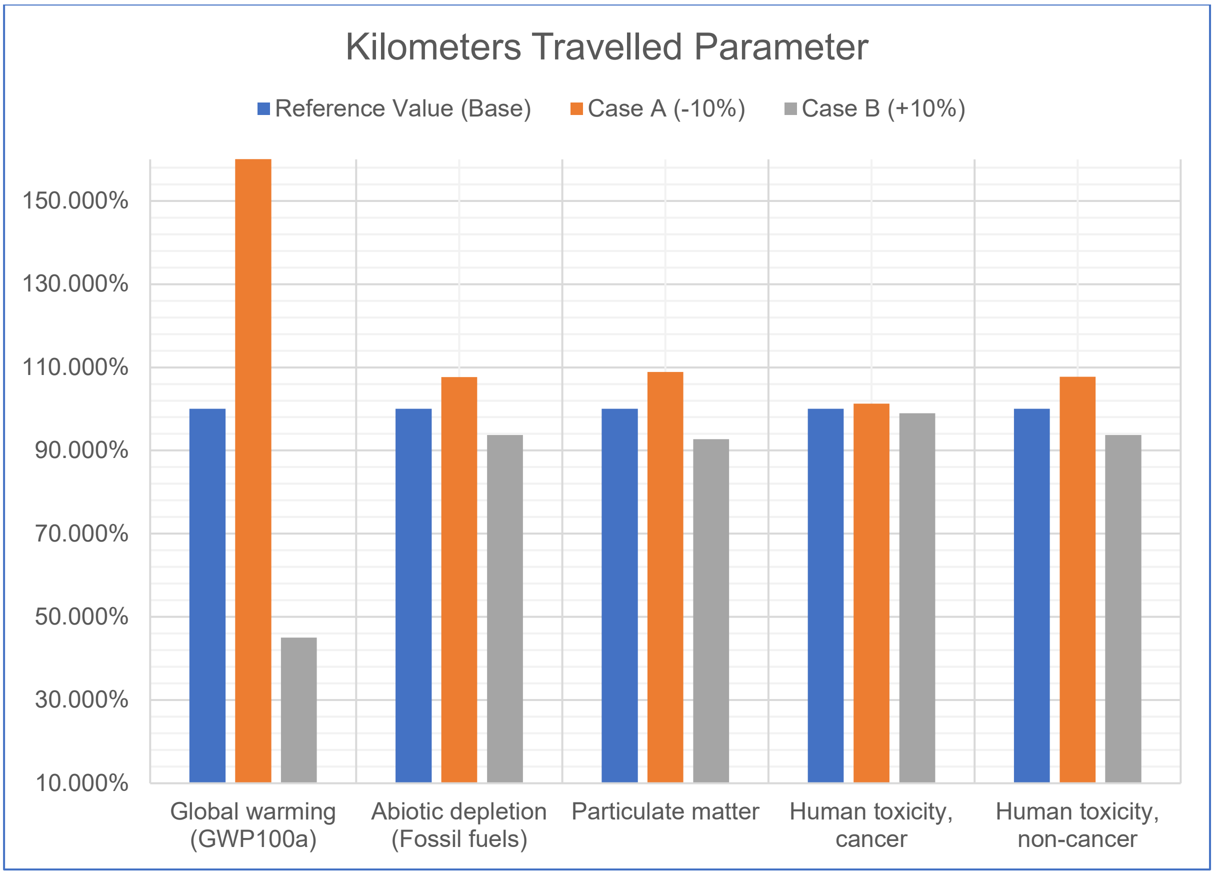


**Figure H.31: Sensitivity Analysis for LCA of E85 Passenger Vehicles (Kilometres Travelled Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.002911901 | -0.011816105 | -60.46 | 60.46 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.584443 | 1.8189183 | -6.89 | 6.89 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 5.72E-05 | 6.72E-05 | -8.03 | 8.03 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.57E-09 | 1.61E-09 | -1.11 | 1.11 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.65E-08 | 1.90E-08 | -6.93 | 6.93 |

**Table H.32: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Fuel Consumption Parameter)**

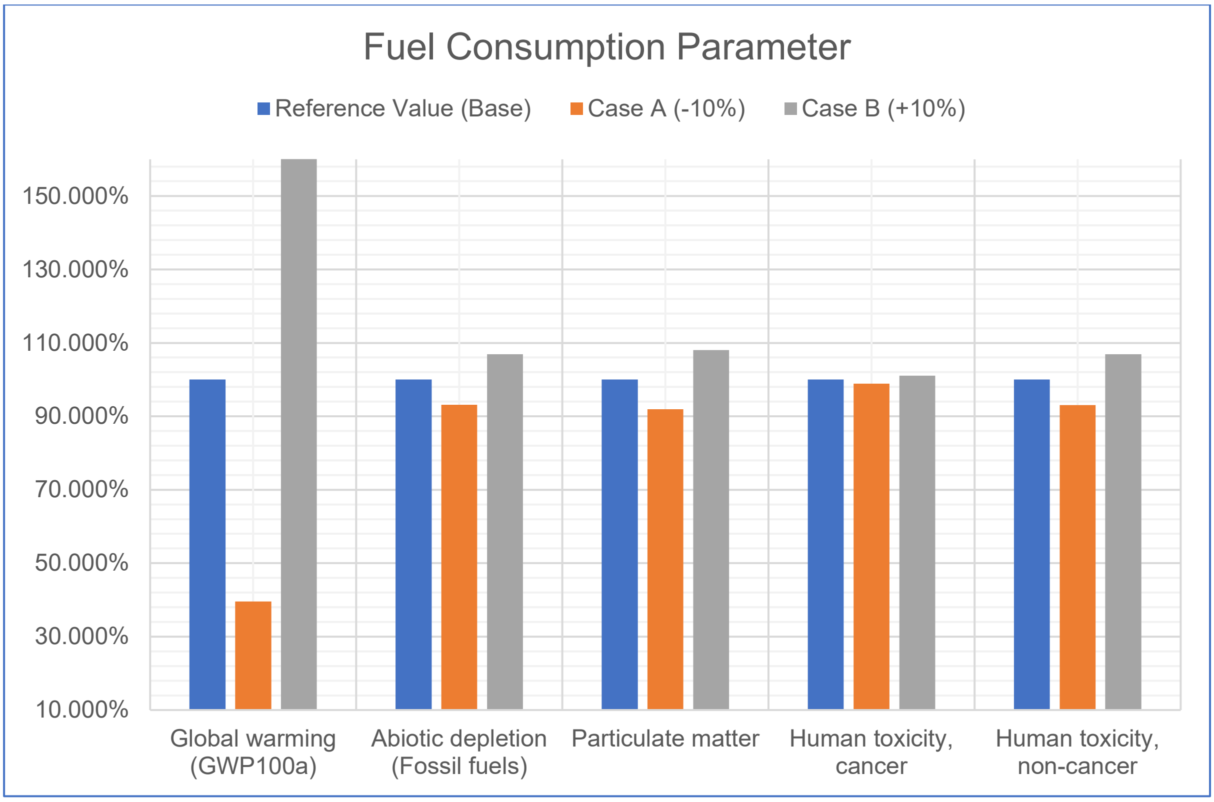


**Figure H.32: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Fuel Consumption Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.008182225 | -0.006694548 | 11.11 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.8907563 | 1.5469824 | 11.11 | -9.09 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.91E-05 | 5.65E-05 | 11.11 | -9.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.77E-09 | 1.44E-09 | 11.11 | -9.09 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.97E-08 | 1.61E-08 | 11.11 | -9.09 |

**Table H.33: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Occupancy Rate Parameter)**

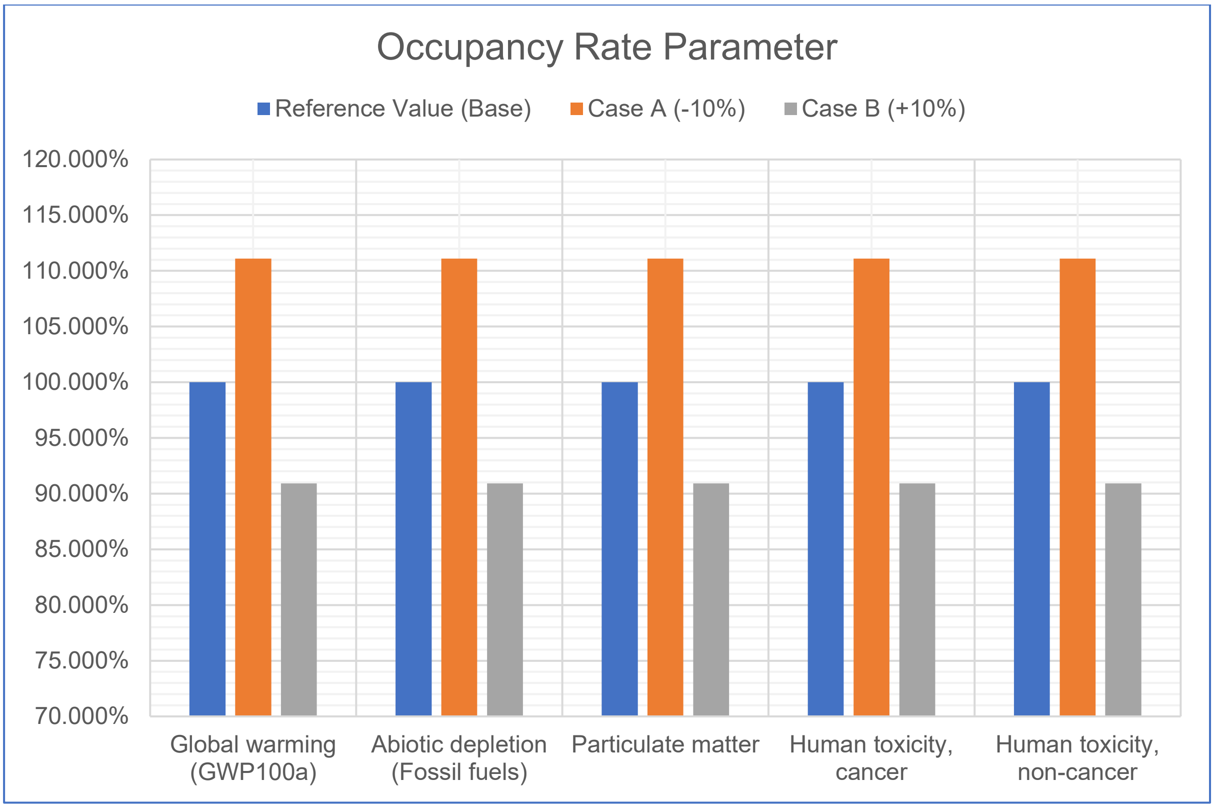


**Figure H.33: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Occupancy Rate Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.01026493 | -0.004463075 | 39.39 | -39.39 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.6612452 | 1.7421162 | -2.38 | 2.38 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.12E-05 | 6.32E-05 | -1.65 | 1.65 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.45E-09 | 1.73E-09 | -8.64 | 8.64 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.73E-08 | 1.82E-08 | -2.47 | 2.47 |

**Table H.34: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

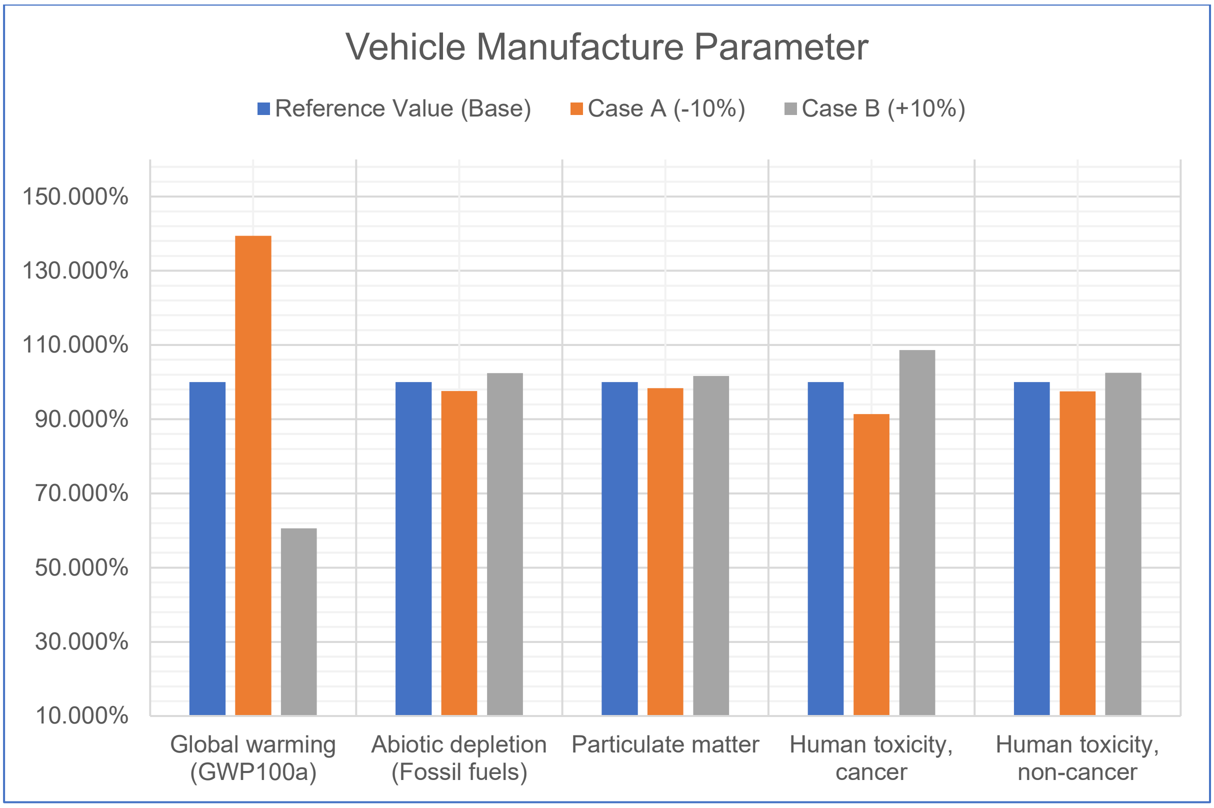


**Figure H.34: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.007391467 | -0.007336539 | 0.37 | -0.37 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.6925639 | 1.7107974 | -0.54 | 0.54 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.22E-05 | 6.22E-05 | -0.02 | 0.02 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.59E-09 | 1.59E-09 | 0.00 | 0.00 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.78E-08 | 1.78E-08 | -0.01 | 0.01 |

**Table H.35: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

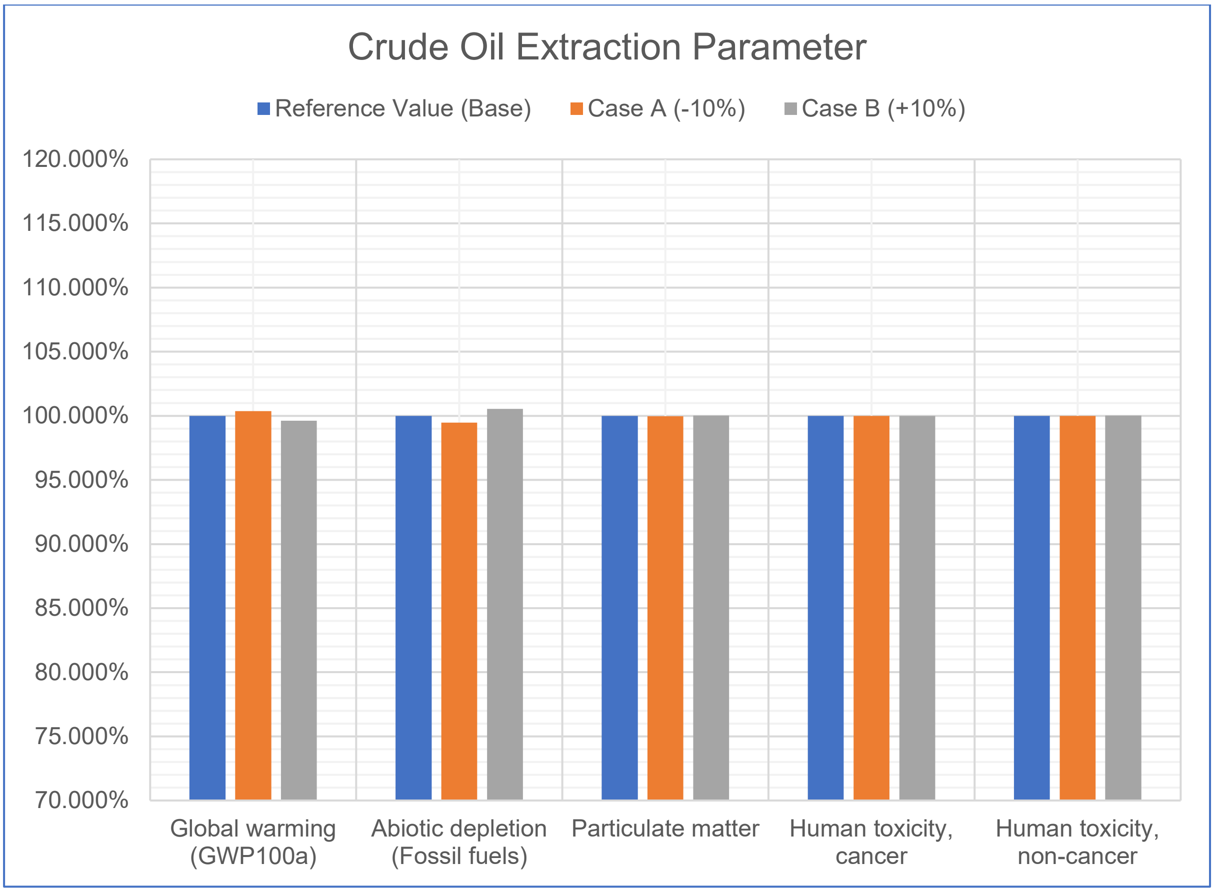


**Figure H.35: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.007419422 | -0.007308584 | 0.75 | -0.75 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.6921925 | 1.7111688 | -0.56 | 0.56 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.22E-05 | 6.22E-05 | -0.06 | 0.06 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.59E-09 | 1.59E-09 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.78E-08 | 1.78E-08 | -0.01 | 0.01 |

**Table H.36: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Crude Oil Refining Parameter)**

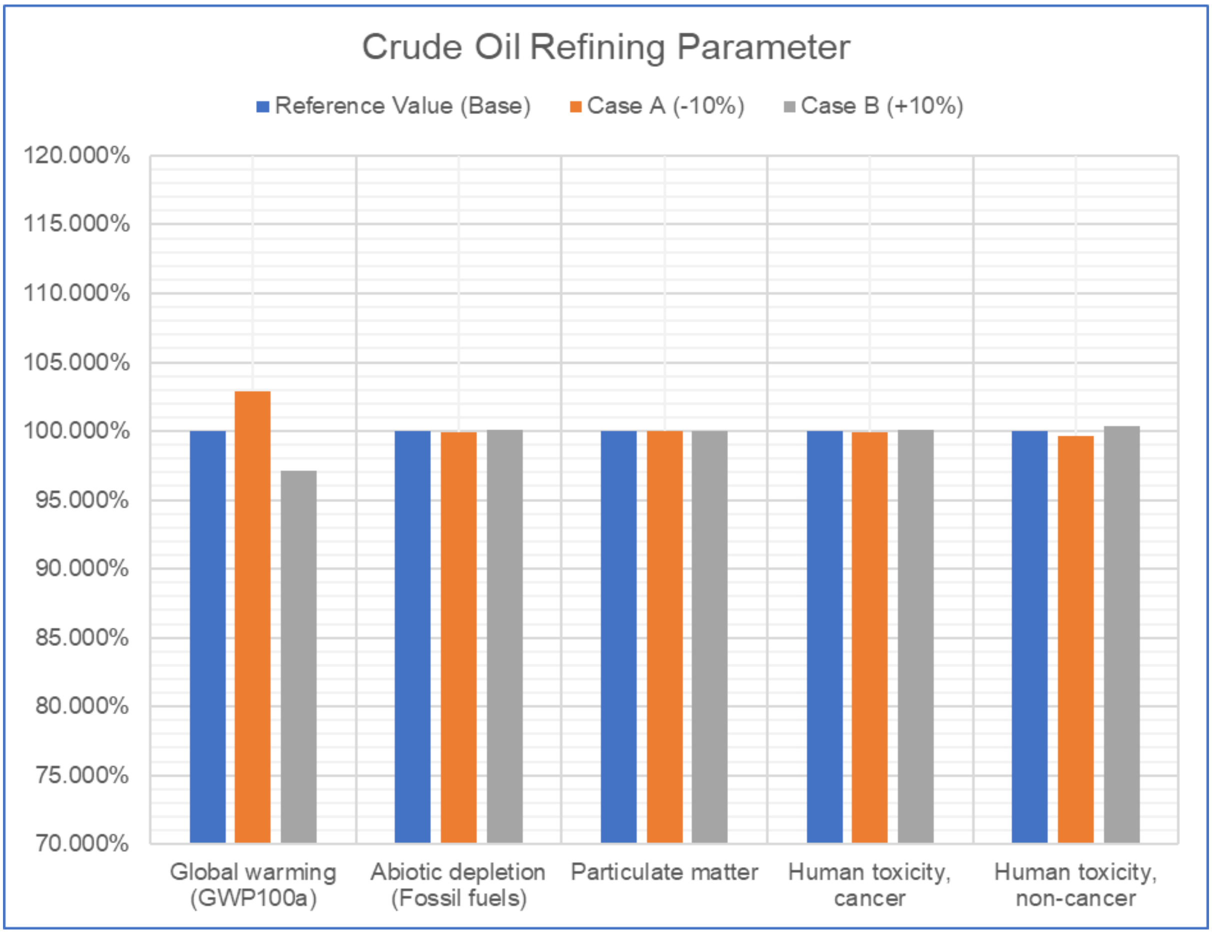


**Figure H.36: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.006178608 | -0.008549398 | -16.10 | 16.10 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.6488703 | 1.754491 | -3.10 | 3.10 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 5.95E-05 | 6.48E-05 | -4.26 | 4.26 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.60E-09 | -0.55 | 0.55 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.68E-08 | 1.87E-08 | -5.38 | 5.38 |

**Table H.37: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Ethanol Production Parameter)**

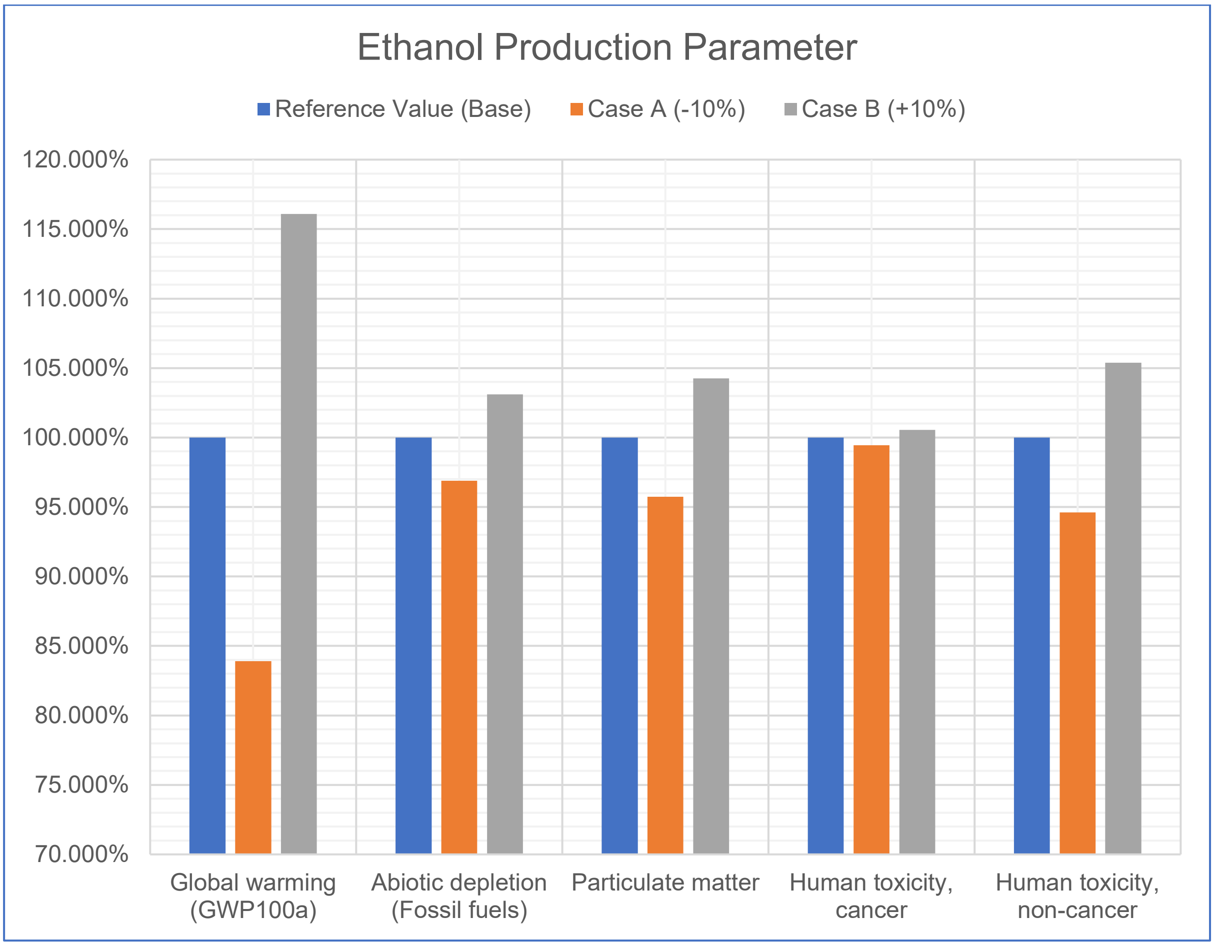


**Figure H.37: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Ethanol Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.006483477 | -0.008244528 | -11.96 | 11.96 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.6488703 | 1.754491 | -3.10 | 3.10 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 5.95E-05 | 6.48E-05 | -4.26 | 4.26 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.58E-09 | 1.60E-09 | -0.55 | 0.55 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.68E-08 | 1.87E-08 | -5.38 | 5.38 |

**Table H.38: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Ethanol Processing Parameter)**

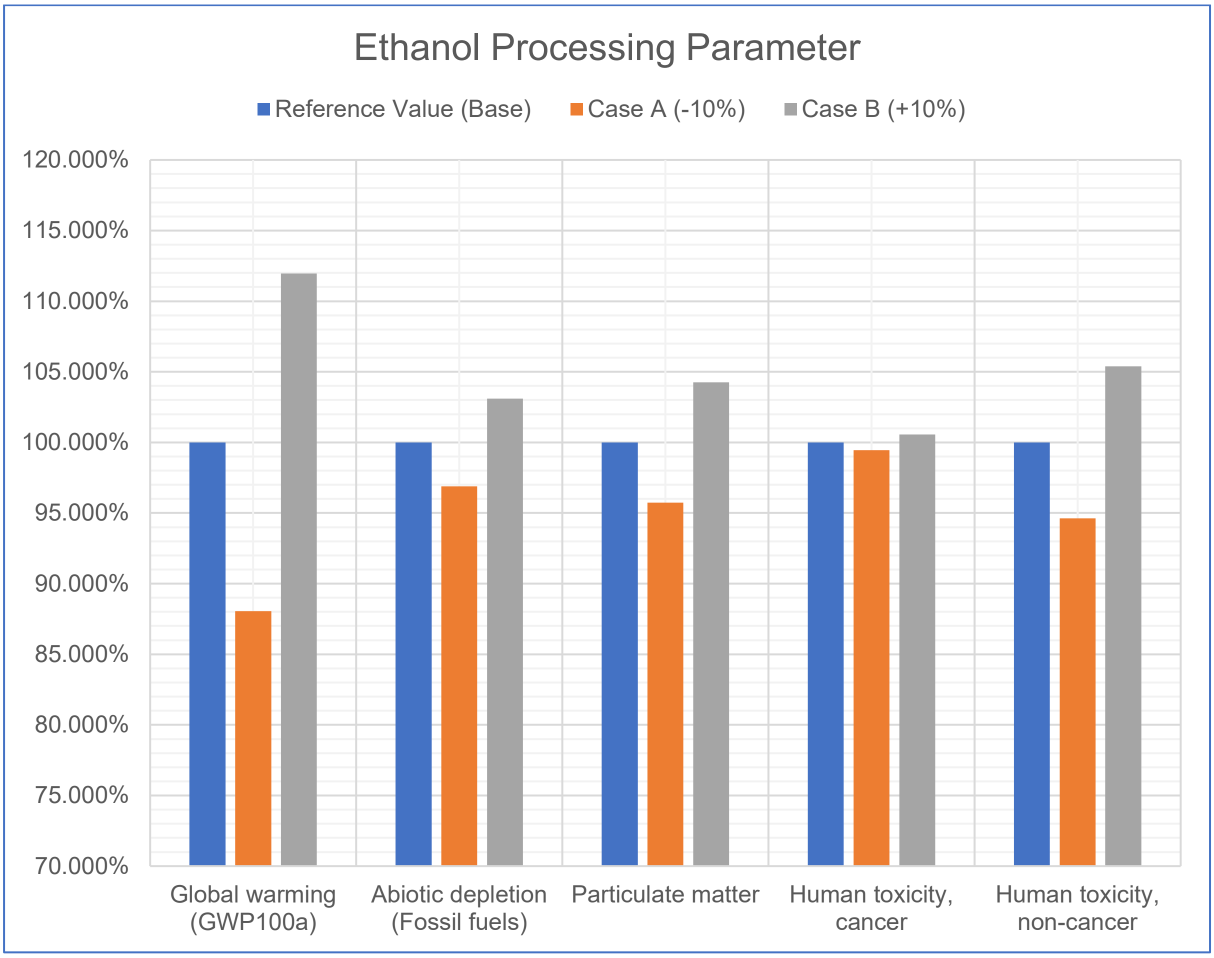


**Figure H.38: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Ethanol Processing Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.007966433 | -0.006761572 | 8.18 | -8.18 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.6903567 | 1.7130046 | -0.67 | 0.67 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.20E-05 | 6.24E-05 | -0.28 | 0.28 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.59E-09 | 1.59E-09 | -0.20 | 0.20 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.77E-08 | 1.78E-08 | -0.23 | 0.23 |

**Table H.39: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

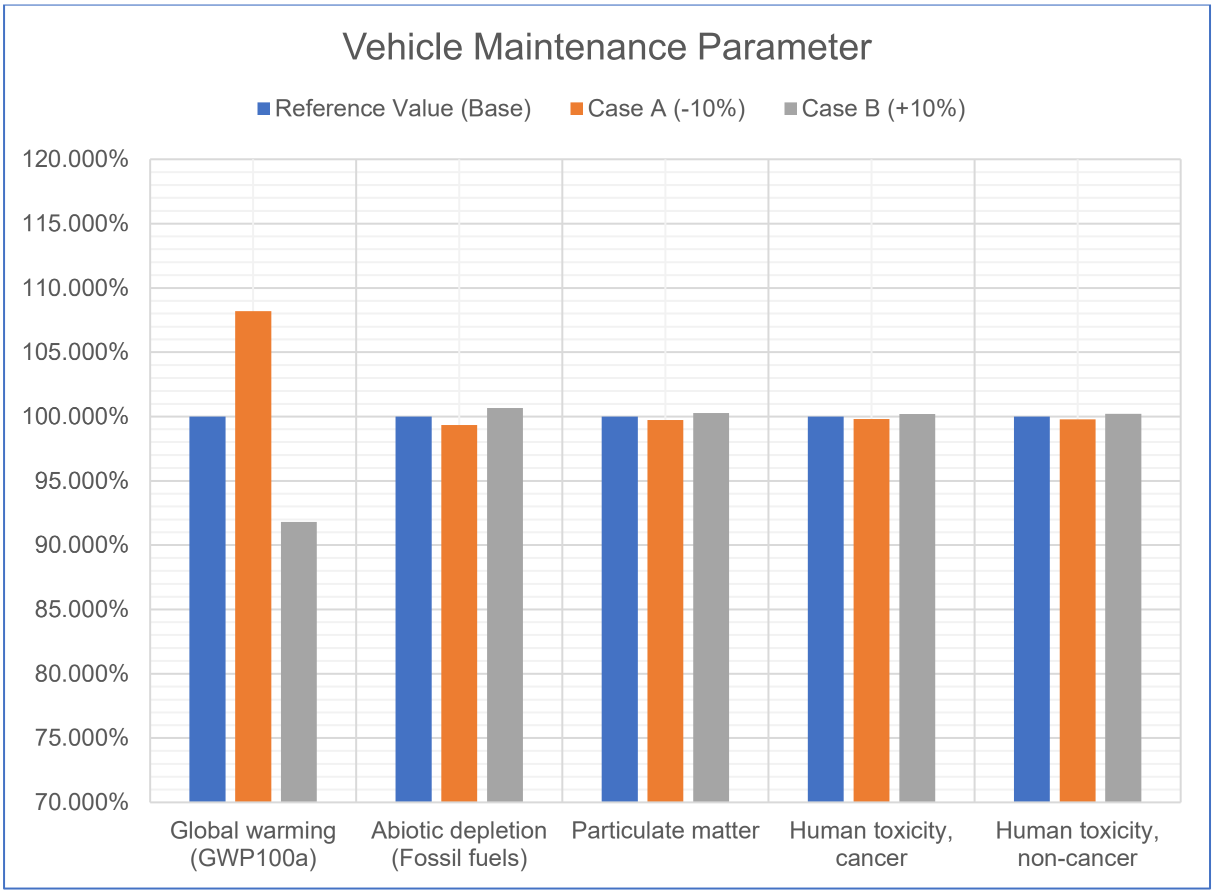


**Figure H.39: Sensitivity Analysis for LCA of $E_{85}$ Passenger Vehicles (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.007364003 | -0.007576347 | -0.007151659 | 2.88 | -2.88 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 1.7016807 | 1.7005097 | 1.7028516 | -0.07 | 0.07 |
| **Particulate Matter (kg/pkm)** | 6.22E-05 | 6.22E-05 | 6.22E-05 | -0.04 | 0.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.59E-09 | 1.59E-09 | 1.59E-09 | -0.06 | 0.06 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 1.78E-08 | 1.77E-08 | 1.78E-08 | -0.38 | 0.38 |

**Table H.40: Sensitivity Analysis for LCA of E$_{85}$ Passenger Vehicles (Vehicle Disposal Parameter)**

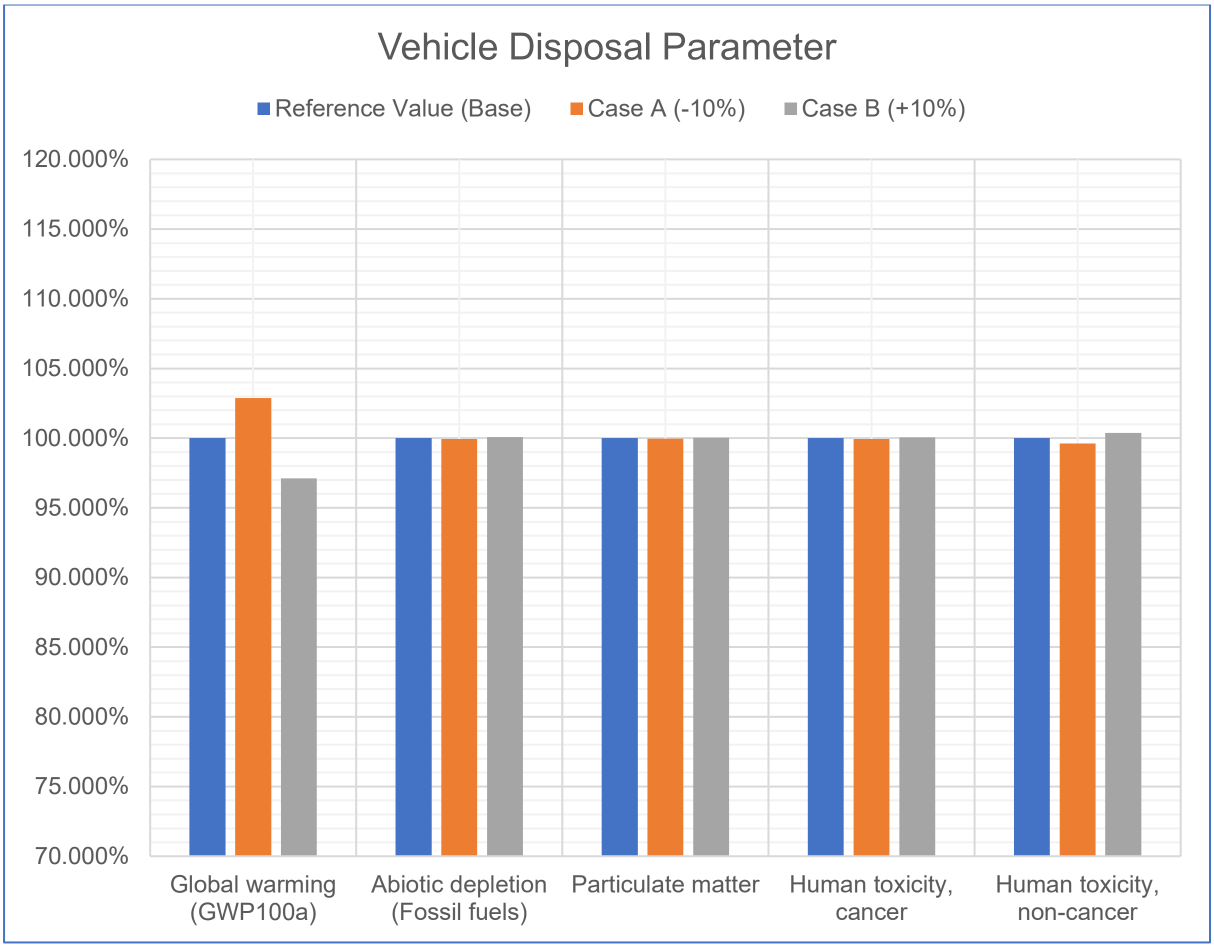


**Figure H.40: Sensitivity Analysis for LCA of E$_{85}$ Passenger Vehicles (Vehicle Disposal Parameter)**

## Biodiesel Blends ($BD_5$) Buses

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.081467678 | 0.070720614 | 7.82 | -6.40 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.99429587 | 0.86292457 | 7.84 | -6.41 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 7.16E-05 | 5.95E-05 | 10.28 | -8.41 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.53E-10 | 4.45E-10 | 0.97 | -0.80 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.36E-09 | 2.29E-09 | 1.55 | -1.27 |

Table H.41: Sensitivity Analysis for LCA of $BD_5$ Buses (Kilometres Travelled Parameter)

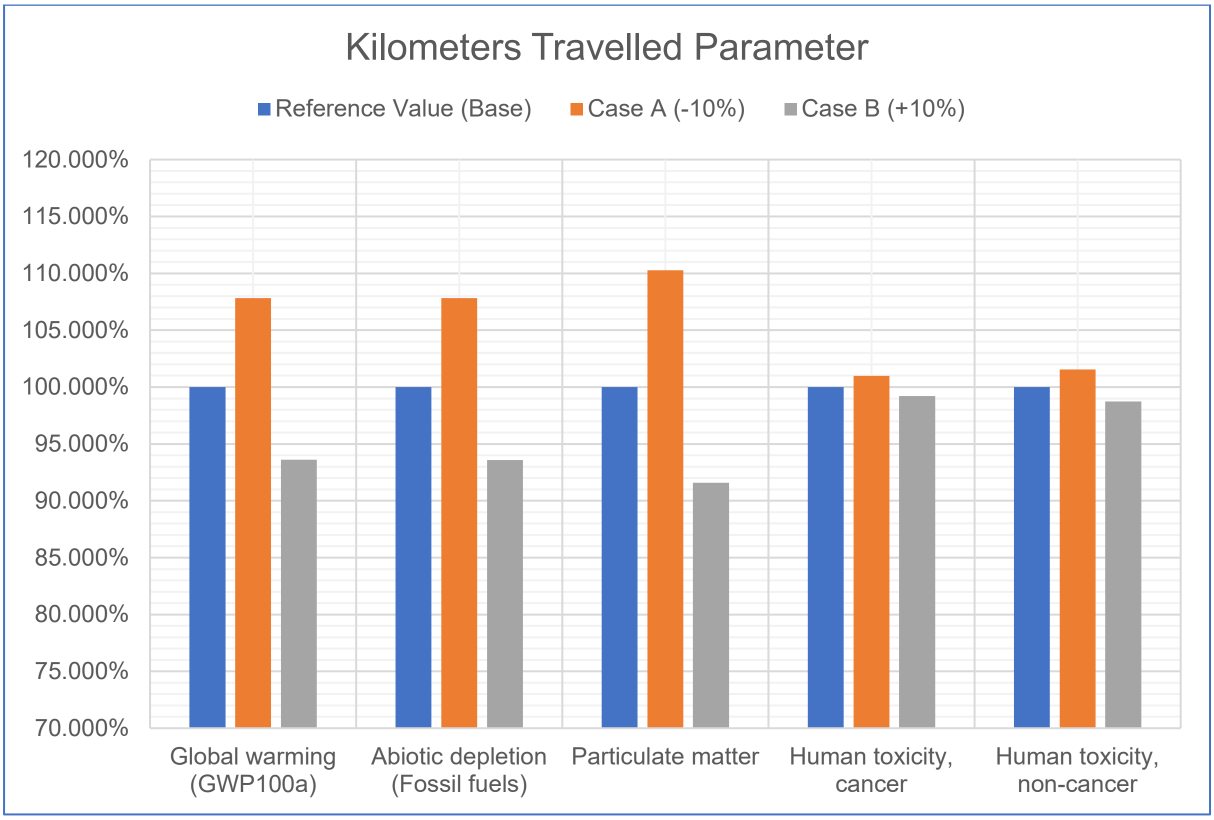


Figure H.41: Sensitivity Analysis for LCA of $BD_5$ Buses (Kilometres Travelled Parameter)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.070236996 | 0.080876589 | -7.04 | 7.04 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.85701286 | 0.98707045 | -7.05 | 7.05 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 5.89E-05 | 7.10E-05 | -9.26 | 9.26 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.45E-10 | 4.53E-10 | -0.88 | 0.88 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.29E-09 | 2.36E-09 | -1.39 | 1.39 |

**Table H.42: Sensitivity Analysis for LCA of $BD_5$ Buses (Fuel Consumption Parameter)**

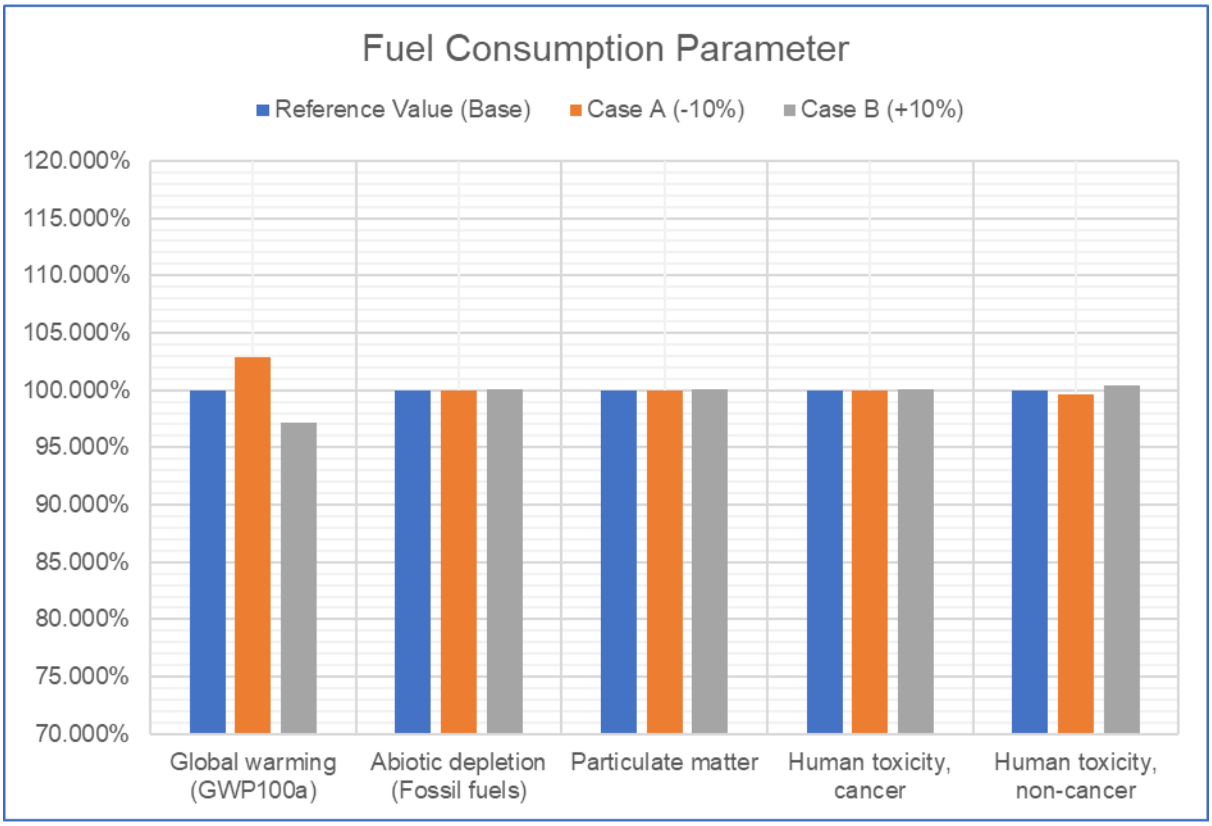


**Figure H.42: Sensitivity Analysis for LCA of $BD_5$ Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.083951992 | 0.068687993 | 11.11 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 1.0244907 | 0.83821969 | 11.11 | -9.09 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 7.22E-05 | 5.90E-05 | 11.11 | -9.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.99E-10 | 4.08E-10 | 11.11 | -9.09 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.58E-09 | 2.11E-09 | 11.11 | -9.09 |

**Table H.43: Sensitivity Analysis for LCA of BD5 Buses (Occupancy Rate Parameter)**

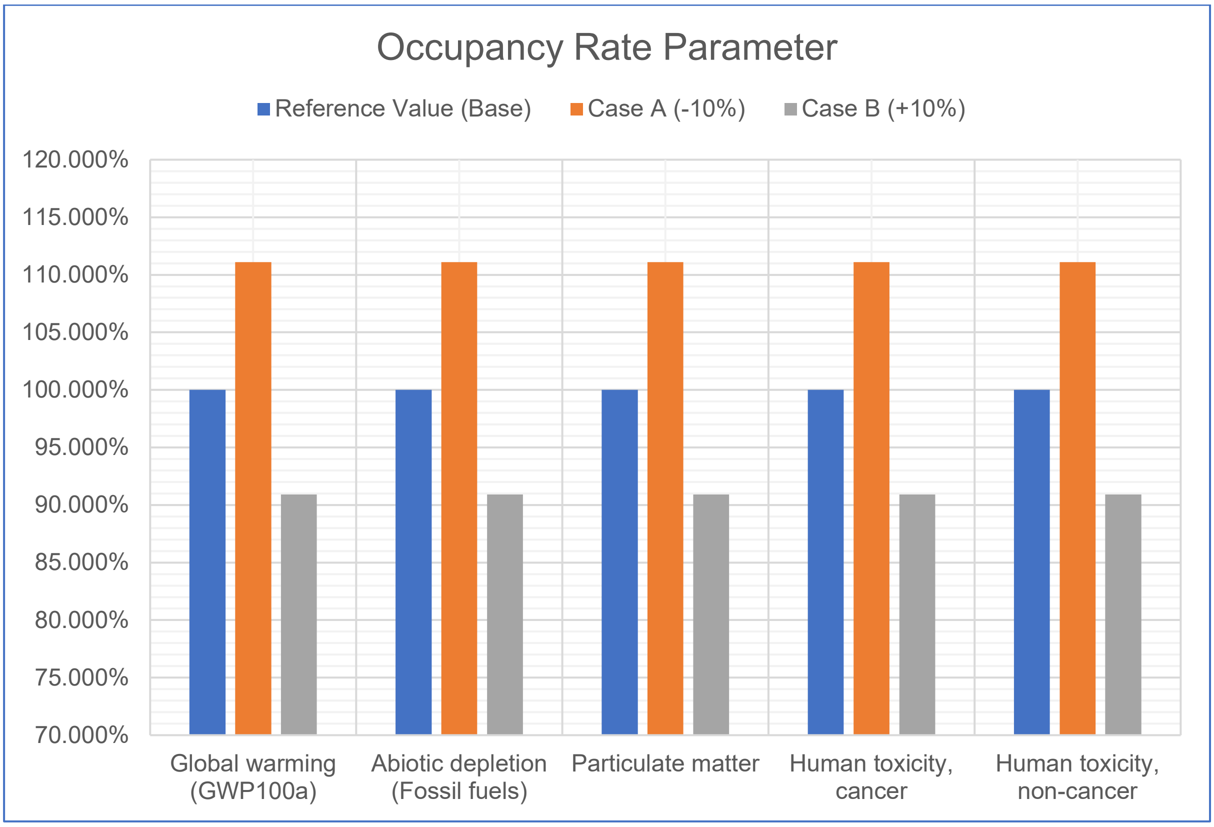


**Figure H.43: Sensitivity Analysis for LCA of BD5 Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.07467189 | 0.076441695 | -1.17 | 1.17 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.9108775 | 0.93320581 | -1.21 | 1.21 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.46E-05 | 6.53E-05 | -0.51 | 0.51 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.11E-10 | 4.87E-10 | -8.44 | 8.44 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.20E-09 | 2.45E-09 | -5.50 | 5.50 |

**Table H.44: Sensitivity Analysis for LCA of BD$_5$ Buses (Vehicle Manufacture Parameter)**

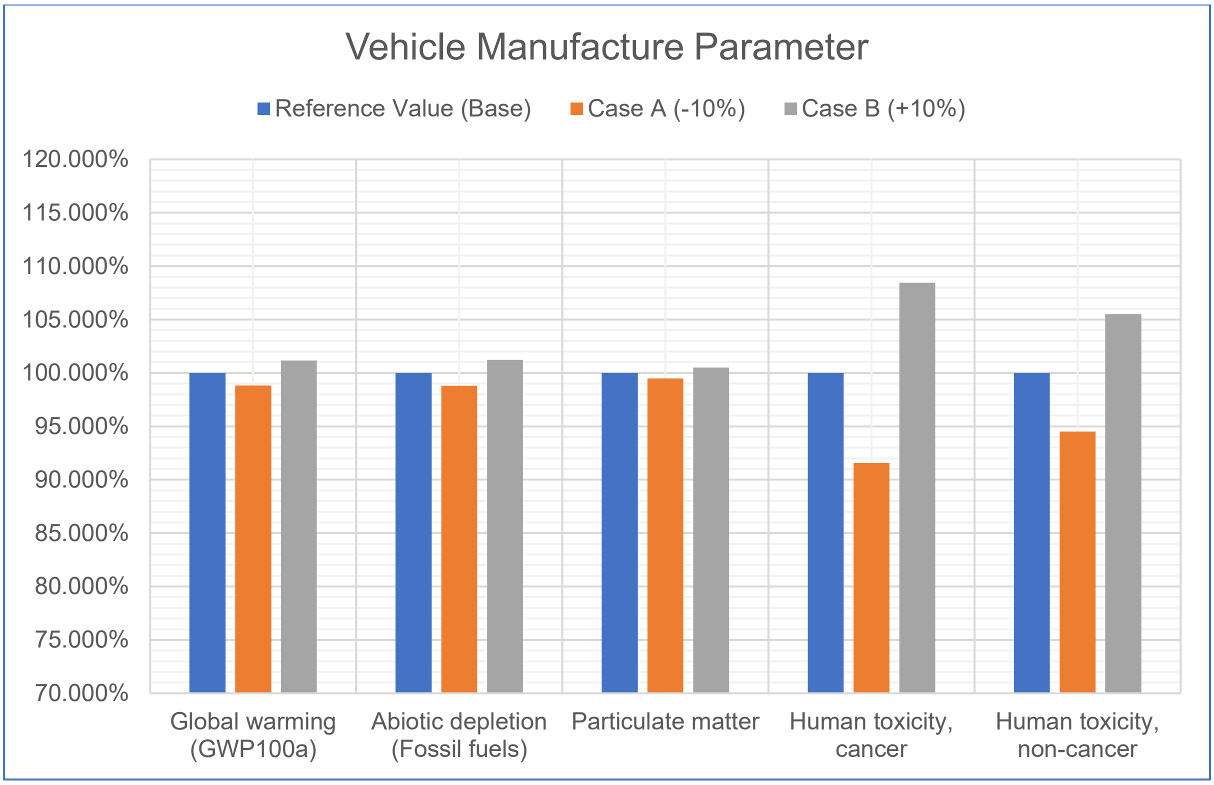


**Figure H.44: Sensitivity Analysis for LCA of BD$_5$ Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.07550796 | 0.075605625 | -0.06 | 0.06 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.90583148 | 0.93825184 | -1.76 | 1.76 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.49E-05 | 6.50E-05 | -0.04 | 0.04 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.49E-10 | 4.49E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.32E-09 | 2.33E-09 | -0.07 | 0.07 |

**Table H.45: Sensitivity Analysis for LCA of $BD_5$ Buses (Crude Oil Extraction Parameter)**

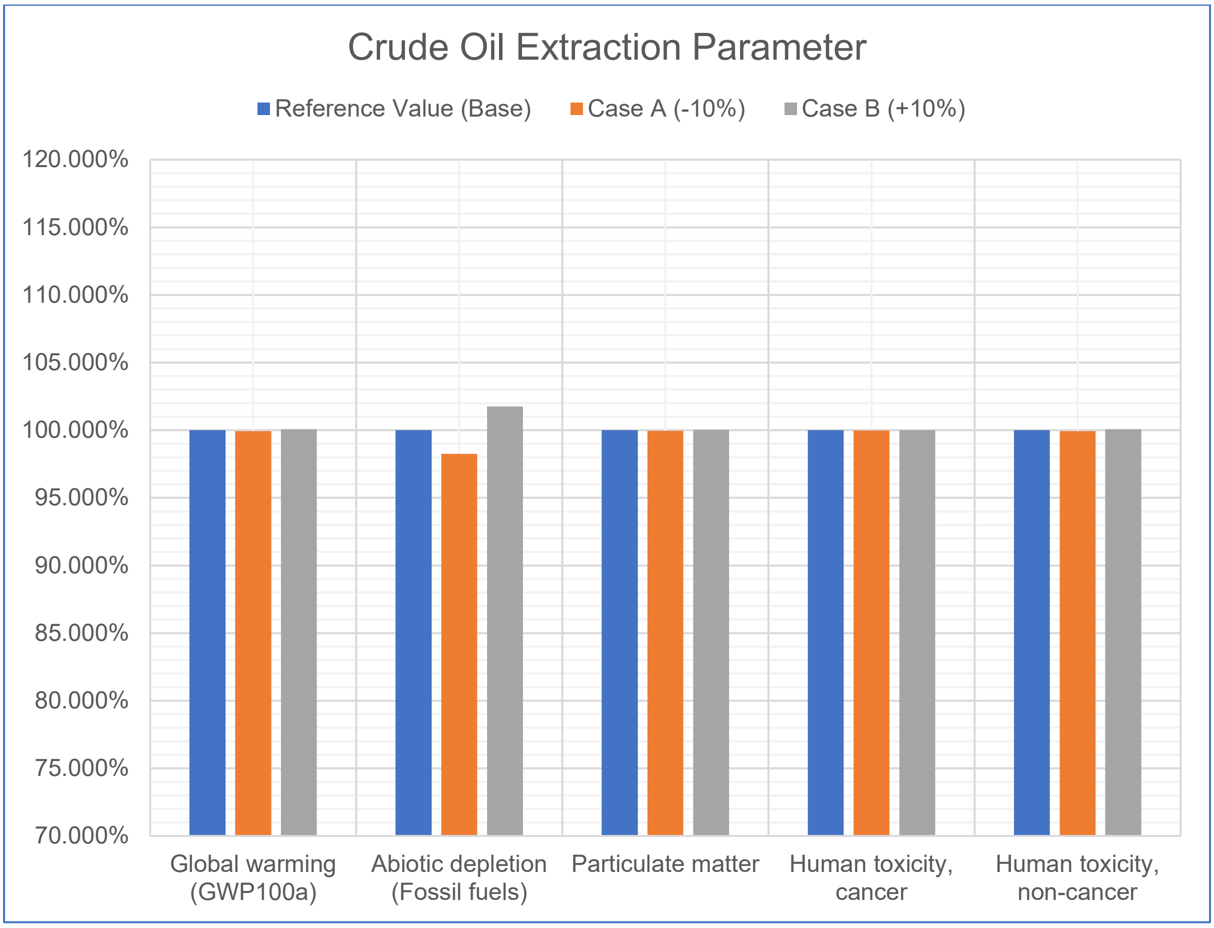


**Figure H.45: Sensitivity Analysis for LCA of $BD_5$ Buses (Crude Oil Extraction Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.075166557 | 0.075947029 | -0.52 | 0.52 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.86626768 | 0.97781563 | -6.05 | 6.05 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.46E-05 | 6.53E-05 | -0.47 | 0.47 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.46E-10 | 4.51E-10 | -0.58 | 0.58 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.31E-09 | 2.34E-09 | -0.79 | 0.79 |

**Table H.46: Sensitivity Analysis for LCA of BD$_5$ Buses (Crude Oil Refining Parameter)**

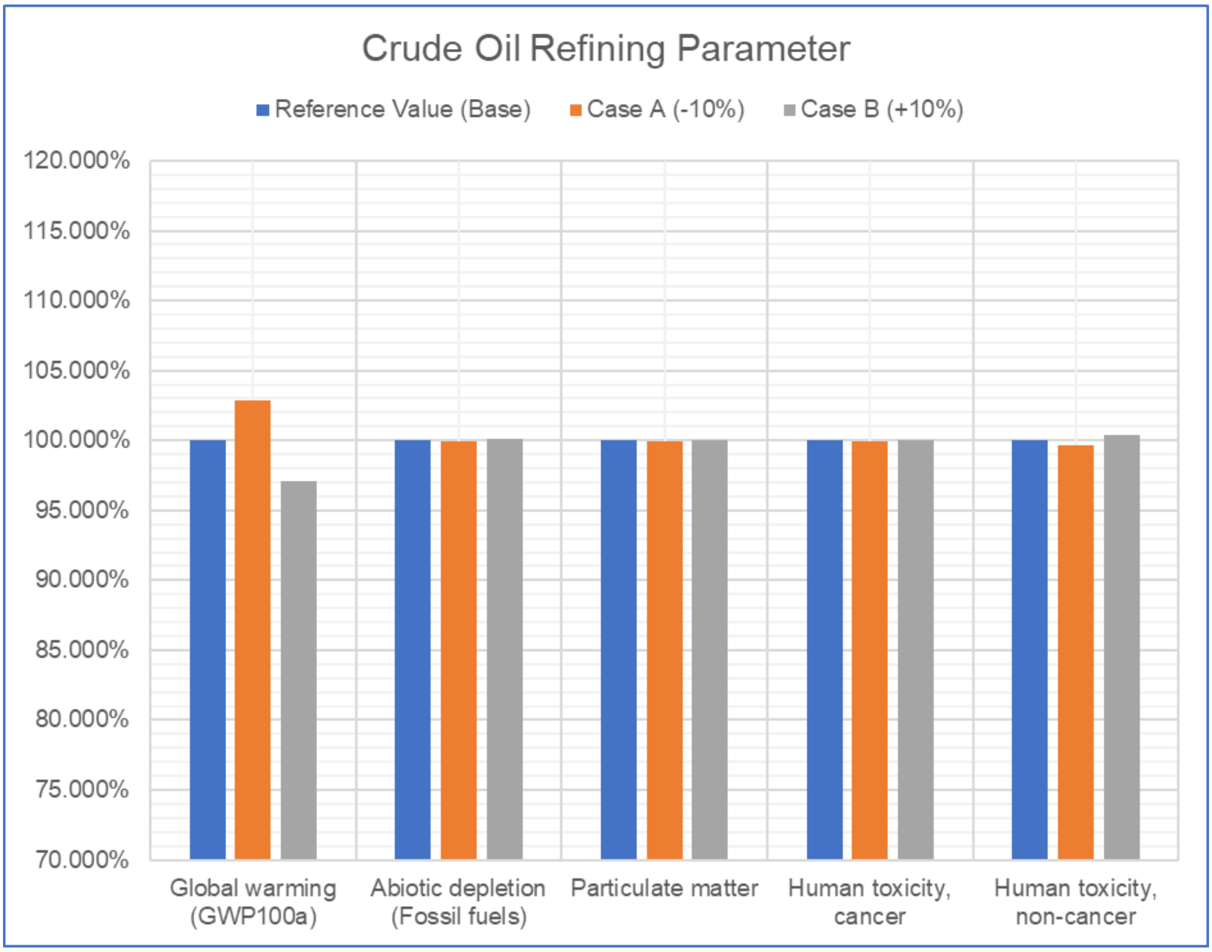


**Figure H.46: Sensitivity Analysis for LCA of BD$_5$ Buses (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.075733392 | 0.075380194 | 0.23 | -0.23 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.92145342 | 0.9226299 | -0.06 | 0.06 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.49E-05 | 6.50E-05 | -0.01 | 0.01 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.49E-10 | 4.49E-10 | -0.03 | 0.03 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.32E-09 | 2.32E-09 | -0.03 | 0.03 |

**Table H.47: Sensitivity Analysis for LCA of BD5 Buses (Biodiesel Production Parameter)**

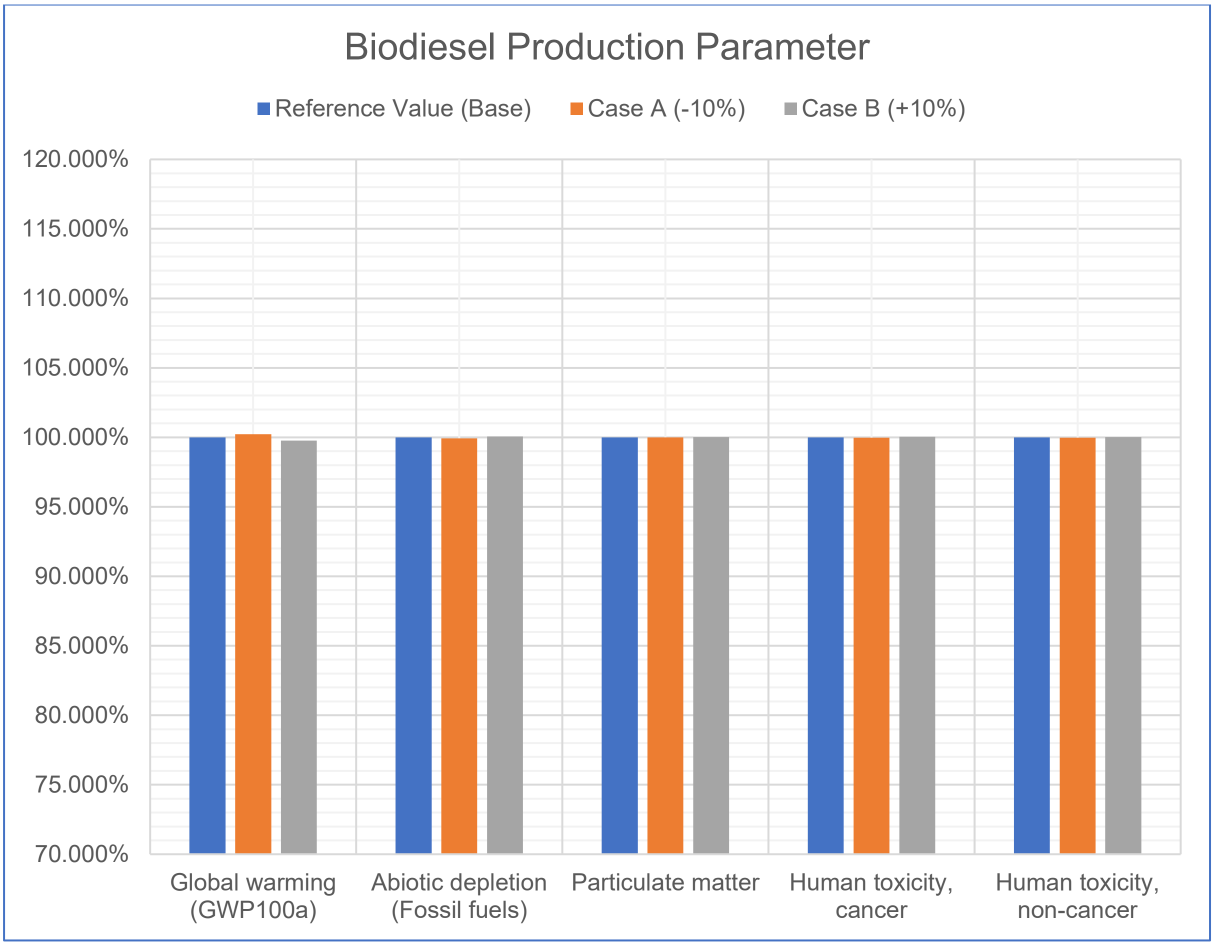


**Figure H.47: Sensitivity Analysis for LCA of BD5 Buses (Biodiesel Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.075556611 | 0.075556974 | -0.0002 | 0.0002 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204165 | 0.92203959 | 0.92204372 | -0.0002 | 0.0002 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.50E-05 | 6.50E-05 | -0.0002 | 0.0002 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.49E-10 | 4.49E-10 | -0.0021 | 0.0021 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.32E-09 | 2.32E-09 | -0.0015 | 0.0015 |

**Table H.48: Sensitivity Analysis for LCA of $BD_5$ Buses (Biodiesel Processing Parameter)**

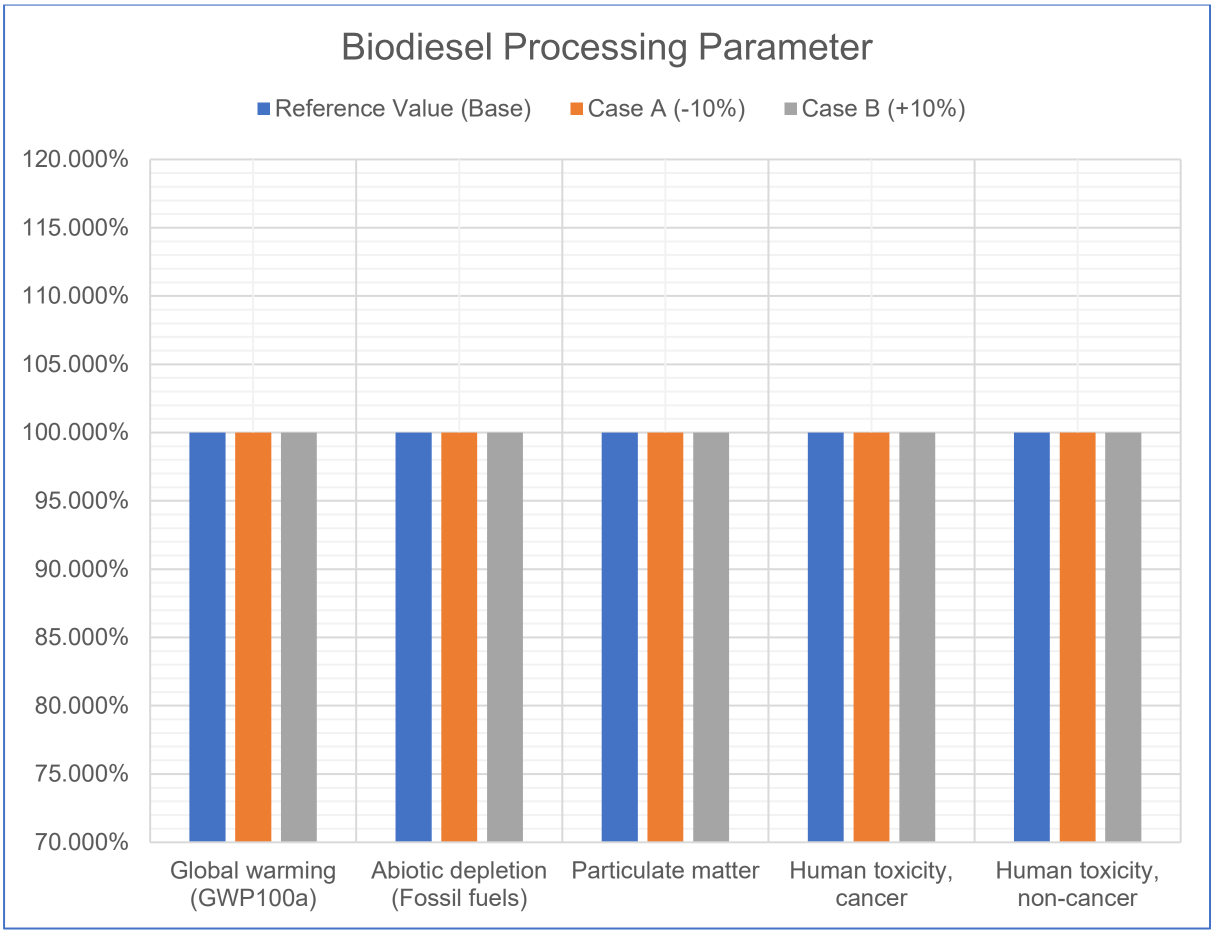


**Figure H.48: Sensitivity Analysis for LCA of $BD_5$ Buses (Biodiesel Processing Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.074229152 | 0.076884433 | -1.76 | 1.76 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204166 | 0.90603905 | 0.93804427 | -1.74 | 1.74 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.48E-05 | 6.51E-05 | -0.23 | 0.23 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.46E-10 | 4.52E-10 | -0.67 | 0.67 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.25E-09 | 2.40E-09 | -3.10 | 3.10 |

**Table H.49: Sensitivity Analysis for LCA of BD5 Buses (Vehicle Maintenance Parameter)**

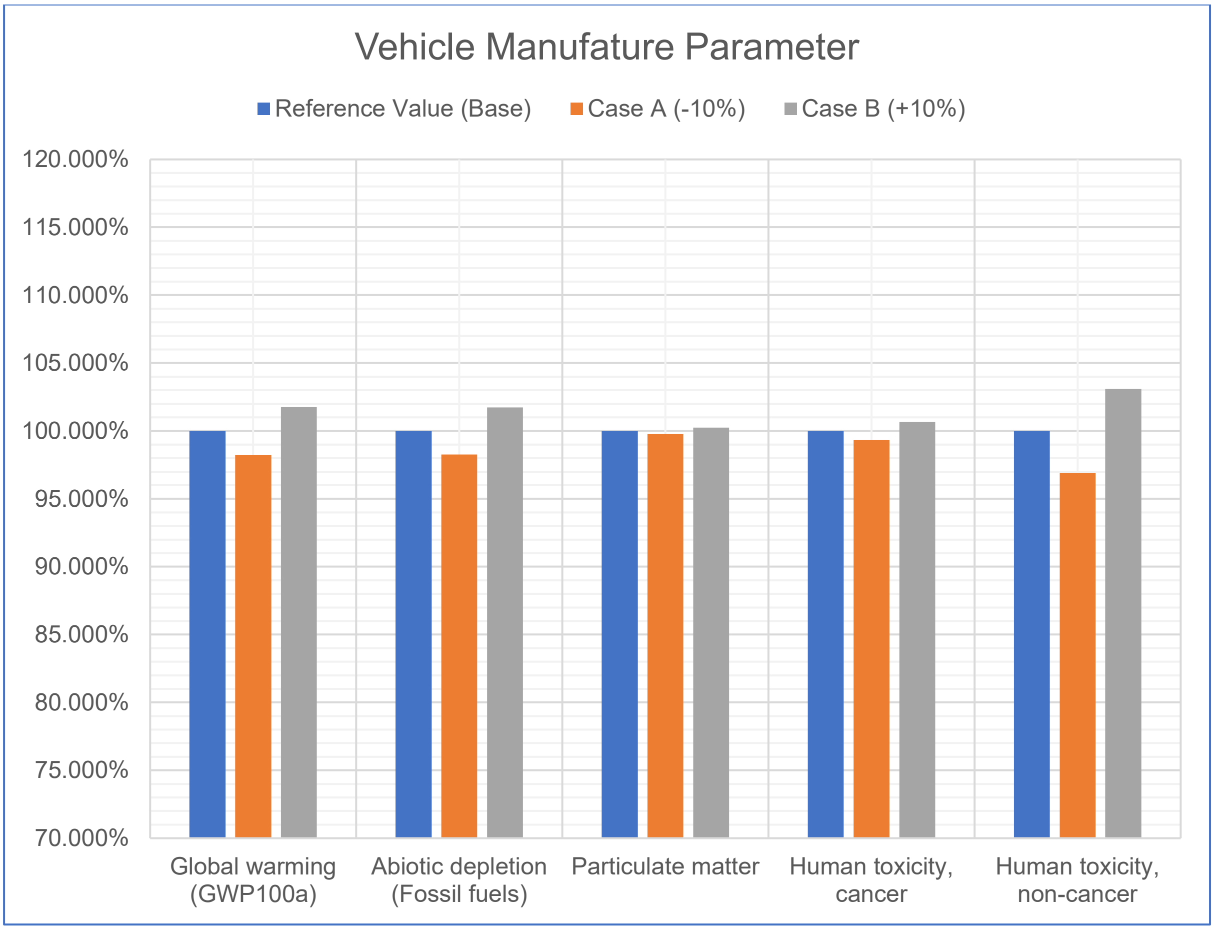


**Figure H.49: Sensitivity Analysis for LCA of BD5 Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.075556793 | 0.075533453 | 0.075580132 | -0.0309 | 0.0309 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.92204165 | 0.92203304 | 0.92205026 | -0.0009 | 0.0009 |
| **Particulate Matter (kg/pkm)** | 6.50E-05 | 6.50E-05 | 6.50E-05 | -0.0007 | 0.0007 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.49E-10 | 4.49E-10 | 4.49E-10 | -0.0213 | 0.0213 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.32E-09 | 2.32E-09 | 2.32E-09 | -0.0111 | 0.0111 |

**Table H.50: Sensitivity Analysis for LCA of BD$_5$ Buses (Vehicle Disposal Parameter)**

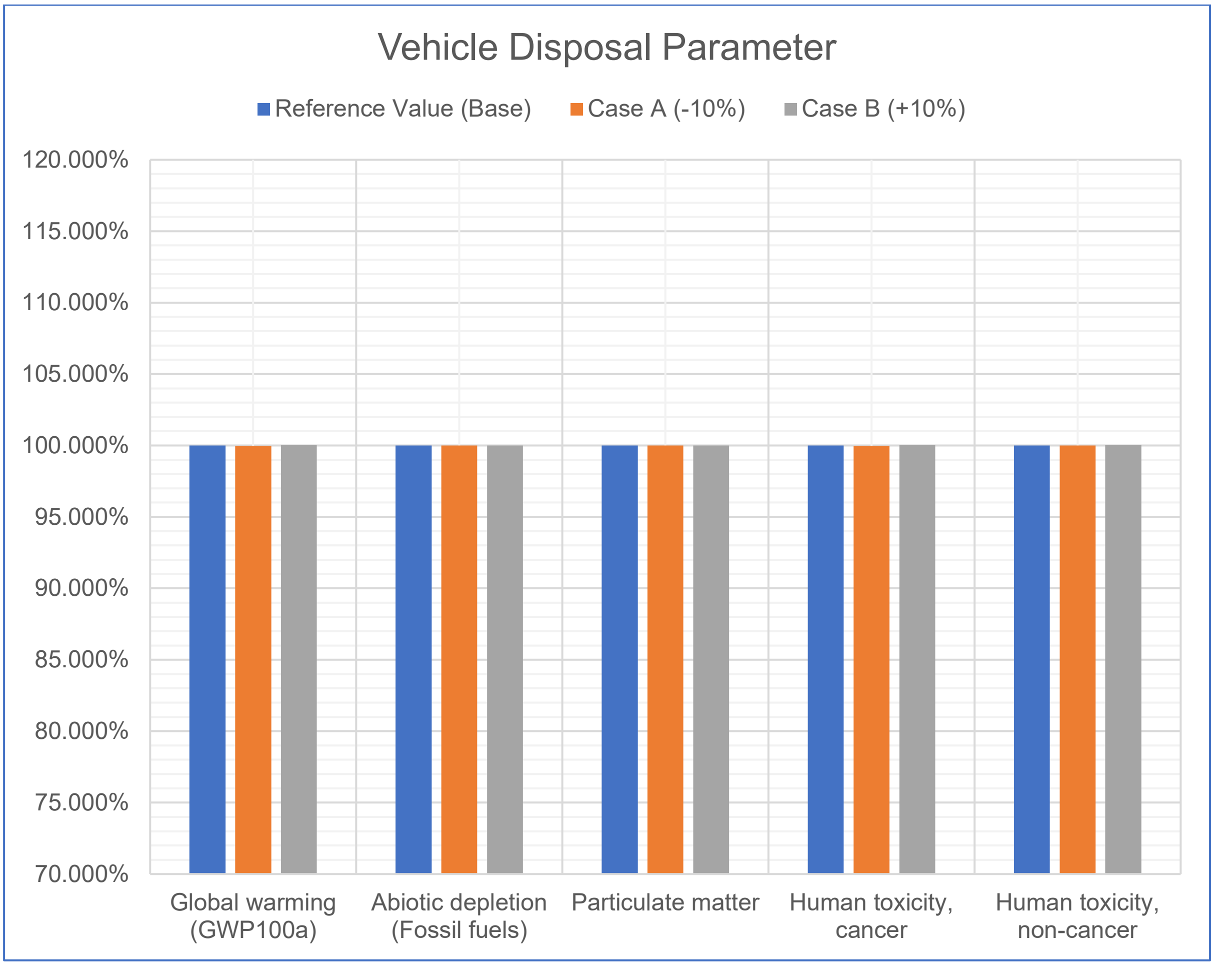


**Figure H.50: Sensitivity Analysis for LCA of BD$_5$ Buses (Vehicle Disposal Parameter)**

### Biodiesel Blends ($BD_{20}$) Buses

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.067660517 | 0.059423846 | 7.18 | -5.87 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.91275399 | 0.79620849 | 7.55 | -6.18 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 7.00E-05 | 5.82E-05 | 10.26 | -8.40 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.54E-10 | 4.46E-10 | 0.99 | -0.81 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.34E-09 | 2.28E-09 | 1.47 | -1.20 |

**Table H.51: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Kilometres Travelled Parameter)**

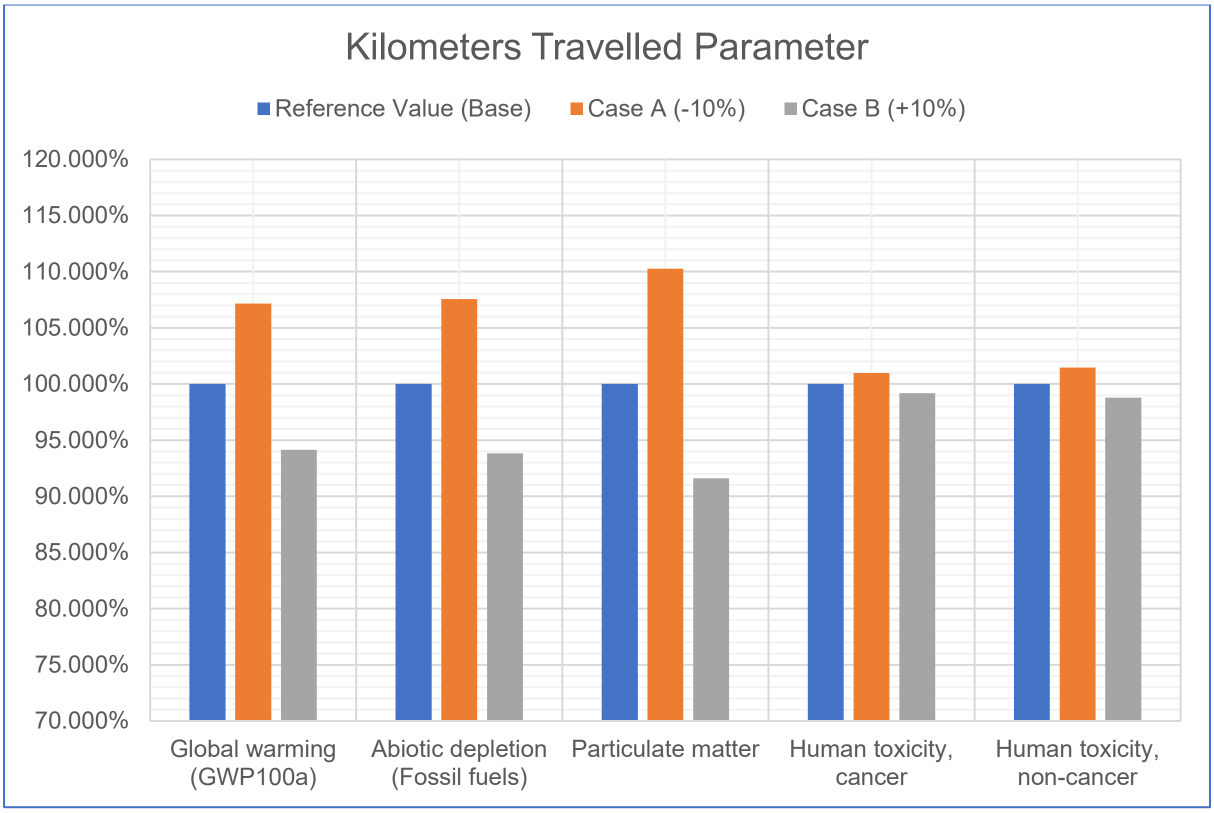


**Figure H.51: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.059053195 | 0.0672075 | -6.46 | 6.46 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.79096394 | 0.90634398 | -6.80 | 6.80 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 5.76E-05 | 6.94E-05 | -9.24 | 9.24 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.46E-10 | 4.54E-10 | -0.89 | 0.89 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.27E-09 | 2.34E-09 | -1.32 | 1.32 |

**Table H.52: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Fuel Consumption Parameter)**

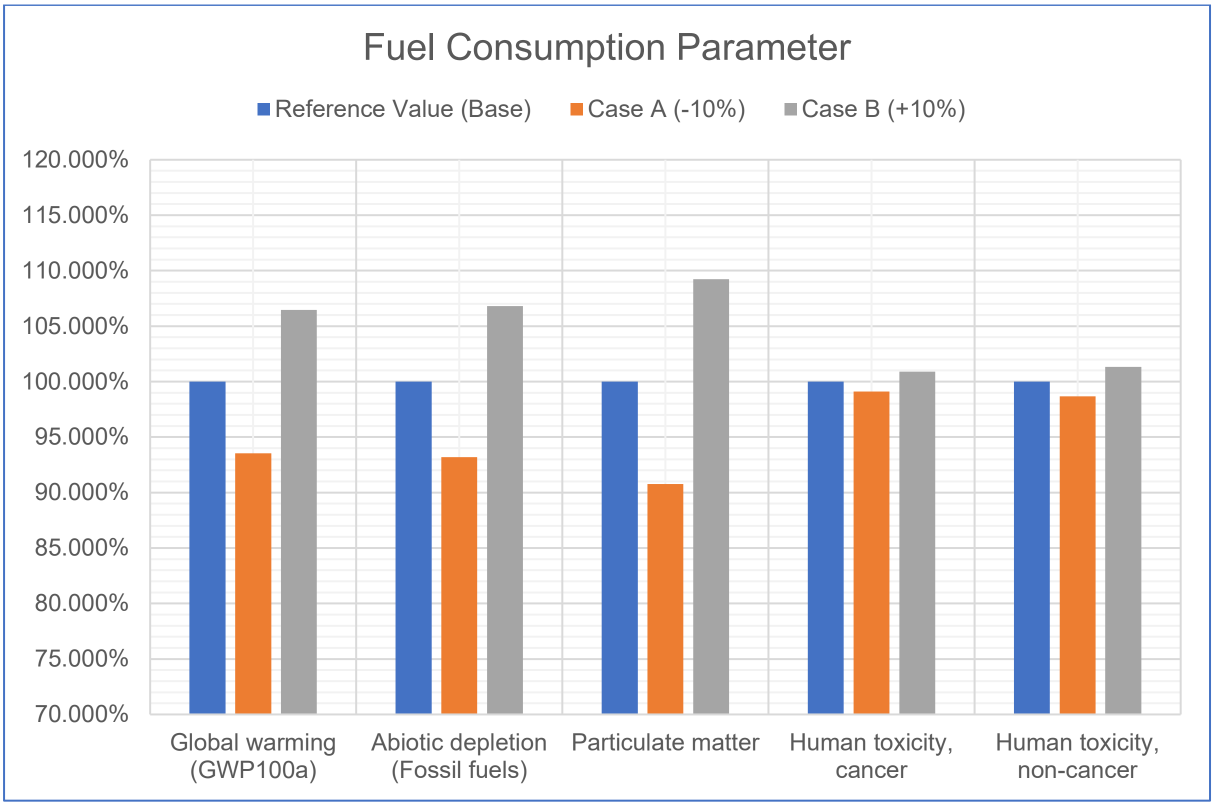


**Figure H.52: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.070144831 | 0.057391225 | 11.11 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.94294885 | 0.7715036 | 11.11 | -9.09 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 7.05E-05 | 5.77E-05 | 11.11 | -9.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 5.00E-10 | 4.09E-10 | 11.11 | -9.09 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.56E-09 | 2.10E-09 | 11.11 | -9.09 |

**Table H.53: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Occupancy Rate Parameter)**

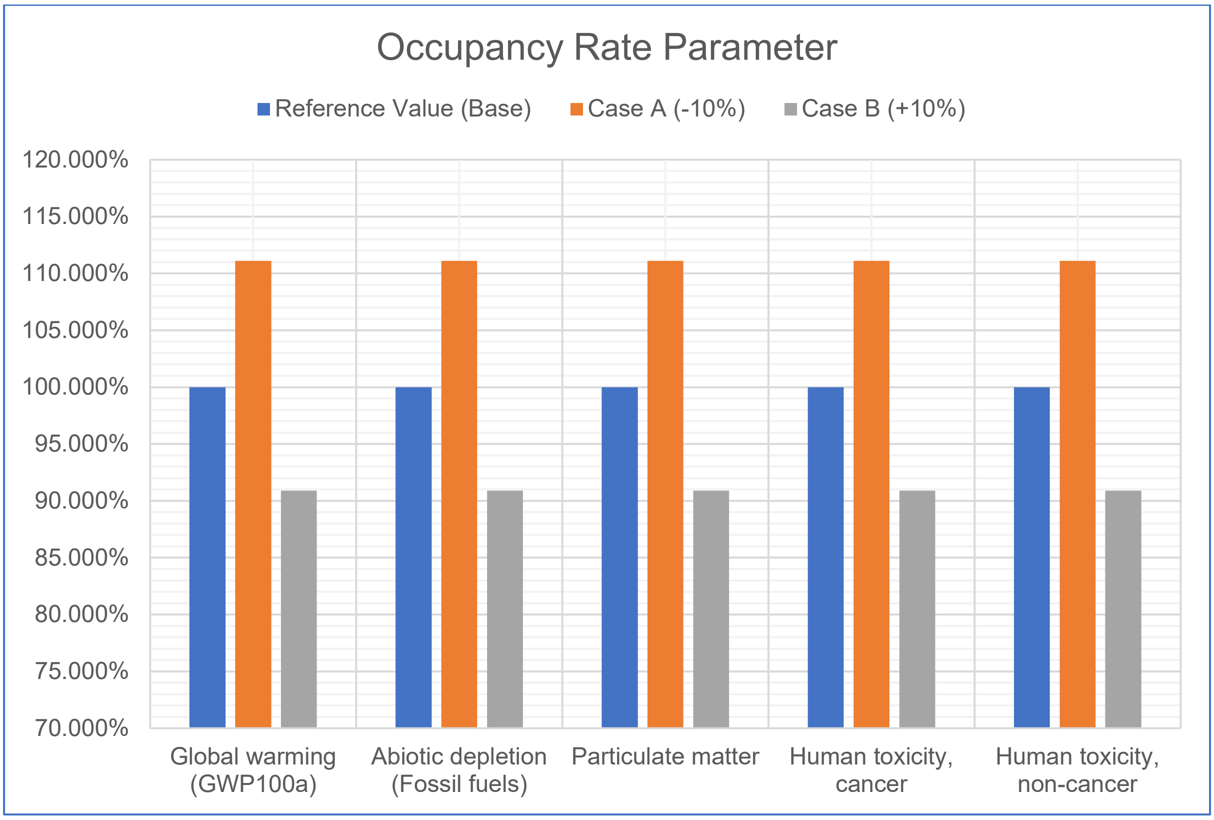


**Figure H.53: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.062245445 | 0.06401525 | -1.40 | 1.40 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.83748981 | 0.85981812 | -1.32 | 1.32 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.32E-05 | 6.38E-05 | -0.52 | 0.52 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.12E-10 | 4.87E-10 | -8.42 | 8.42 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.18E-09 | 2.43E-09 | -5.54 | 5.54 |

**Table H.54: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Vehicle Manufacture Parameter)**

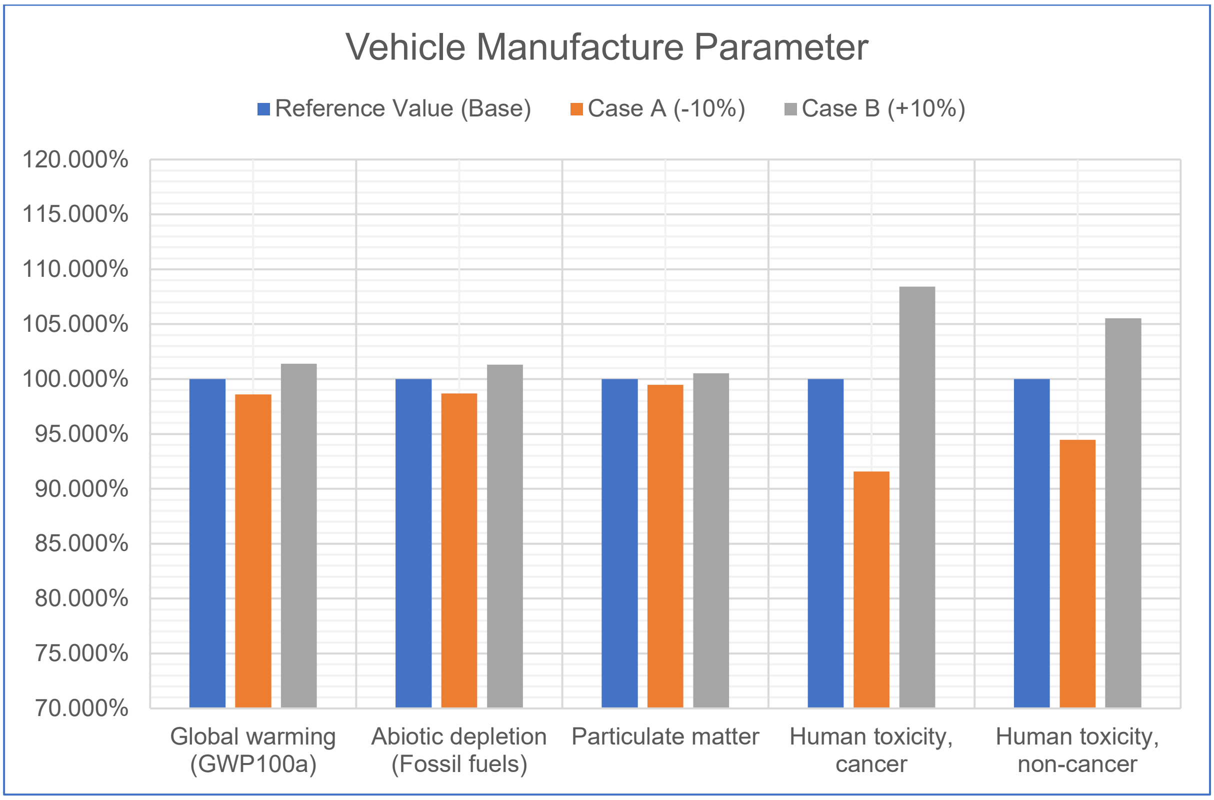


**Figure H.54: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.063088596 | 0.063172099 | -0.07 | 0.07 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.83479426 | 0.86251367 | -1.63 | 1.63 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.35E-05 | 6.35E-05 | -0.03 | 0.03 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.50E-10 | 4.50E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.30E-09 | 2.31E-09 | -0.06 | 0.06 |

Table H.55: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Crude Oil Extraction Parameter)

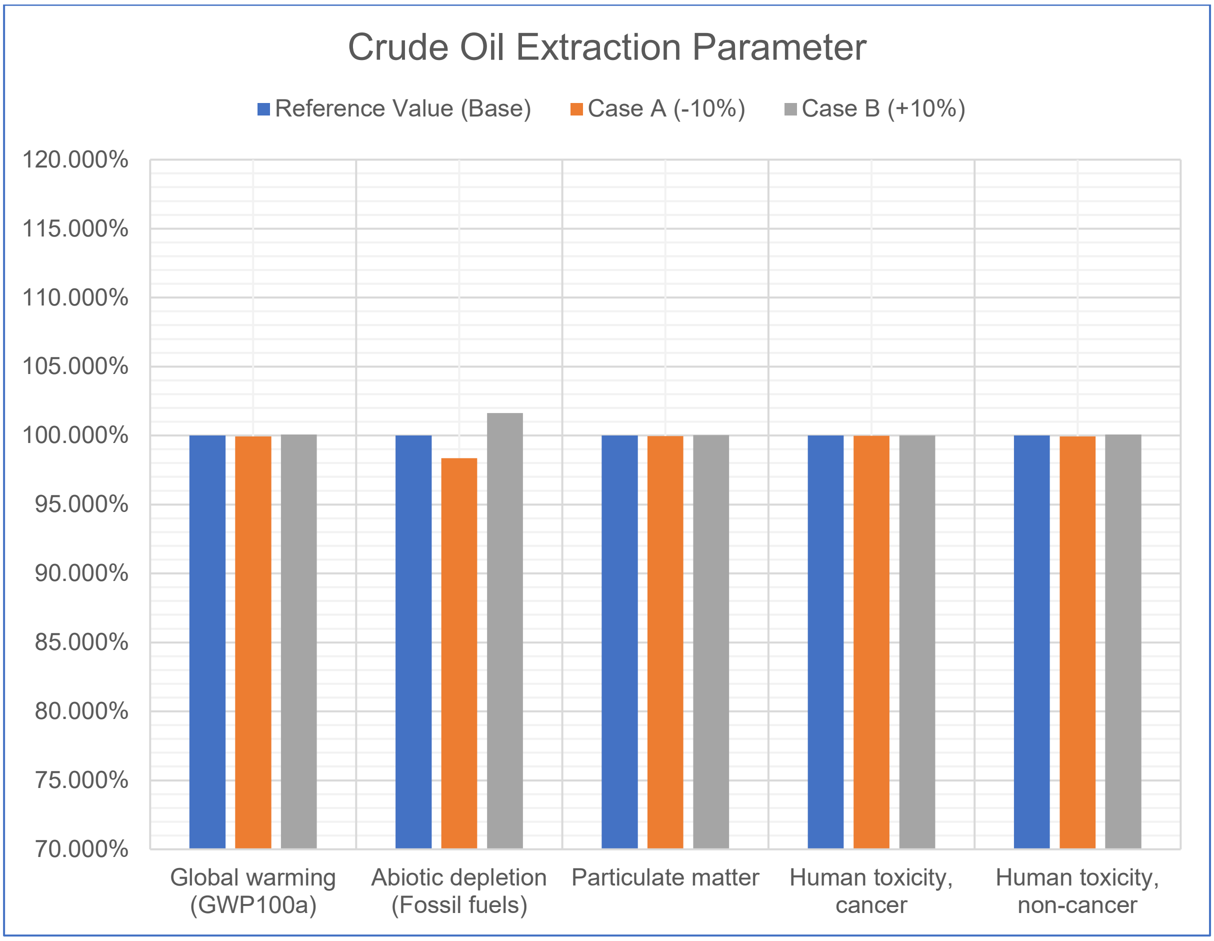


Figure H.55: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Crude Oil Extraction Parameter)

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.062796696 | 0.063463999 | -0.53 | 0.53 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.80096721 | 0.89634071 | -5.62 | 5.62 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.32E-05 | 6.38E-05 | -0.42 | 0.42 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.47E-10 | 4.52E-10 | -0.50 | 0.50 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.29E-09 | 2.32E-09 | -0.68 | 0.68 |

**Table H.56: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Crude Oil Refining Parameter)**

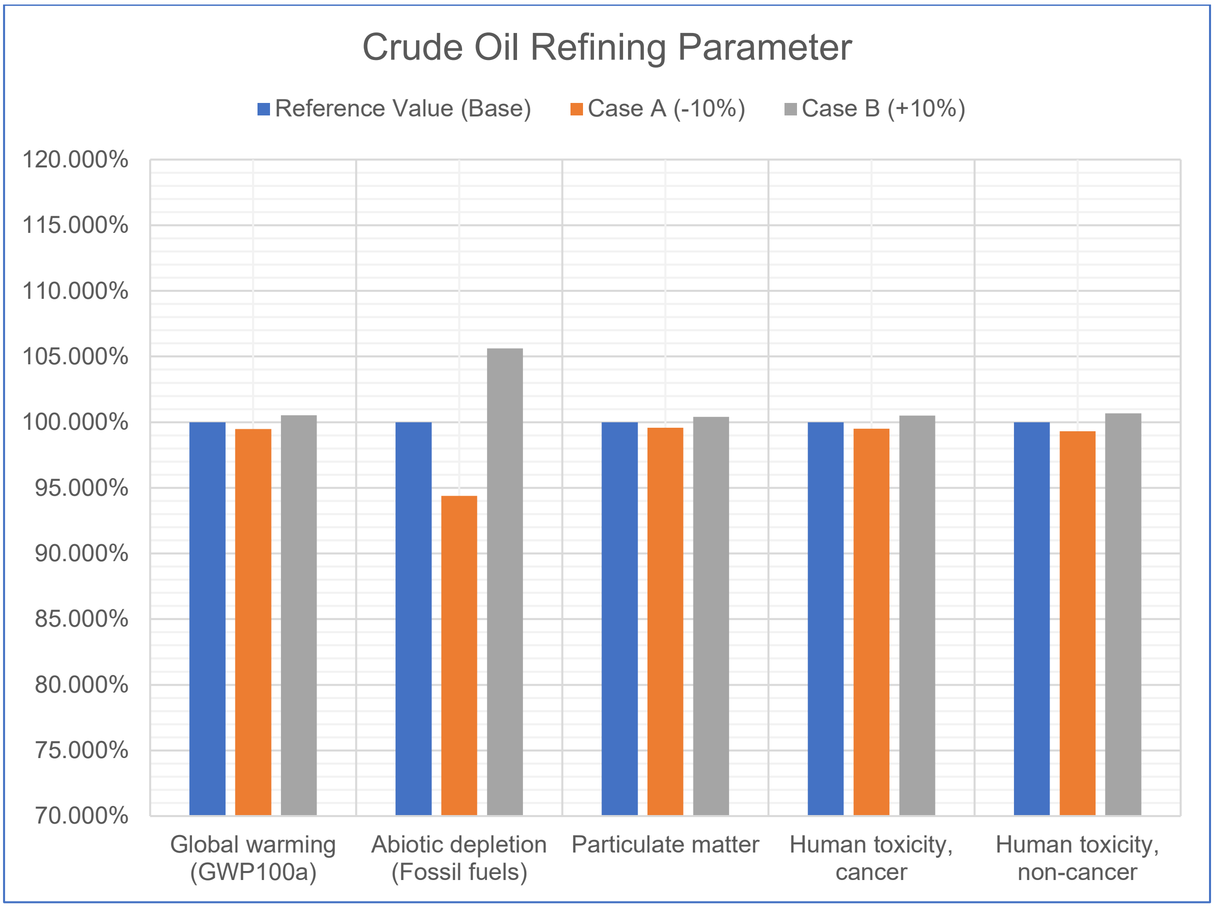


**Figure H.56: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.063834978 | 0.062425718 | 1.12 | -1.12 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.84630689 |  | -0.28 | 0.28 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.35E-05 | 6.35E-05 | -0.02 | 0.02 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.49E-10 | 4.50E-10 | -0.13 | 0.13 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.30E-09 | 2.31E-09 | -0.10 | 0.10 |

**Table H.57: Sensitivity Analysis for LCA of BD$_{20}$ Buses (Biodiesel Production Parameter)**

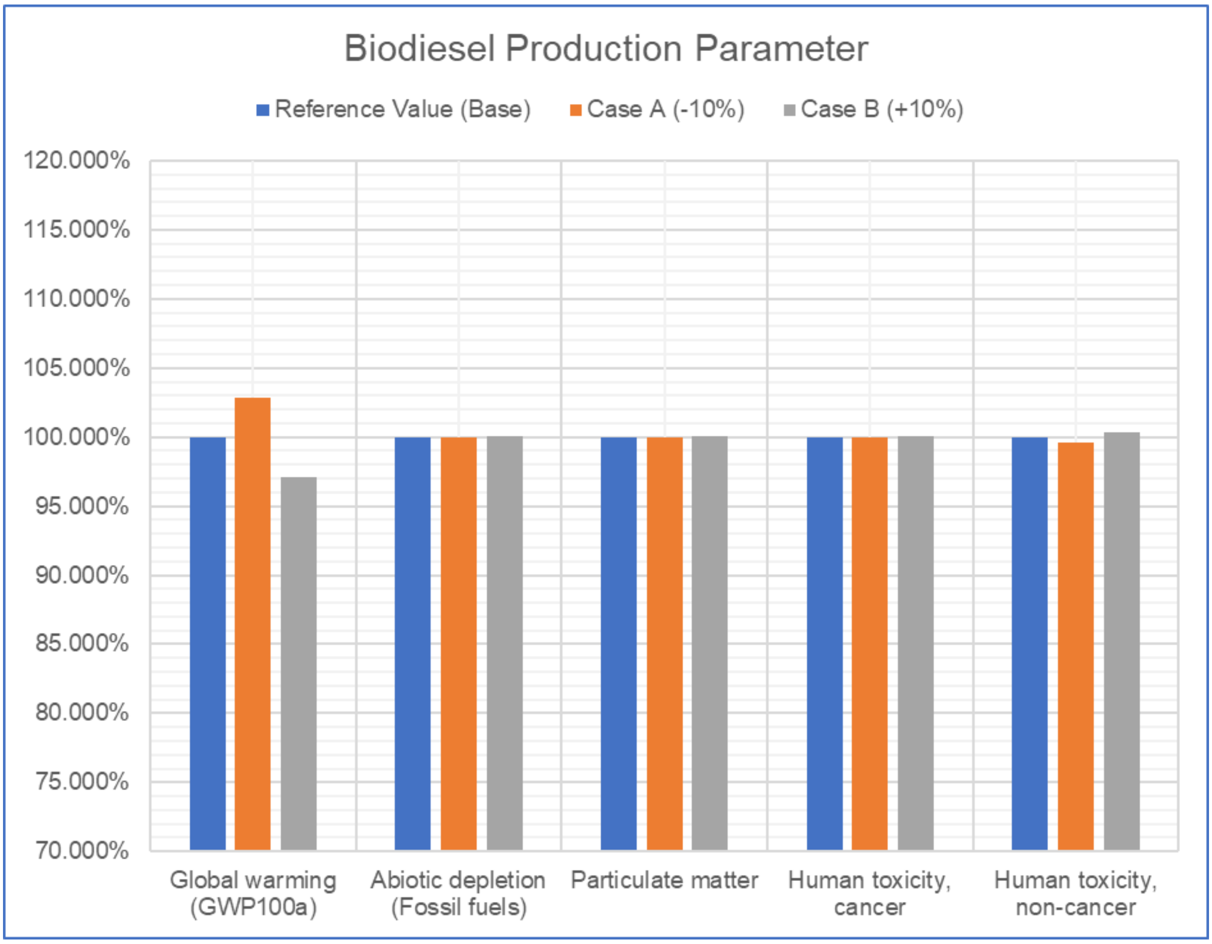


**Figure H.57: Sensitivity Analysis for LCA of BD$_{20}$ Buses (Biodiesel Production Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.063129622 | 0.063131073 | 0.00 | 0.00 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.84864571 | 0.84866222 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.35E-05 | 6.35E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.50E-10 | 4.50E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.31E-09 | 2.31E-09 | -0.01 | 0.01 |

**Table H.58: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Biodiesel Processing Parameter)**

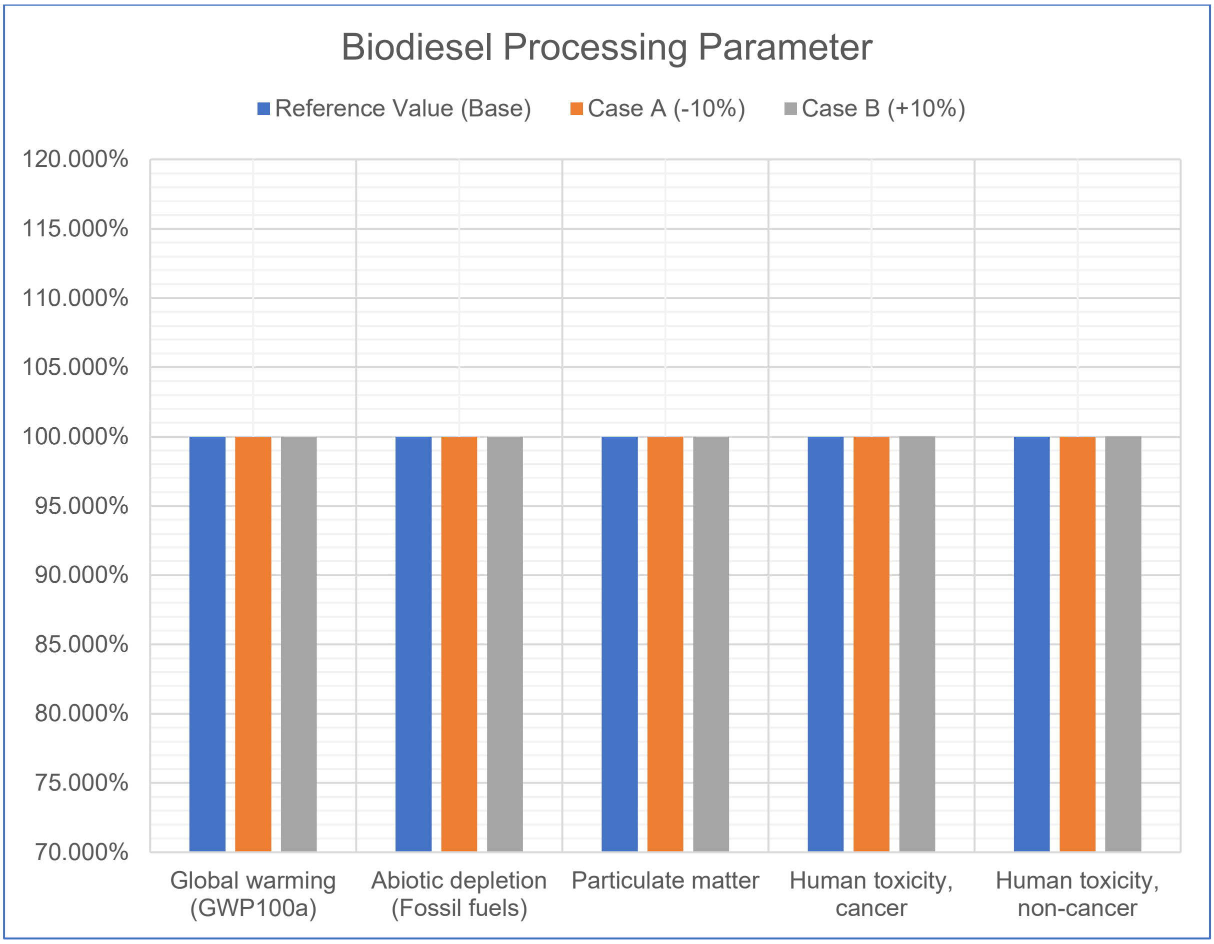


**Figure H.58: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Biodiesel Processing Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.061802707 | 0.06445797 | -2.10 | 2.10 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.83265135 | 0.86465658 | -1.89 | 1.89 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.33E-05 | 6.36E-05 | -0.66 | 0.66 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.5E-10 | 4.47E-10 | 4.53E-10 | -3.12 | 3.12 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.31E-09 | 2.31E-09 | -0.01 | 0.01 |

**Table H.59: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Vehicle Maintenance Parameter)**

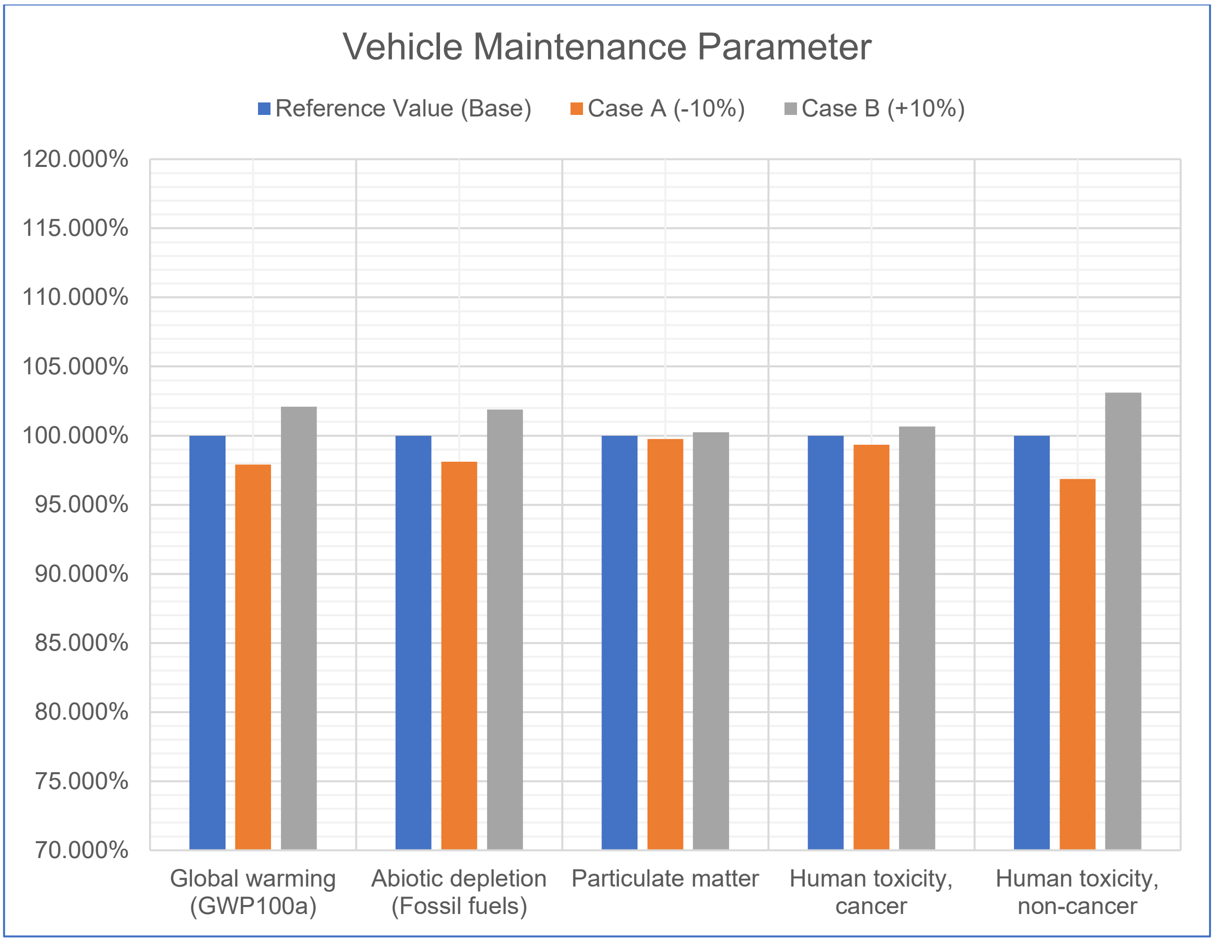


**Figure H.59: Sensitivity Analysis for LCA of $BD_{20}$ Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.063130348 | 0.063107008 | 0.063153687 | -0.04 | 0.04 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84865396 | 0.84864535 | 0.84866257 | 0.00 | 0.0 |
| **Particulate Matter (kg/pkm)** | 6.35E-05 | 6.35E-05 | 6.35E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.50E-10 | 4.49E-10 | 4.50E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.31E-09 | 2.31E-09 | 2.31E-09 | -0.01 | 0.01 |

**Table H.60: Sensitivity Analysis for LCA of BD20 Buses (Vehicle Disposal Parameter)**

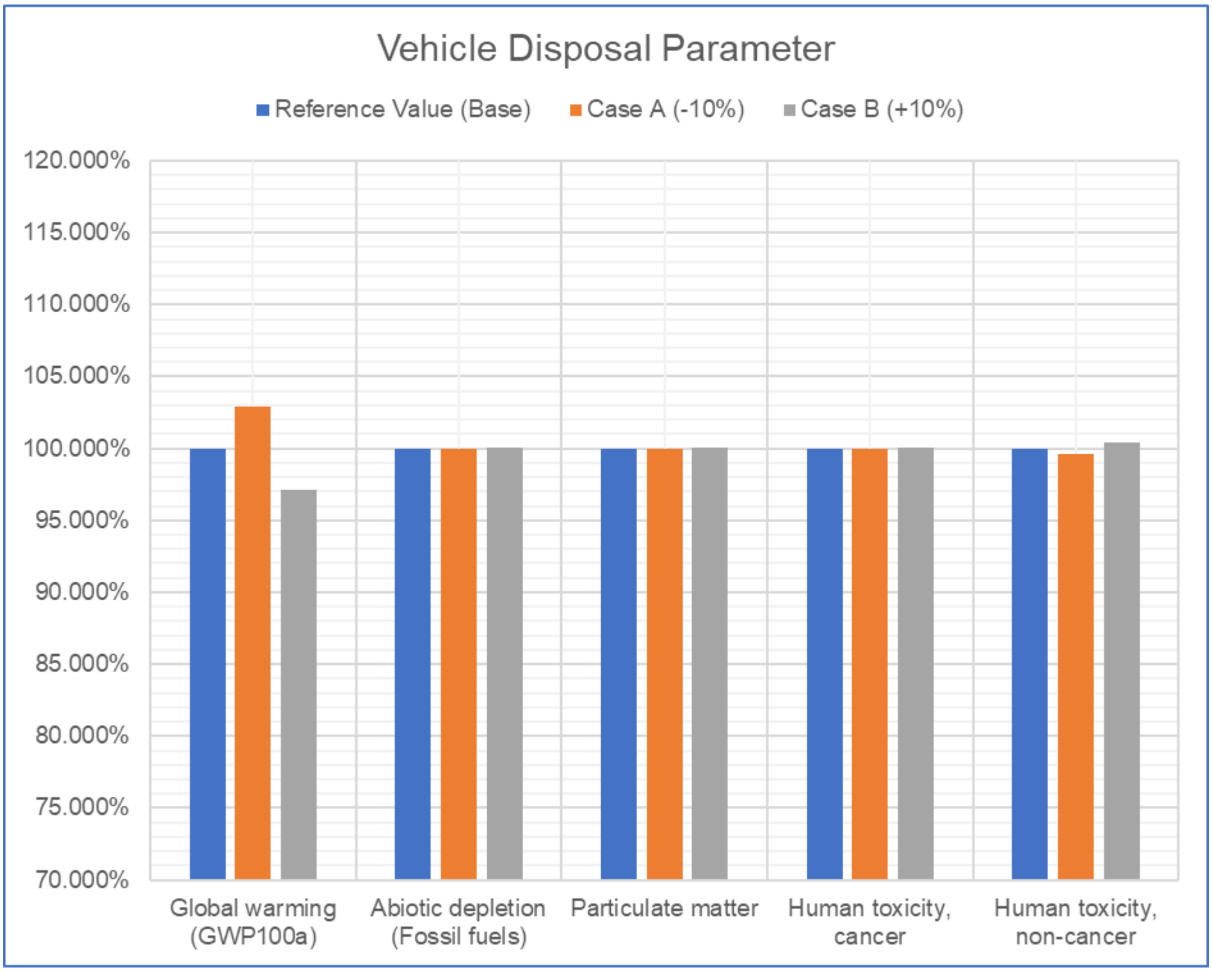


**Figure H.60: Sensitivity Analysis for LCA of BD20 Buses (Vehicle Disposal Parameter)**

## Pure Biodiesel ($BD_{100}$) Buses

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -0.005320456 | -0.000287859 | 108.44 | -88.72 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.42561076 | 0.39763676 | 3.75 | -3.07 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 6.25E-05 | 5.20E-05 | 10.16 | -8.32 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.58E-10 | 4.49E-10 | 1.07 | -0.87 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.21E-09 | 2.17E-09 | 0.96 | -0.78 |

**Table H.61: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Kilometres Travelled Parameter)**

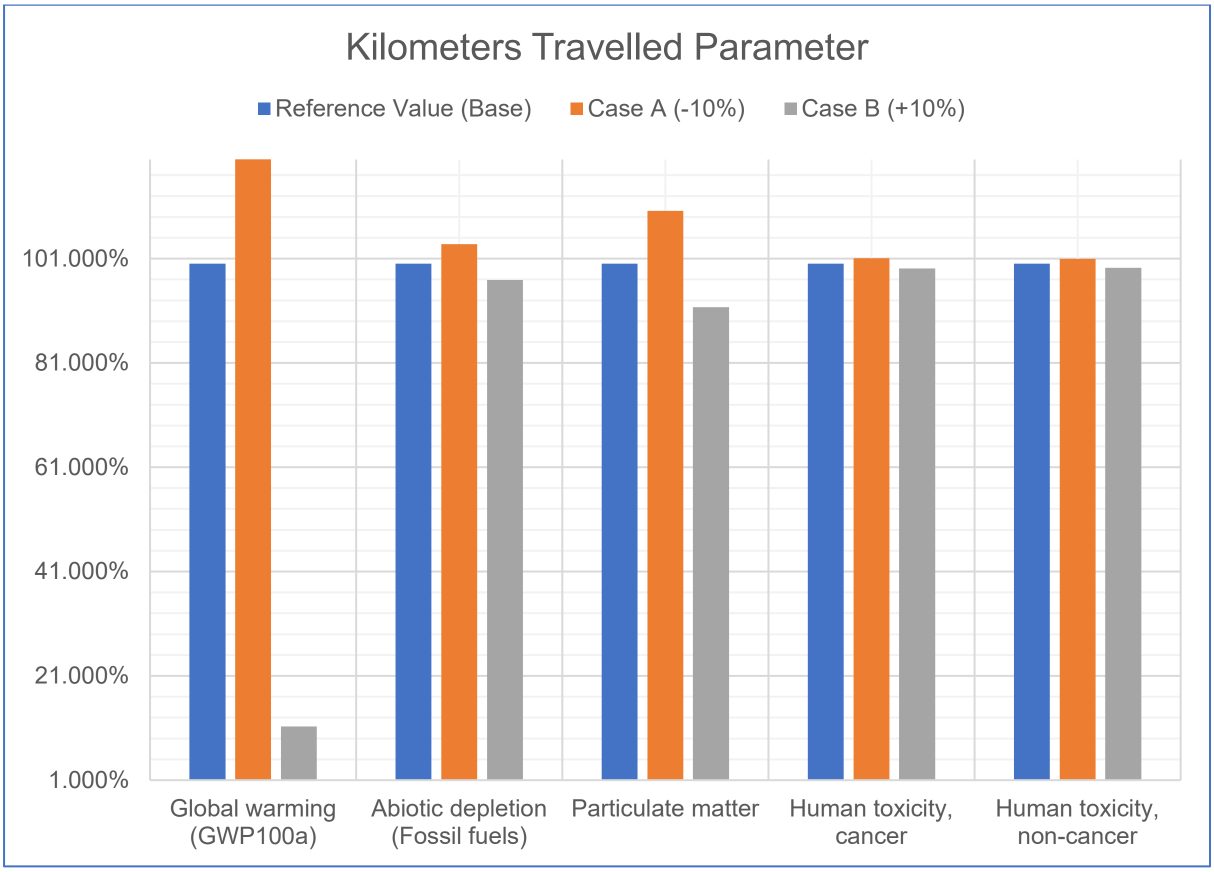


**Figure H.61: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -6.14E-05 | -0.005043663 | -97.59 | 97.59 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.39637793 | 0.42407219 | -3.38 | 3.38 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.15E-05 | 6.19E-05 | -9.15 | 9.15 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.49E-10 | 4.57E-10 | -0.96 | 0.96 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.17E-09 | 2.21E-09 | -0.86 | 0.86 |

**Table H.62: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Fuel Consumption Parameter)**

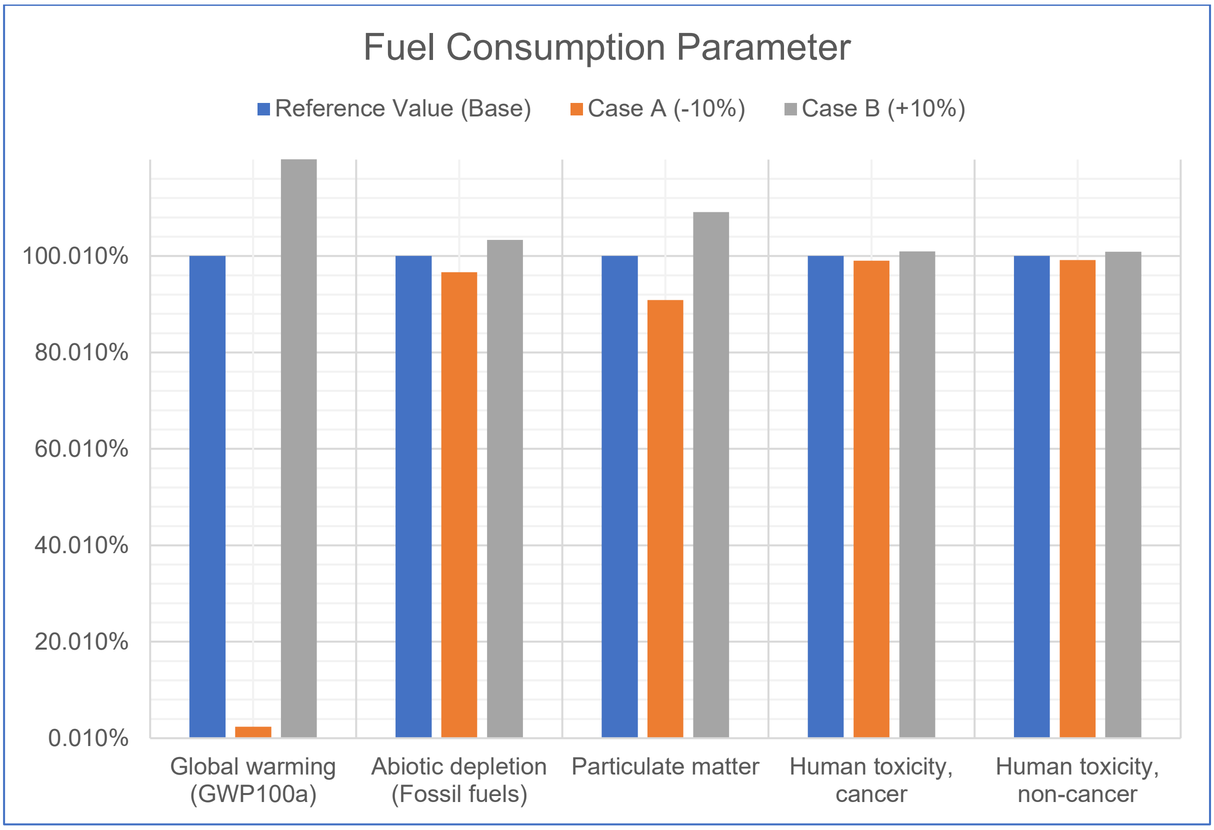


**Figure H.62: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -0.002836142 | -0.00232048 | 11.11 | -9.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.45580562 | 0.37293187 | 11.11 | -9.09 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 6.30E-05 | 5.16E-05 | 11.11 | -9.09 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 5.03E-10 | 4.12E-10 | 11.11 | -9.09 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.43E-09 | 1.99E-09 | 11.11 | -9.09 |

**Table H.63: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Occupancy Rate Parameter)**

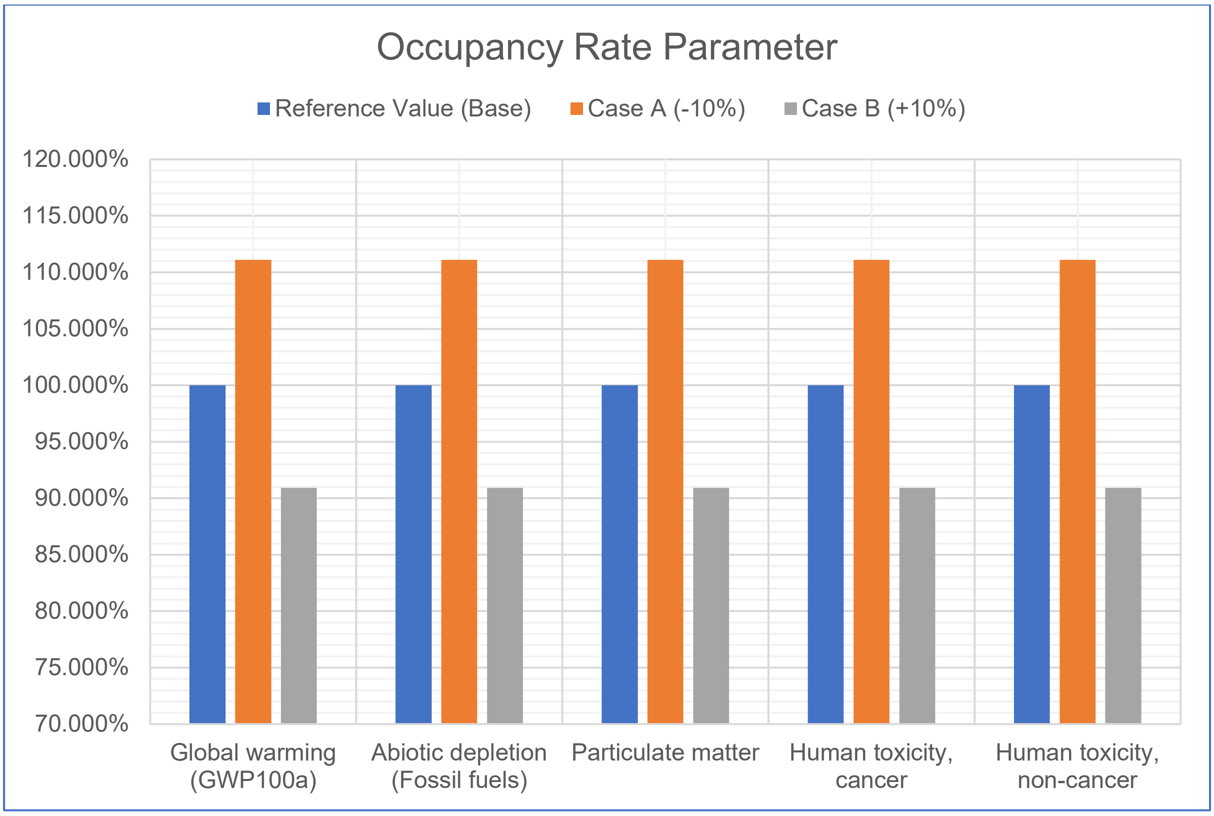


**Figure H.63: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -0.00343743 | -0.001667625 | 34.67 | -34.67 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.3990609 | 0.42138921 | -2.72 | 2.72 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.64E-05 | 5.71E-05 | -0.58 | 0.58 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.15E-10 | 4.91E-10 | -8.36 | 8.36 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.06E-09 | 2.32E-09 | -5.84 | 5.84 |

**Table H.64: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Vehicle Manufacture Parameter)**

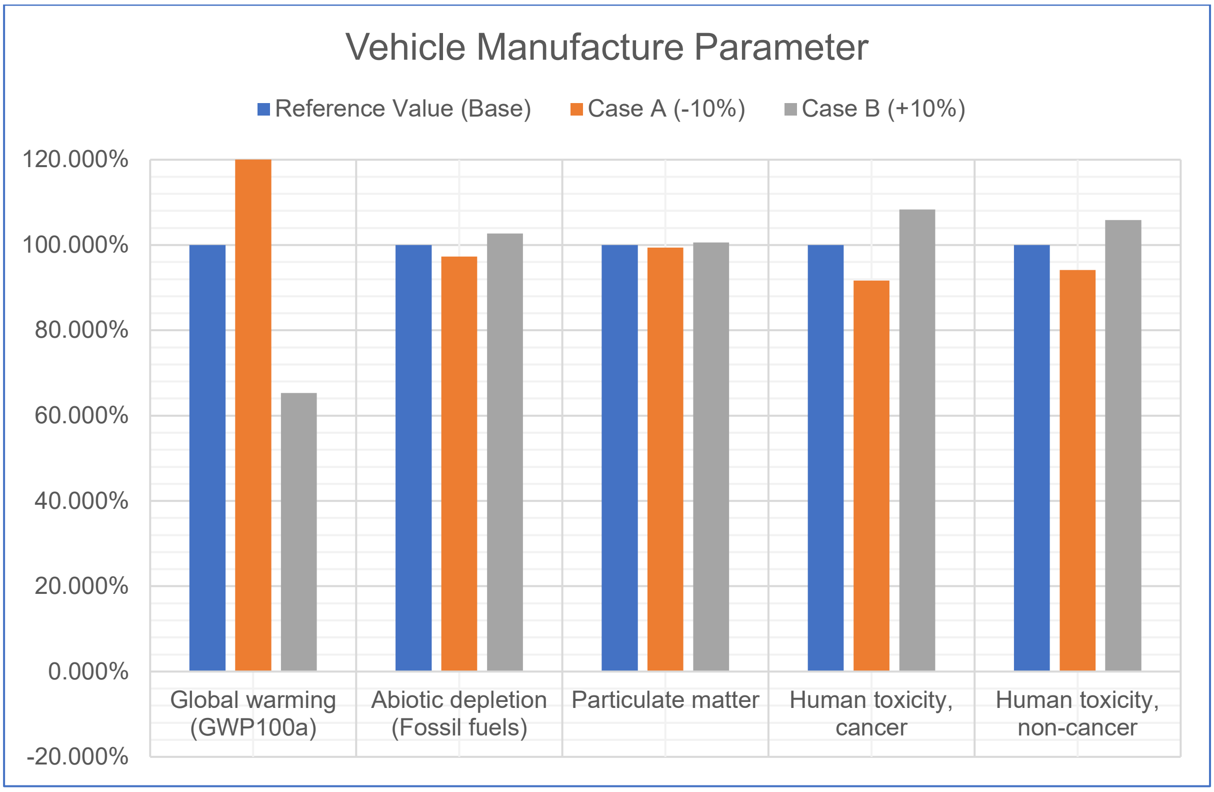


**Figure H.64: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | 0.001114845 | -0.006219901 | -143.68 | 143.68 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.39800928 | 0.42244084 | -2.98 | 2.98 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.67E-05 | 5.68E-05 | -0.14 | 0.14 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.50E-10 | 4.56E-10 | -0.67 | 0.67 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.18E-09 | 2.20E-09 | -0.57 | 0.57 |

**Table H.65: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Biodiesel Production Parameter)**

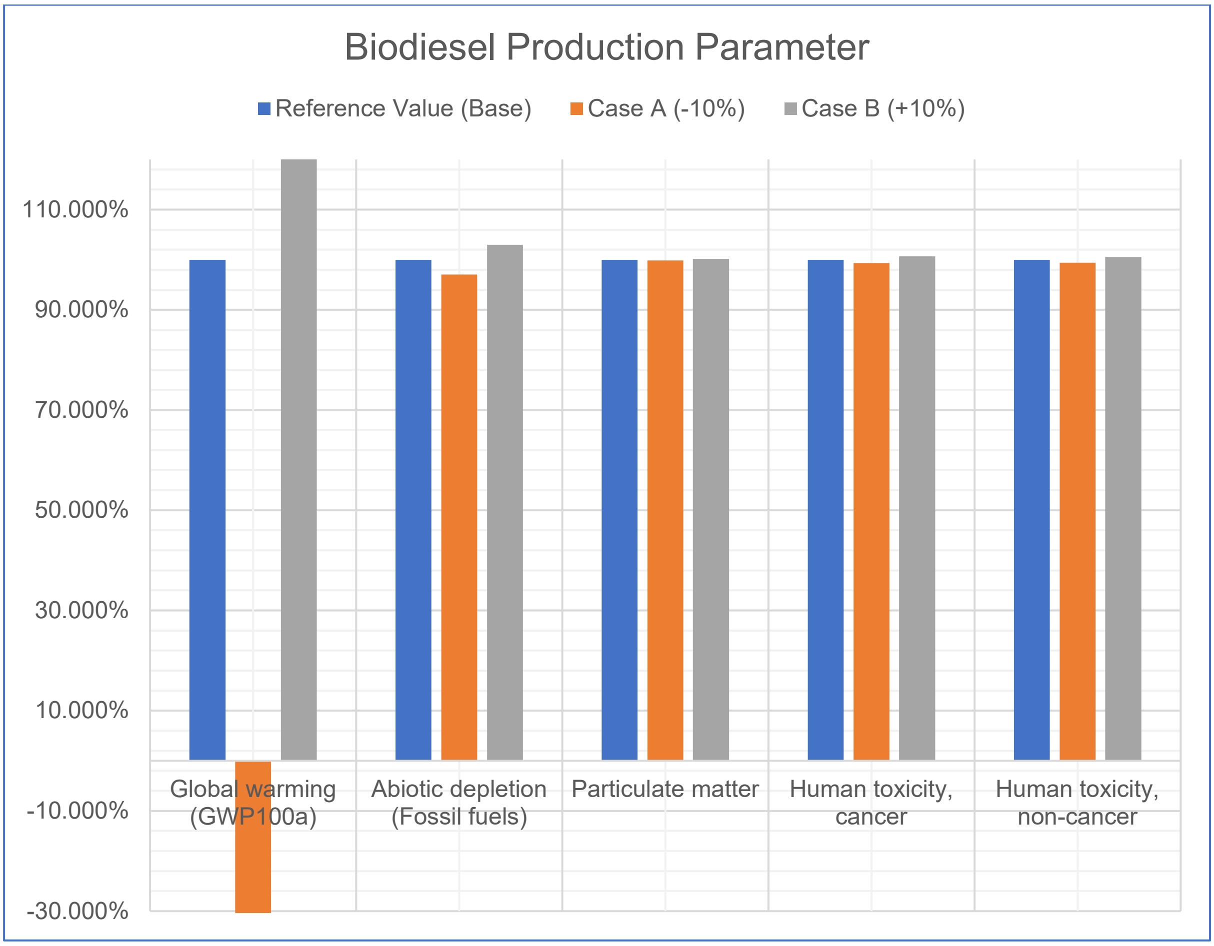


**Figure H.65: Sensitivity Analysis for LCA of $BD_{100}$ Buses (Biodiesel Production Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -0.002556303 | -0.002548753 | 0.15 | -0.15 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.41018211 | 0.41026801 | -0.01 | 0.01 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.67E-05 | 5.67E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.53E-10 | 4.53E-10 | -0.04 | 0.04 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.19E-09 | 2.19E-09 | -0.03 | 0.03 |

**Table H.66: Sensitivity Analysis for LCA of BD$_{100}$ Buses (Biodiesel Processing Parameter)**

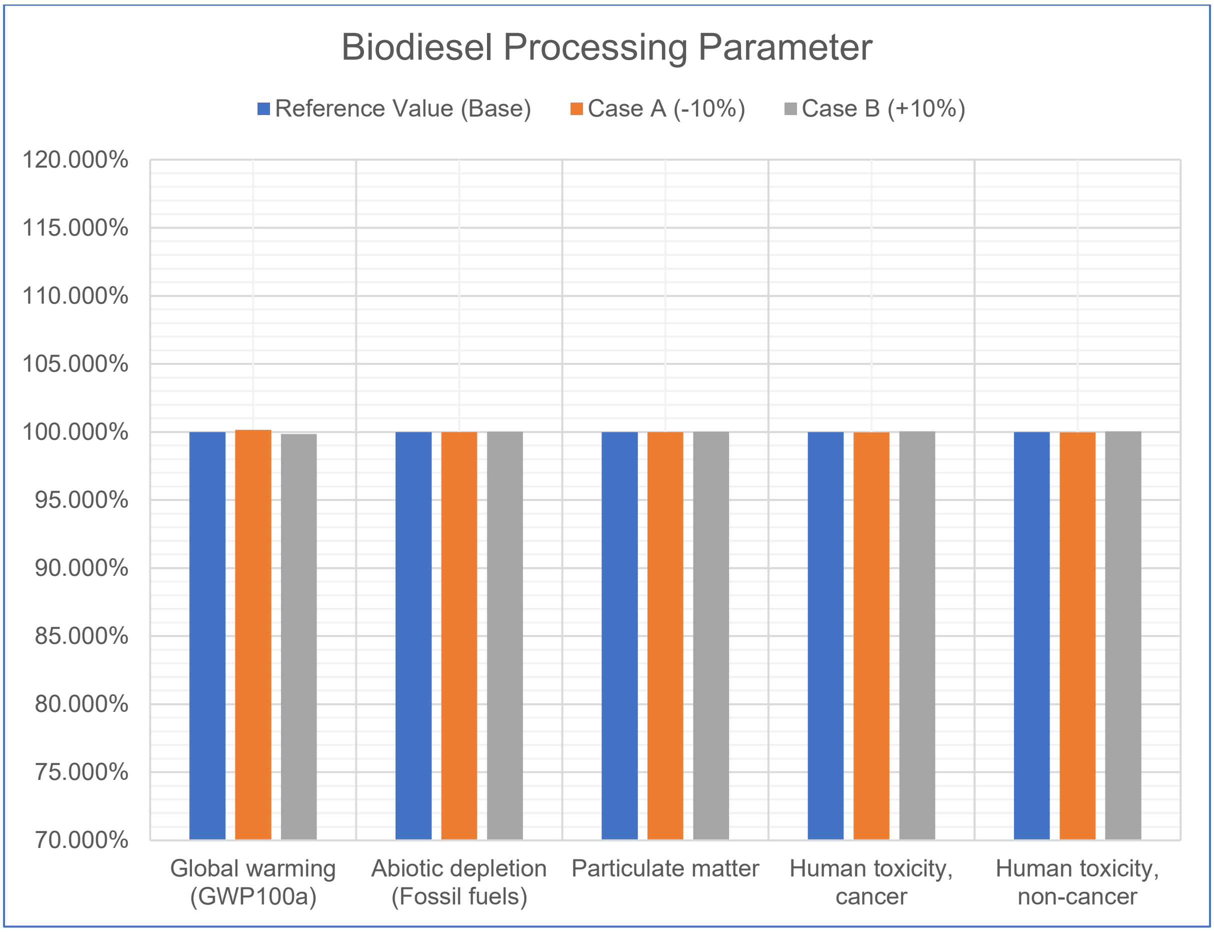


**Figure H.66: Sensitivity Analysis for LCA of BD$_{100}$ Buses (Biodiesel Processing Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -0.003880168 | -0.001224887 | 52.01 | -52.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.39422245 | 0.42622767 | -3.90 | 3.90 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.66E-05 | 5.69E-05 | -0.27 | 0.27 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.50E-10 | 4.56E-10 | -0.66 | 0.66 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.12E-09 | 2.26E-09 | -3.29 | 3.29 |

**Table H.67: Sensitivity Analysis for LCA of BD100 Buses (Vehicle Maintenance Parameter)**

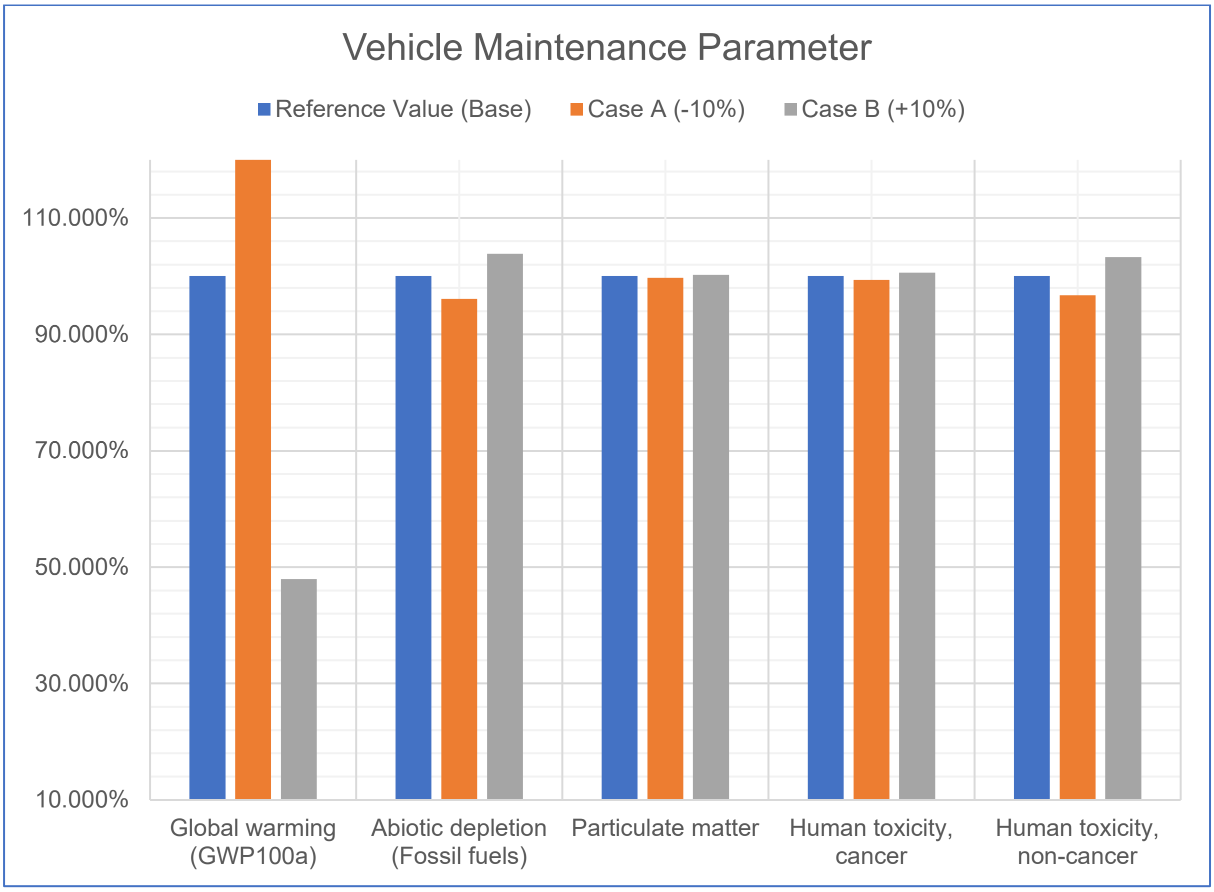


**Figure H.67: Sensitivity Analysis for LCA of BD100 Buses (Vehicle Maintenance Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | -0.002552528 | -0.002575868 | -0.002529188 | 0.91 | -0.91 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.41022506 | 0.41021645 | 0.41023367 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 5.67E-05 | 5.67E-05 | 5.67E-05 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 4.53E-10 | 4.53E-10 | 4.53E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 2.19E-09 | 2.19E-09 | 2.19E-09 | -0.01 | 0.01 |

**Table H.68: Sensitivity Analysis for LCA of BD$_{100}$ Buses (Vehicle Disposal Parameter)**

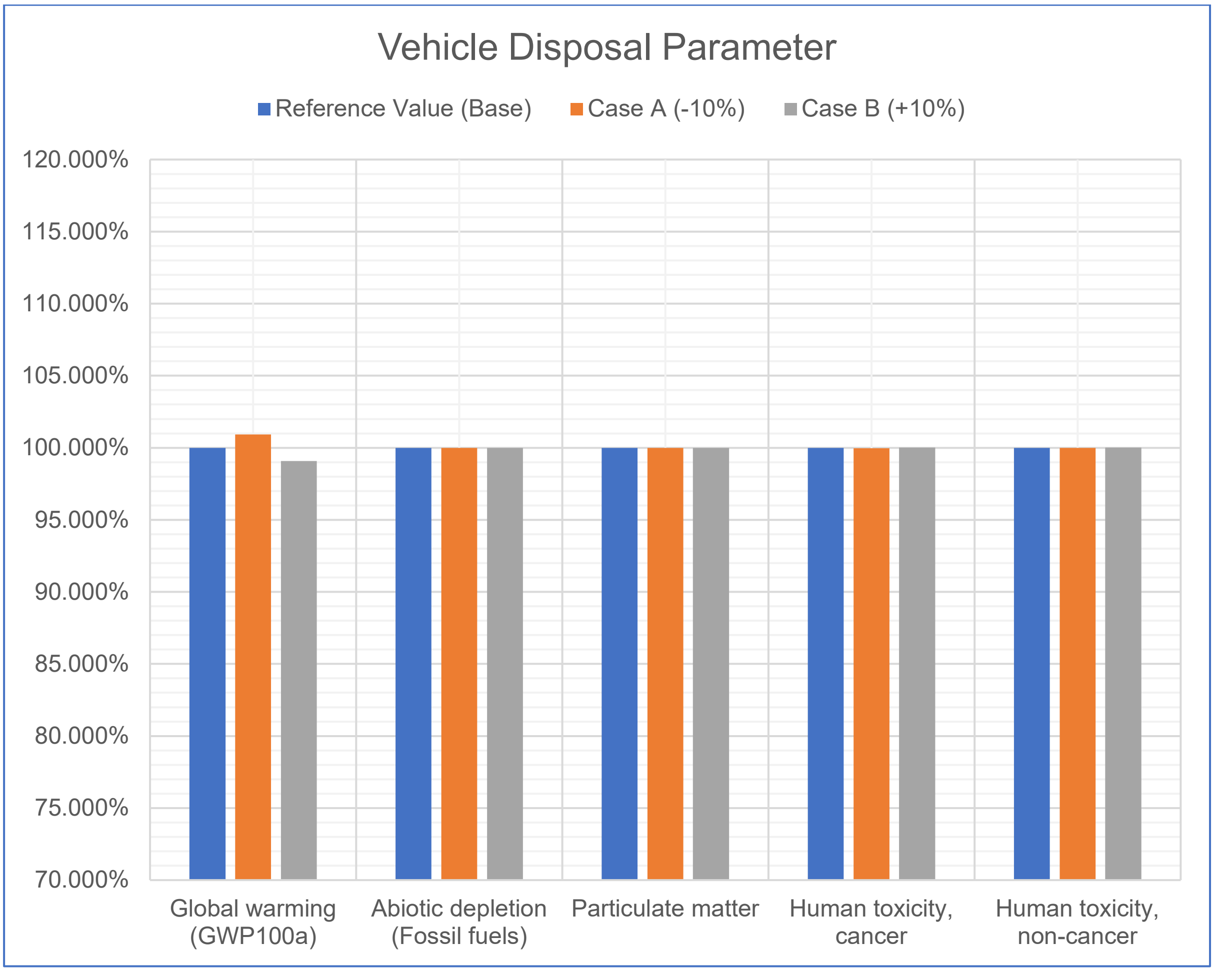


**Figure H.68: Sensitivity Analysis for LCA of BD$_{100}$ Buses (Vehicle Disposal Parameter)**

# APPENDIX I: SENSITIVITY ANALYSIS FOR LCA OF DPTI BUS TRIAL

### 1902/ LSD Scania Buses

| Impact category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.063967354 | 0.065800933 | -1 | 1 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.70078743 | 0.84537022 | -9 | 9 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 7.53E-06 | 9.01E-06 | -9 | 9 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.13E-10 | 1.22E-10 | -4 | 4 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 6.87E-10 | 7.58E-10 | -5 | 5 |

**Table I.1: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Fuel Consumption Parameter)**

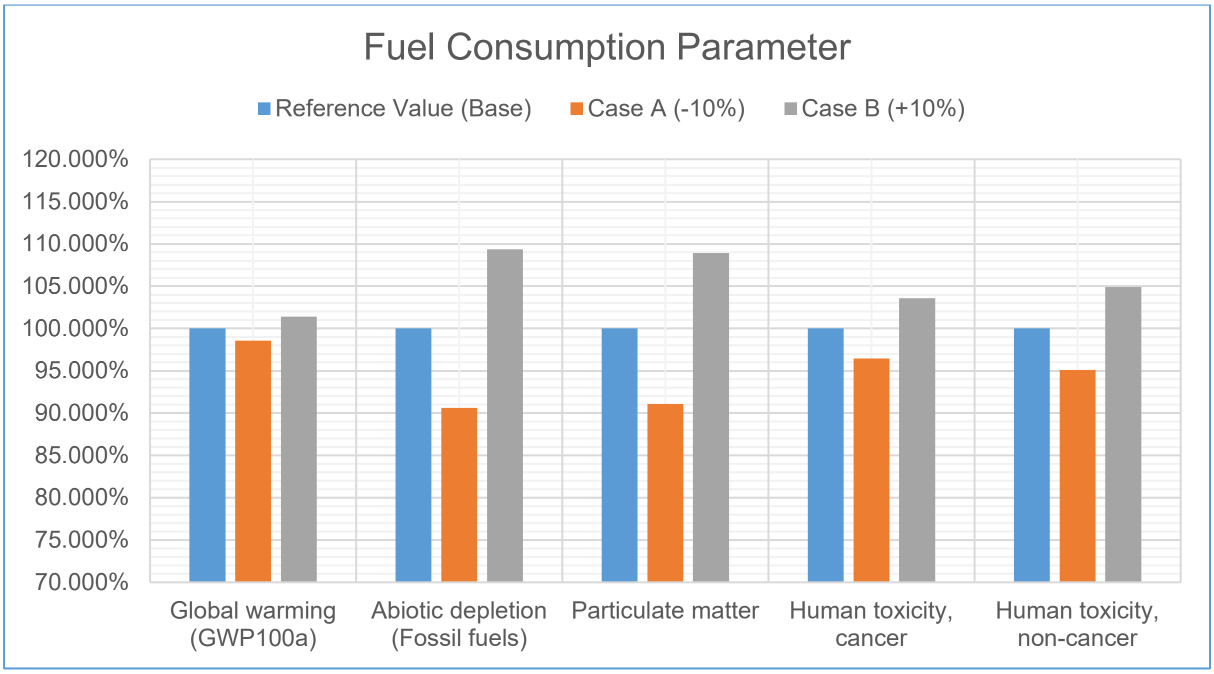


**Figure I.1: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Fuel Consumption Parameter)**

| Impact category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.071222159 | 0.059773538 | 10 | -8 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.8483861 | 0.71237587 | 10 | -8 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 9.00E-06 | 7.69E-06 | 9 | -7 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.14E-10 | 1.21E-10 | -2 | 3 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 7.25E-10 | 7.27E-10 | 0 | 1 |

**Table I.2: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Occupancy Rate Parameter)**

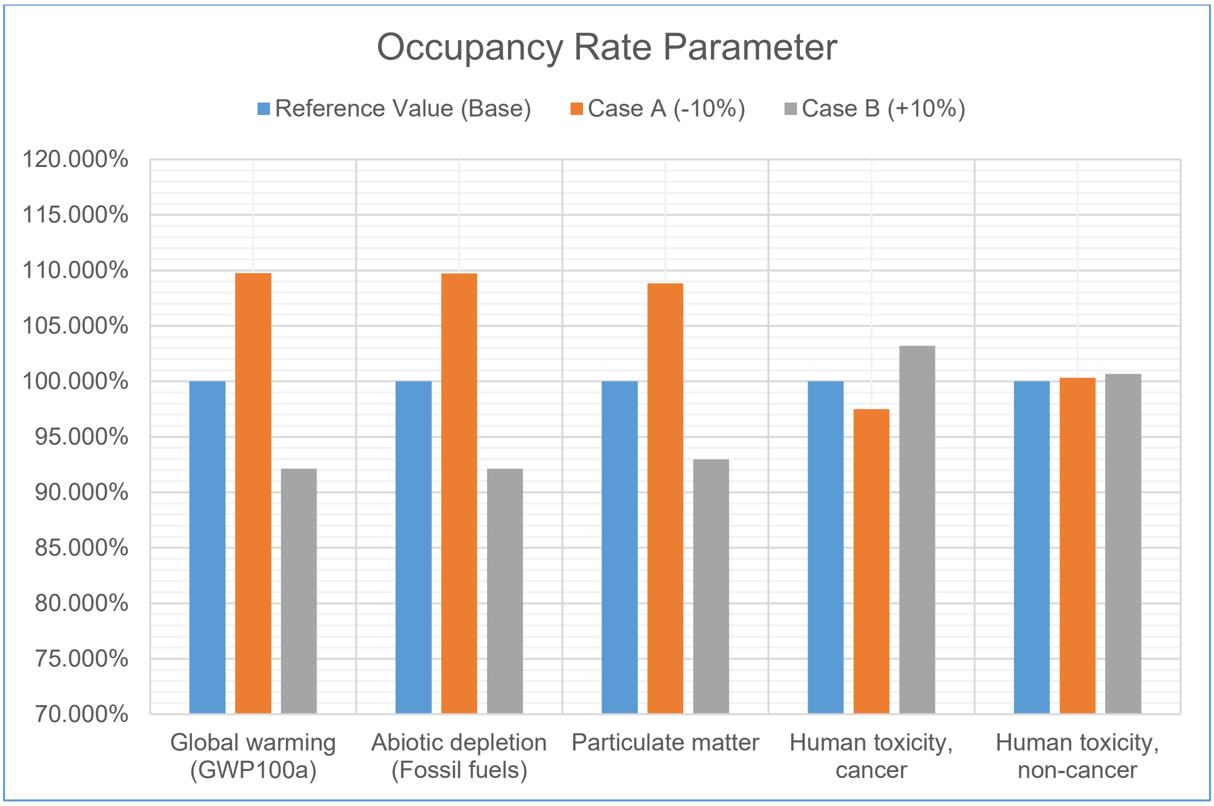


**Figure I.2: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Occupancy Rate Parameter)**

| Impact category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.064720793 | 0.065047494 | 0 | 0 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.77101796 | 0.77513969 | 0 | 0 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 8.21E-06 | 8.33E-06 | -1 | 1 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.10E-10 | 1.24E-10 | -6 | 6 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 6.99E-10 | 7.46E-10 | -3 | 3 |

Table I.3: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Vehicle Manufacture Parameter)

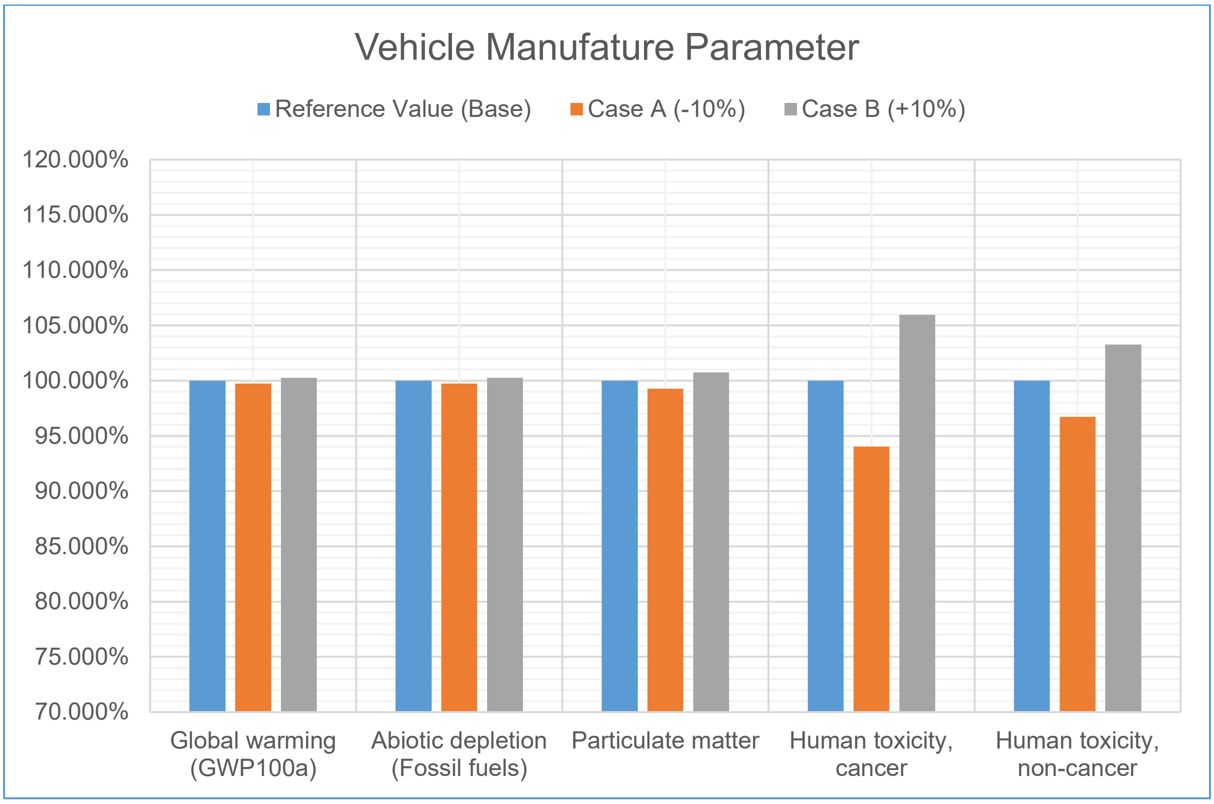


Figure I.3: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Vehicle Manufacture Parameter)

| **Impact category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.064829295 | 0.064938992 | 0 | 0 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.75487155 | 0.7912861 | -2 | 2 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 8.25E-06 | 8.30E-06 | 0 | 0 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.17E-10 | 0 | 0 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 7.20E-10 | 7.24E-10 | 0 | 0 |

**Table I.4: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Crude Oil Extraction Parameter)**

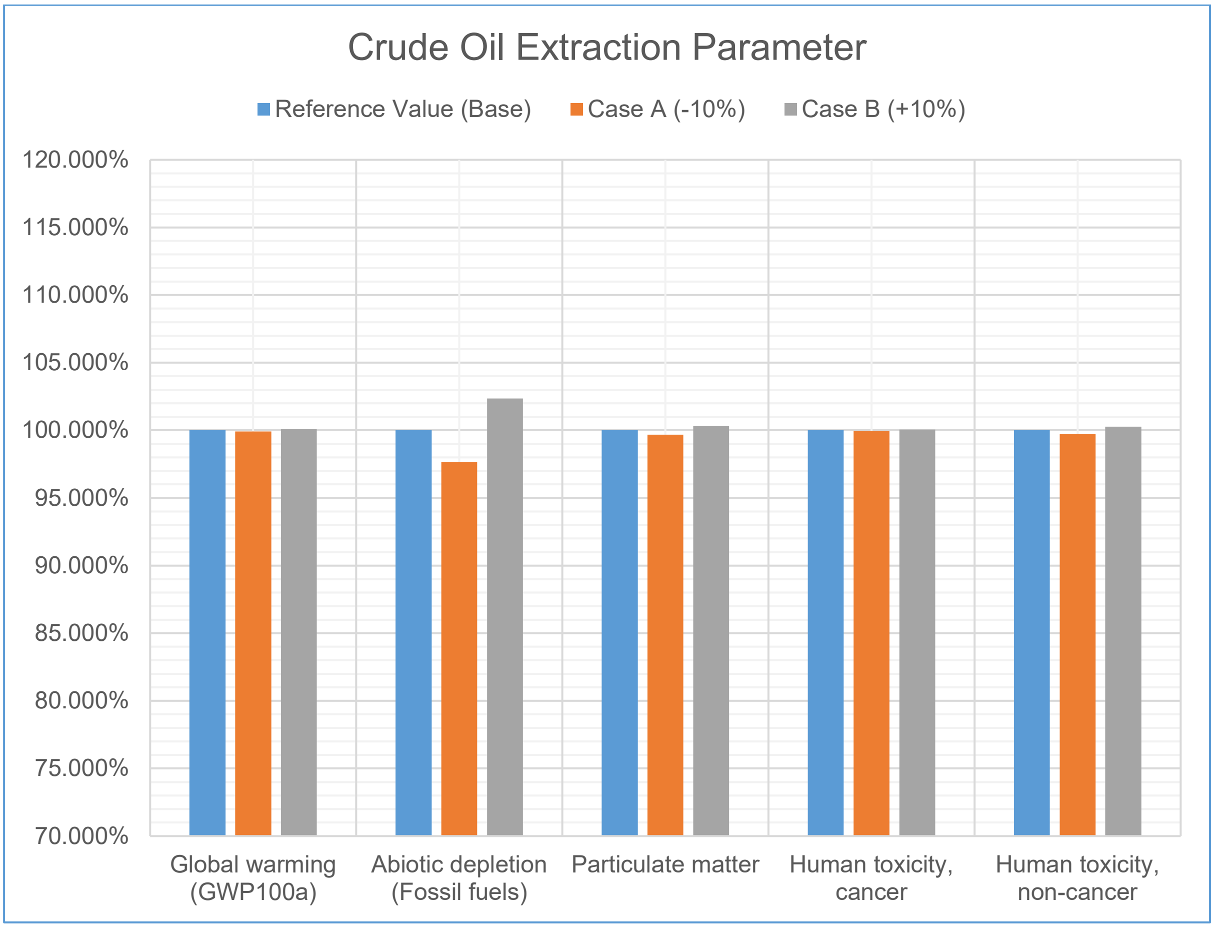


**Figure I.4: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Crude Oil Extraction Parameter)**

| Impact category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.06444583 | 0.065322456 | -1 | 1 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.71043349 | 0.83572415 | -8 | 8 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 7.93E-06 | 8.62E-06 | -4 | 4 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.14E-10 | 1.20E-10 | -3 | 3 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 7.02E-10 | 7.43E-10 | -3 | 3 |

**Table I.5: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (crude oil refining parameter)**

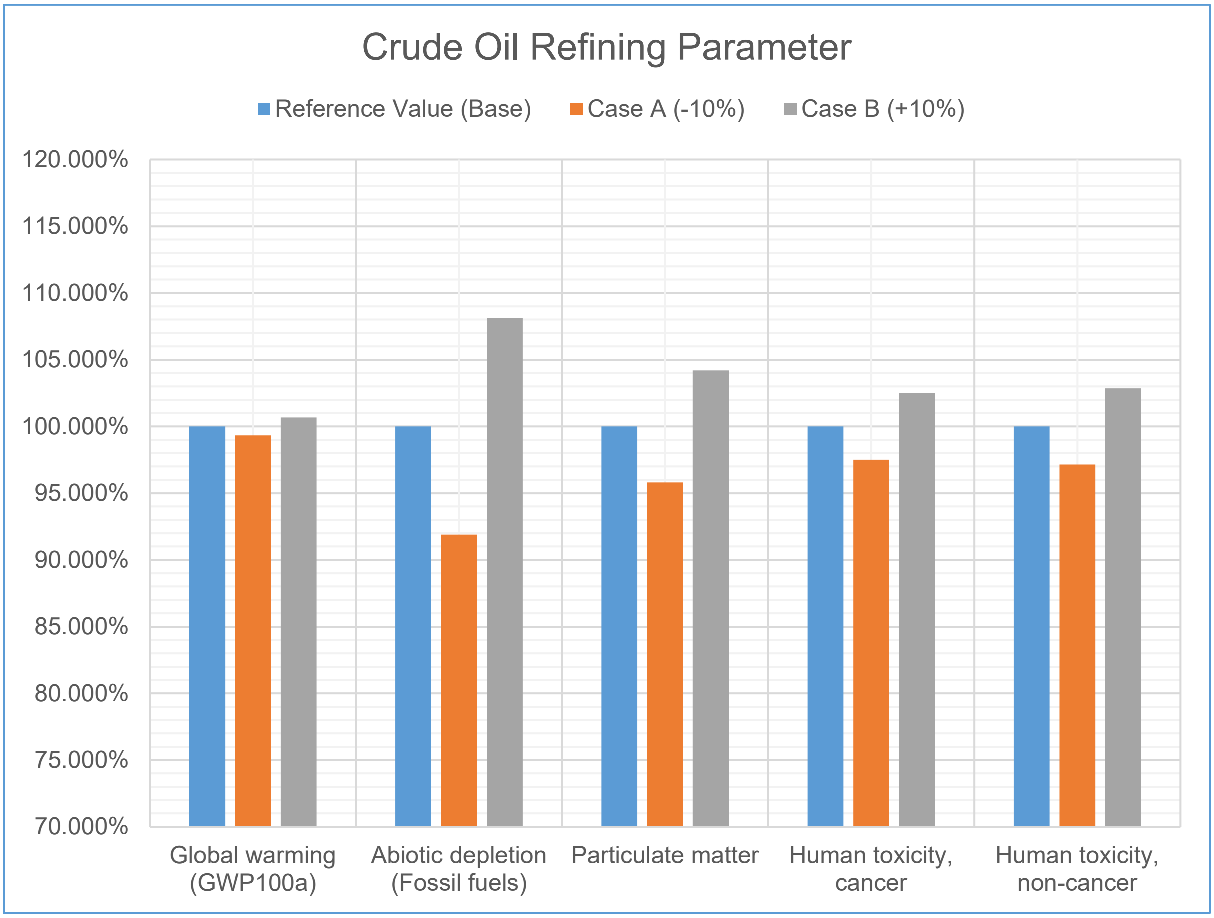


**Figure I.5: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (crude oil refining parameter)**

| **Impact category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.064639065 | 0.065129222 | 0 | 0 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.77012479 | 0.77603286 | 0 | 0 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 8.24E-06 | 8.30E-06 | 0 | 0 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.18E-10 | 0 | 0 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 7.09E-10 | 7.36E-10 | -2 | 2 |

Table I.6: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Vehicle Maintenance Parameter)

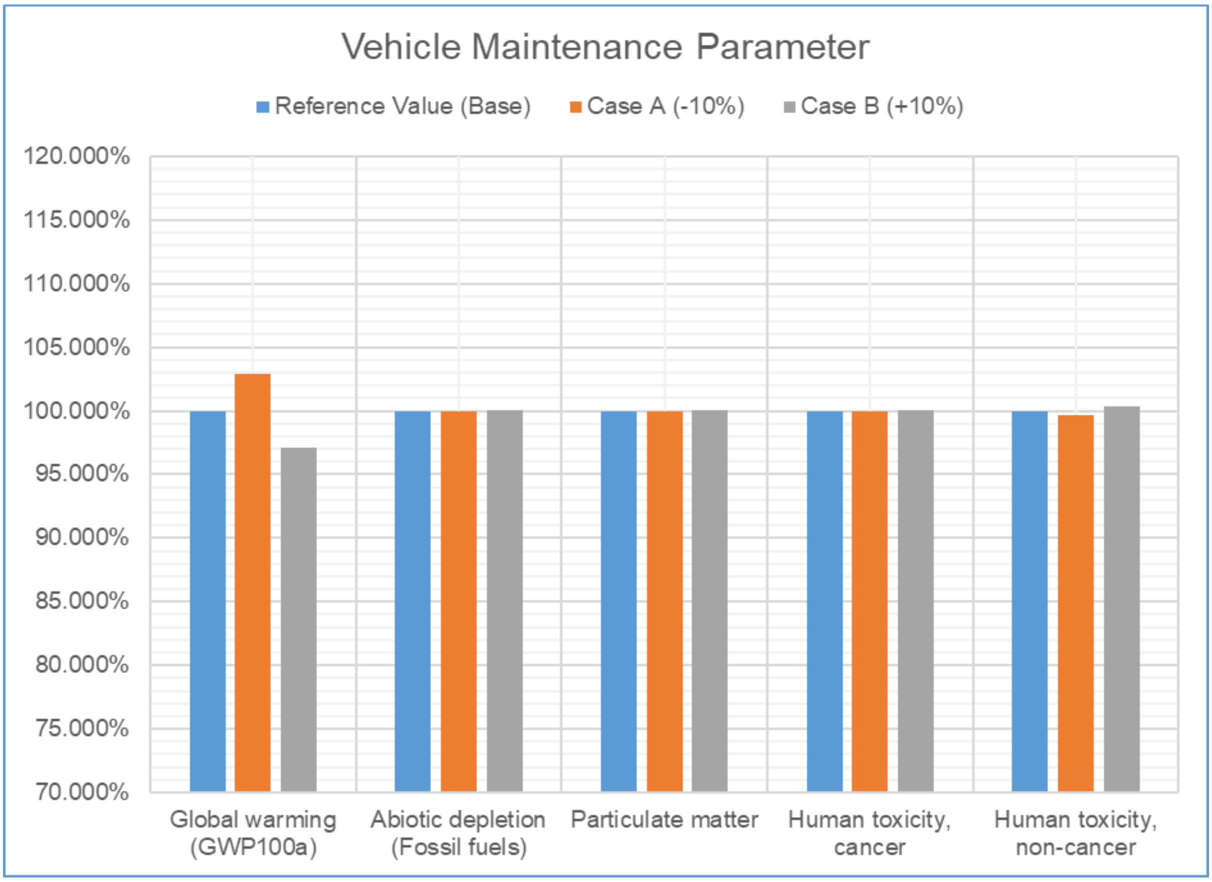


Figure I.6: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Vehicle Maintenance Parameter)

| **Impact category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg/pkm)** | 0.064884143 | 0.064879835 | 0.064888452 | -0.01 | 0.01 |
| **Abiotic depletion (Fossil fuels) (MJ/pkm)** | 0.77307882 | 0.77307723 | 0.77308041 | 0.00 | 0.00 |
| **Particulate matter(kg/pkm)** | 8.27E-06 | 8.27E-06 | 8.27E-06 | 0.00 | 0.00 |
| **Human toxicity, cancer(kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.17E-10 | -0.02 | 0.02 |
| **Human toxicity, non-cancer(kg/pkm)** | 7.22E-10 | 7.22E-10 | 7.22E-10 | -0.01 | 0.01 |

**Table I.7: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Vehicle Disposal Parameter)**

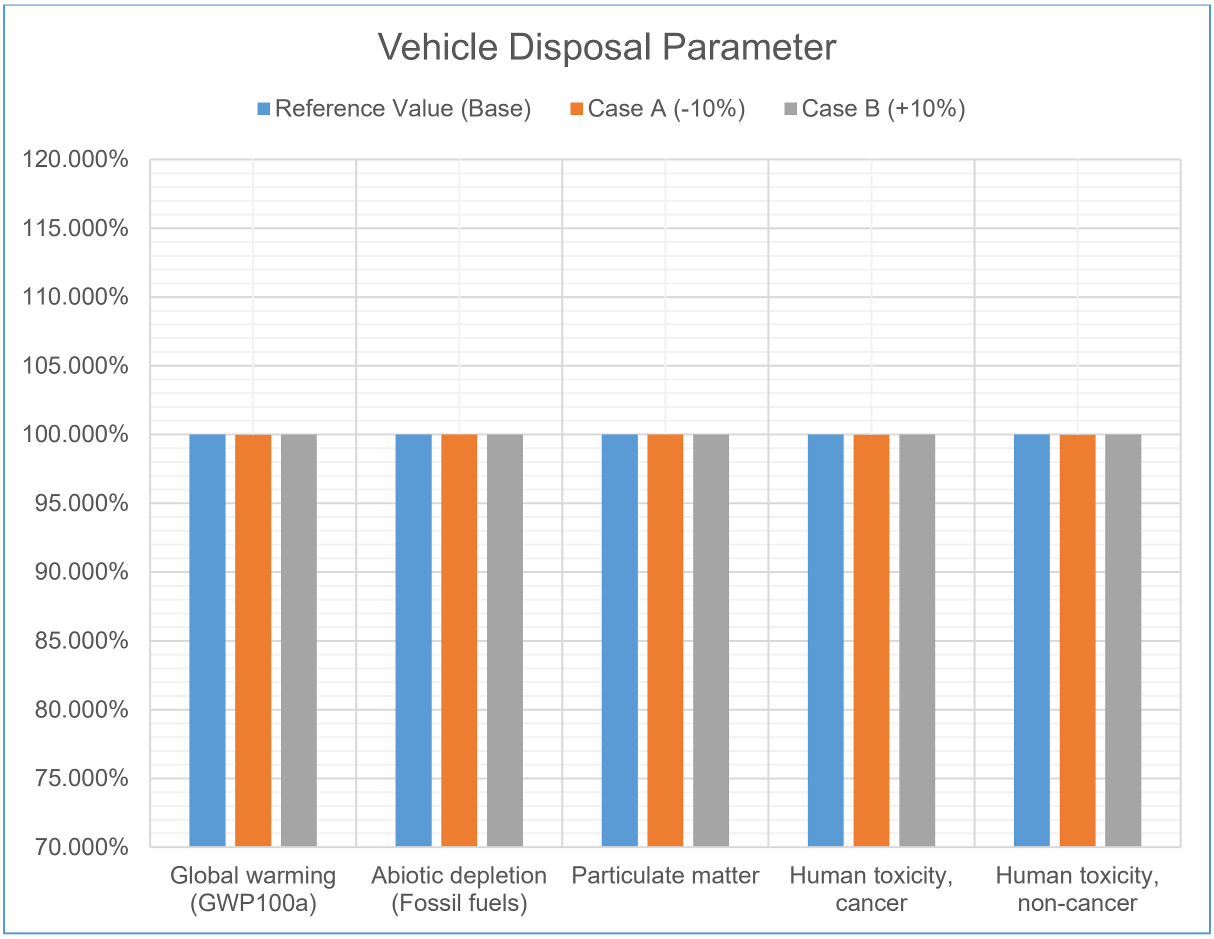


**Figure I.7: Sensitivity Analysis for LCA of 1902/ LSD Scania Buses (Vehicle Disposal Parameter)**

**1905/Micro Hybrid Buses**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.062546837 | 0.068636322 | 0.057638611 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.82669379 | 0.6947047 | 10 | -8 |
| **Particulate Matter(kg/pkm)** | 8.11E-06 | 8.81E-06 | 7.55E-06 | 9 | -7 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.19E-10 | 1.15E-10 | 1.23E-10 | -3 | 3 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 6.89E-10 | 6.93E-10 | 6.93E-10 | 1 | 0 |

**Table I.8: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Occupancy Rate Parameter)**

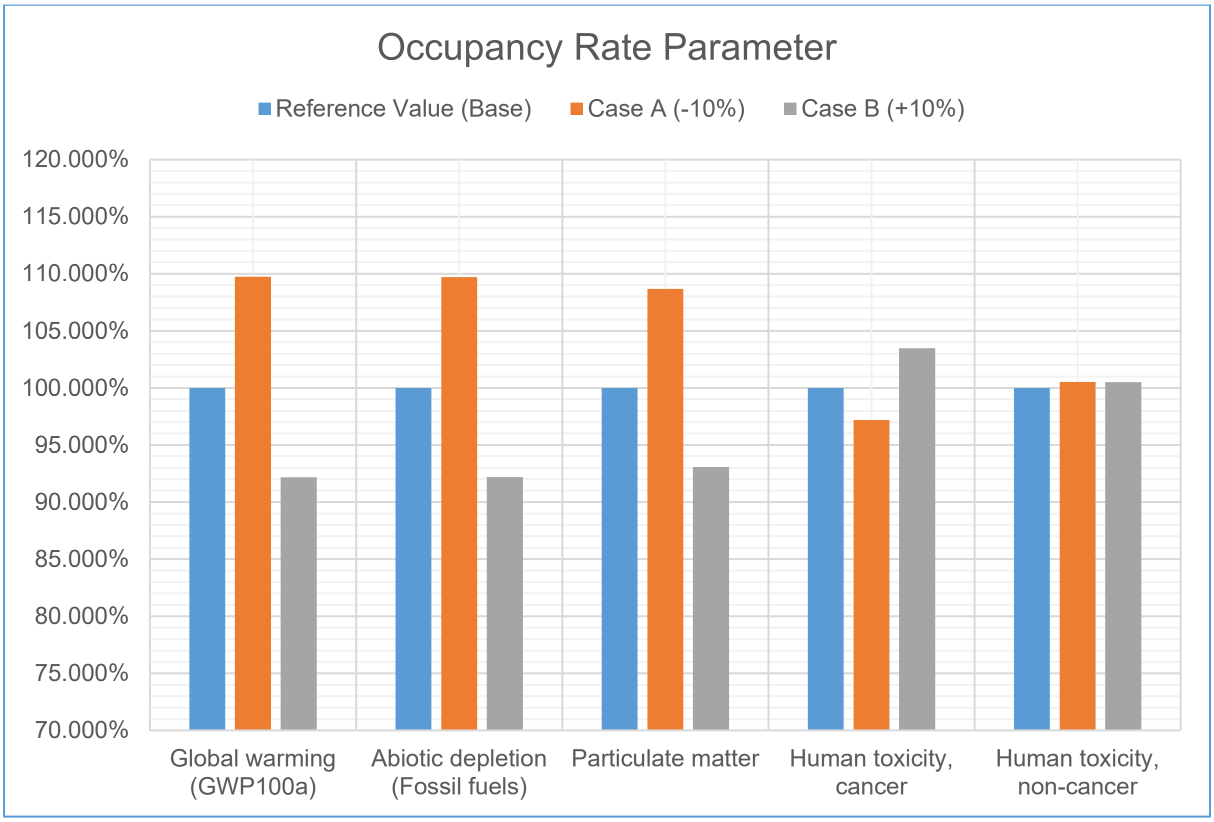


**Figure I.8: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Occupancy Rate Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.062546837 | 0.062380444 | 0.062713229 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.75150518 | 0.75568686 | 0 | 0 |
| **Particulate Matter(kg/pkm)** | 8.11E-06 | 8.04E-06 | 8.17E-06 | -1 | 1 |
| **Human Toxicity, Cancer(kg/pkm)** | 1.19E-10 | 1.11E-10 | 1.26E-10 | -6 | 6 |
| **Human Toxicity, Non-Cancer(kg/pkm)** | 6.89E-10 | 6.64E-10 | 7.15E-10 | -4 | 4 |

**Table I.9: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Vehicle Manufacture Parameter)**

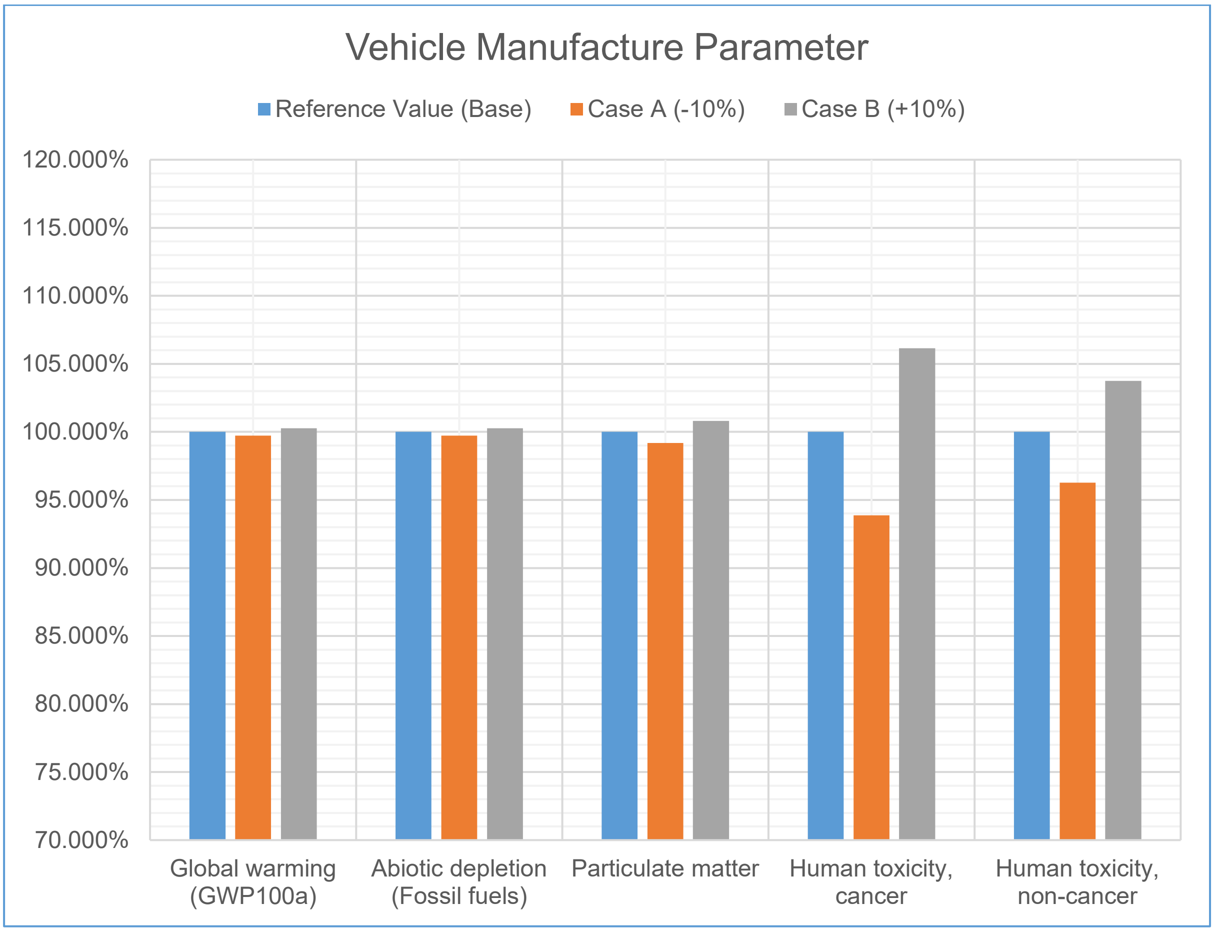


**Figure I.9: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.062546837 | 0.062310573 | 0.0627831 | -0.4 | 0.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.75065149 | 0.75654055 | -0.4 | 0.4 |
| **Particulate Matter (kg/pkm)** | 8.11E-06 | 8.08E-06 | 8.14E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.19E-10 | 1.18E-10 | 1.19E-10 | -0.4 | 0.4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.89E-10 | 6.81E-10 | 6.98E-10 | -1.3 | 1.3 |

**Table I.10: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Vehicle Maintenance Parameter)**

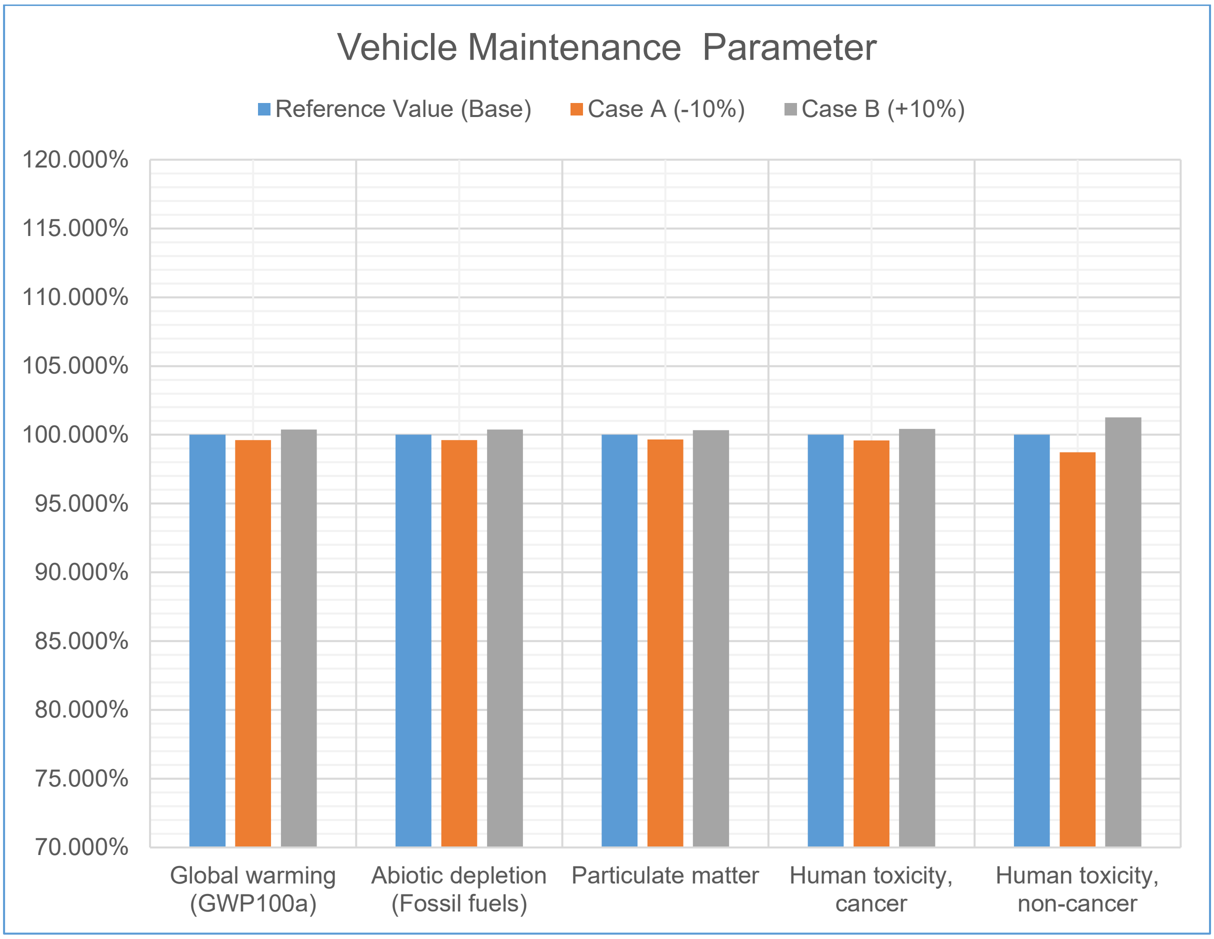


**Figure I.10: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.062546837 | 0.069043768 | 0.057231166 | 10.4 | -8.5 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.83173148 | 0.68966701 | 10.4 | -8.5 |
| **Particulate Matter (kg/pkm)** | 8.11E-06 | 8.91E-06 | 7.46E-06 | 9.8 | -8.0 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.19E-10 | 1.23E-10 | 1.15E-10 | 3.8 | -3.1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.89E-10 | 7.27E-10 | 6.58E-10 | 5.5 | -4.5 |

**Table I.11: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Kilometres Travelled Parameter)**

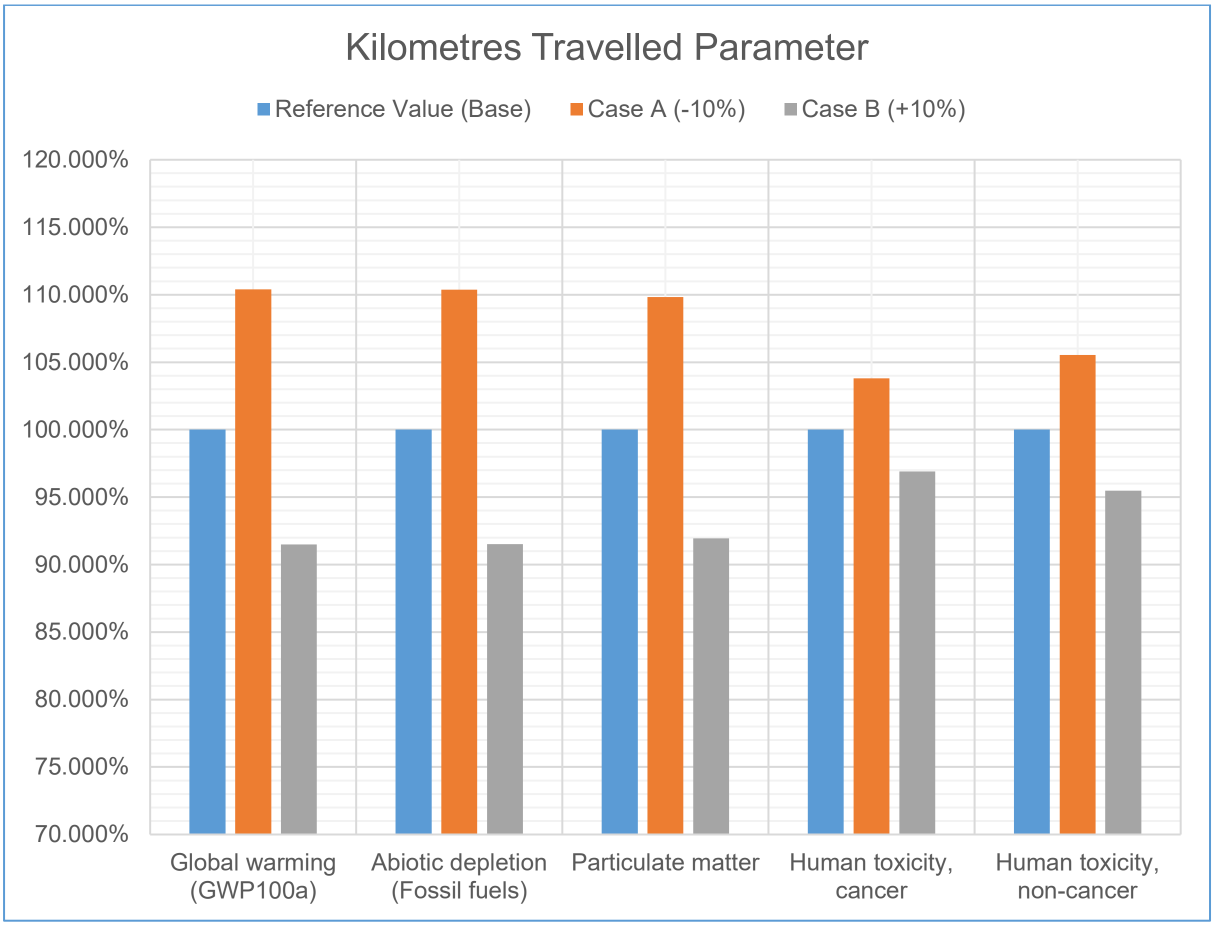


**Figure I.11: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.062546837 | 0.061655023 | 0.06343865 | -1.4 | 1.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.68327411 | 0.82391794 | -9.3 | 9.3 |
| **Particulate Matter (kg/pkm)** | 8.11E-06 | 7.39E-06 | 8.83E-06 | -8.9 | 8.9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.19E-10 | 1.15E-10 | 1.23E-10 | -3.4 | 3.4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.89E-10 | 6.55E-10 | 7.24E-10 | -5.0 | 5.0 |

**Table I.12: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Fuel Consumption Parameter)**

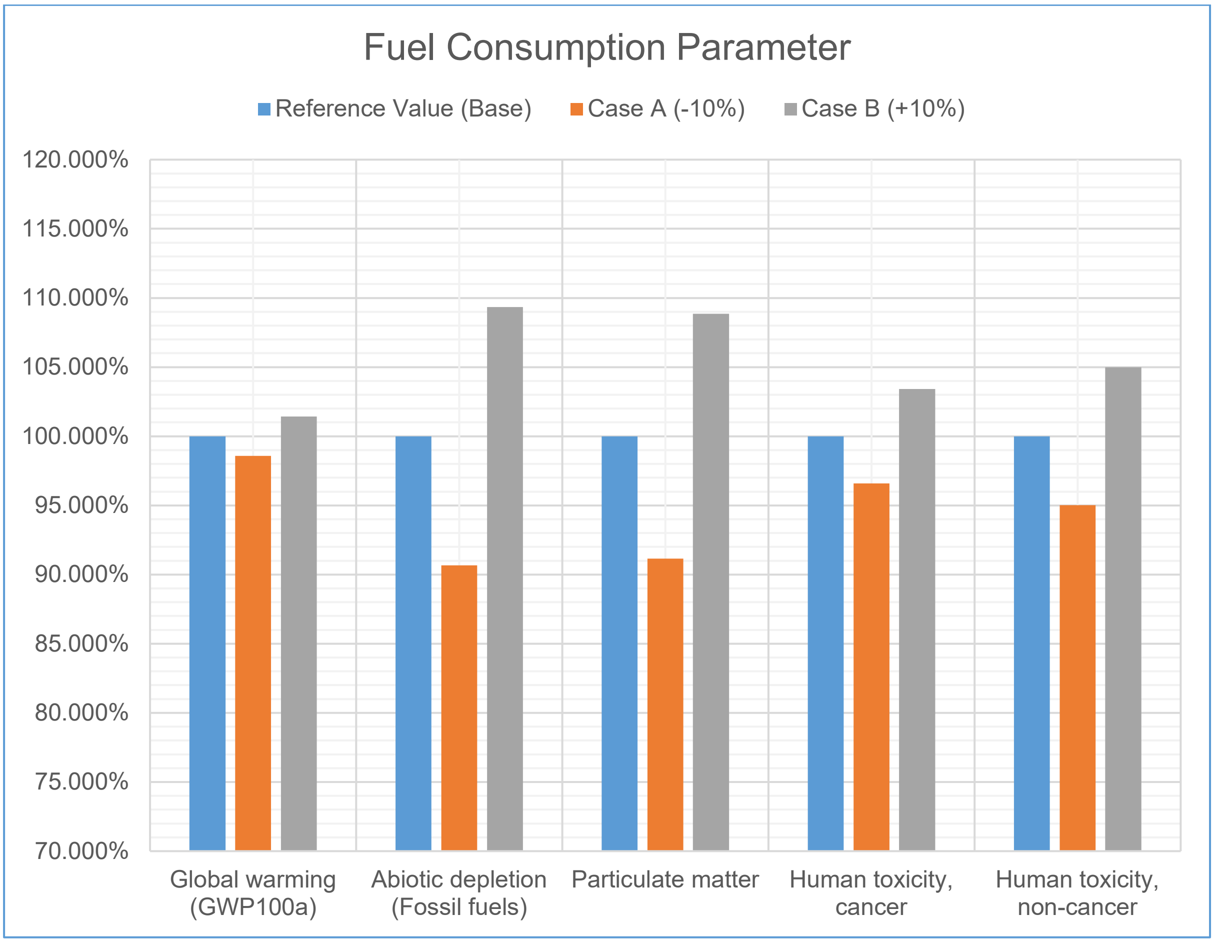


**Figure I.12: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Fuel Consumption Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.062546837 | 0.062542046 | 0.062551627 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.75359371 | 0.75359834 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 8.11E-06 | 8.11E-06 | 8.11E-06 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.19E-10 | 1.19E-10 | 1.19E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.89E-10 | 6.89E-10 | 6.89E-10 | -0.01 | 0.01 |

**Table I.13: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Vehicle Disposal Parameter)**

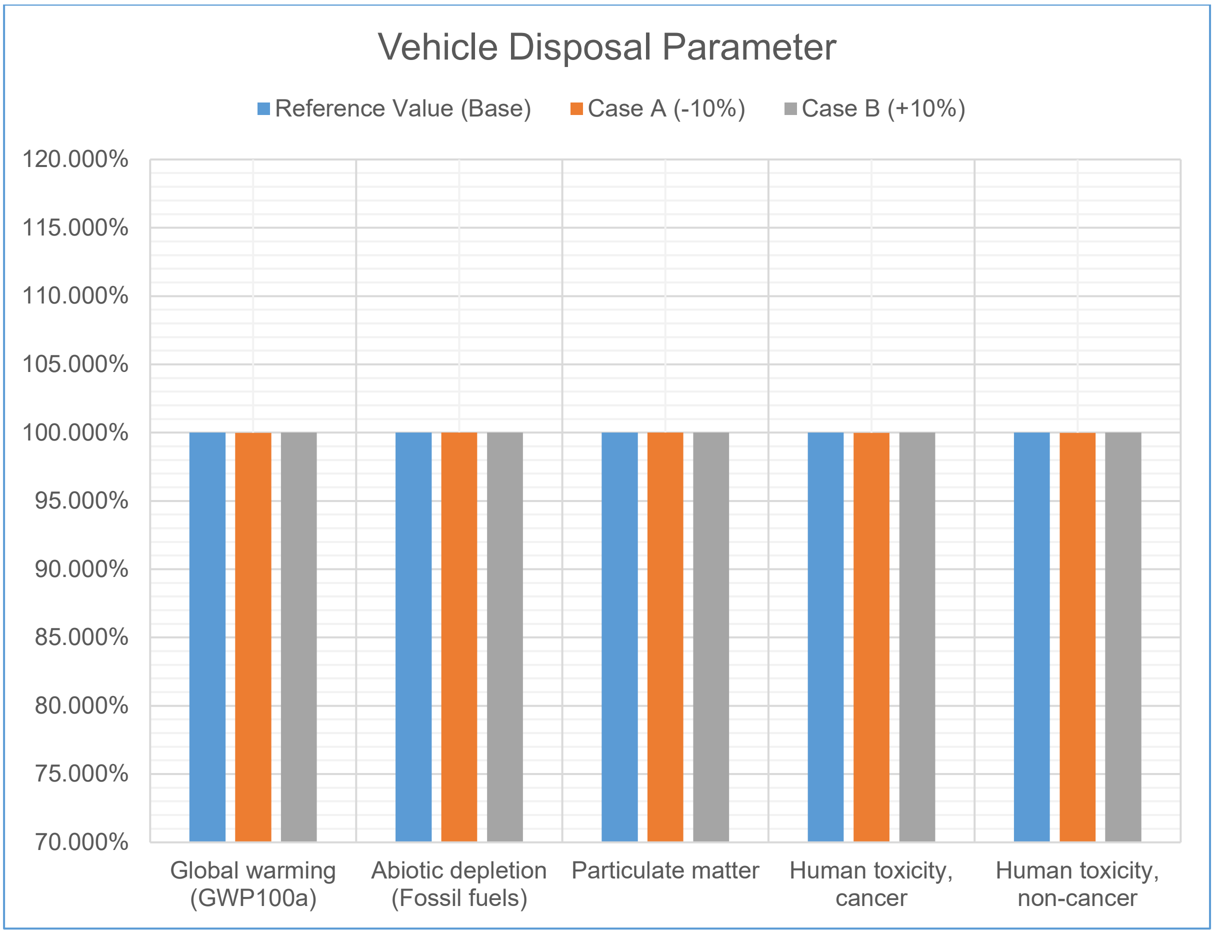


**Figure I.13: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Vehicle Disposal Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.062546837 | 0.062493482 | 0.062600191 | -0.09 | 0.09 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.75359602 | 0.73588478 | 0.77130726 | -2.35 | 2.35 |
| **Particulate matter (kg/pkm)** | 8.11E-06 | 8.08E-06 | 8.13E-06 | -0.33 | 0.33 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.19E-10 | 1.19E-10 | 1.19E-10 | -0.05 | 0.05 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.89E-10 | 6.87E-10 | 6.91E-10 | -0.27 | 0.27 |

**Table I.14: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Crude Oil Extraction Parameter)**

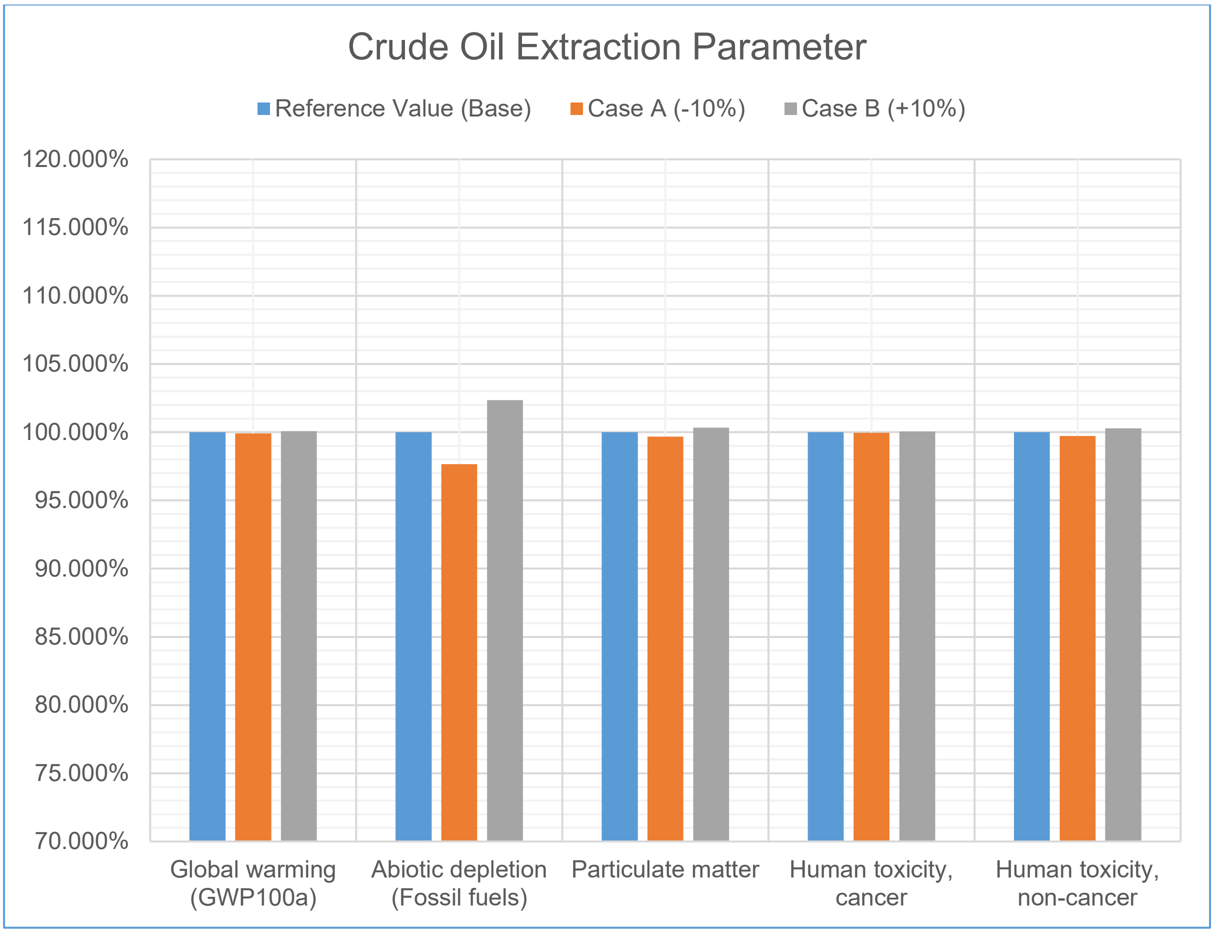


**Figure I.14: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Crude Oil Extraction Parameter)**

| Impact Category | Reference value (base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.062546837 | 0.062120465 | 0.062973208 | -0.68 | 0.68 |
| **Abiotic Depletion (Fossil fuels) (MJ/pkm)** | 0.75359602 | 0.69265737 | 0.81453467 | -8.09 | 8.09 |
| **Particulate Matter (kg/pkm)** | 8.11E-06 | 7.77E-06 | 8.44E-06 | -4.16 | 4.16 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.19E-10 | 1.16E-10 | 1.22E-10 | -2.40 | 2.40 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 6.89E-10 | 6.69E-10 | 7.09E-10 | -2.92 | 2.92 |

**Table I.15: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Crude Oil Refining Parameter)**

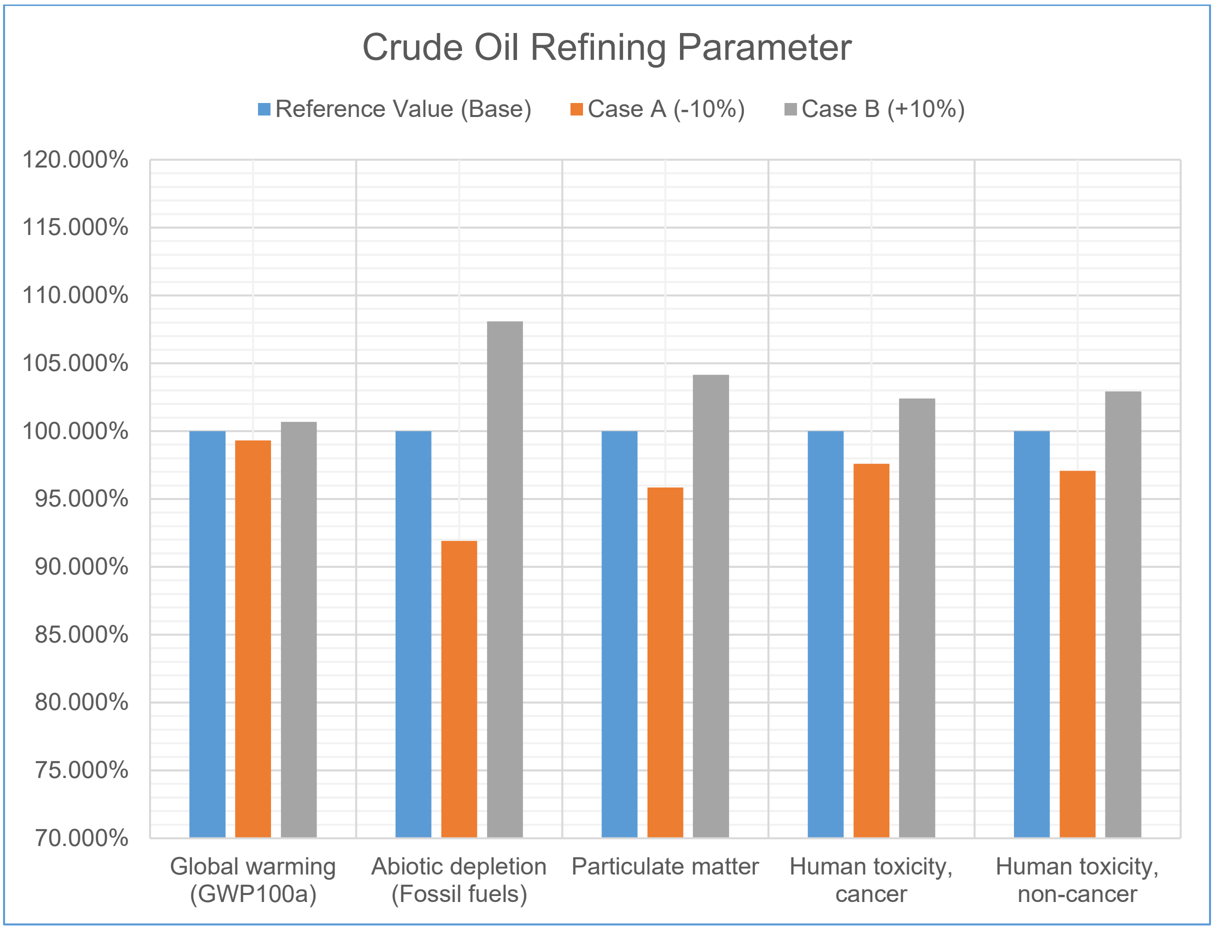


**Figure I.15: Sensitivity Analysis for LCA of 1905/Micro Hybrid Buses (Crude Oil Refining Parameter)**

**2450/ Scania LSD Buses**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.07108031 | 0.059657479 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.84660849 | 0.71092145 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 8.98E-06 | 7.68E-06 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.14E-10 | 1.21E-10 | -2 | 3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.24E-10 | 7.26E-10 | 0 | 1 |

**Table I.16: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Occupancy Rate Parameter)**

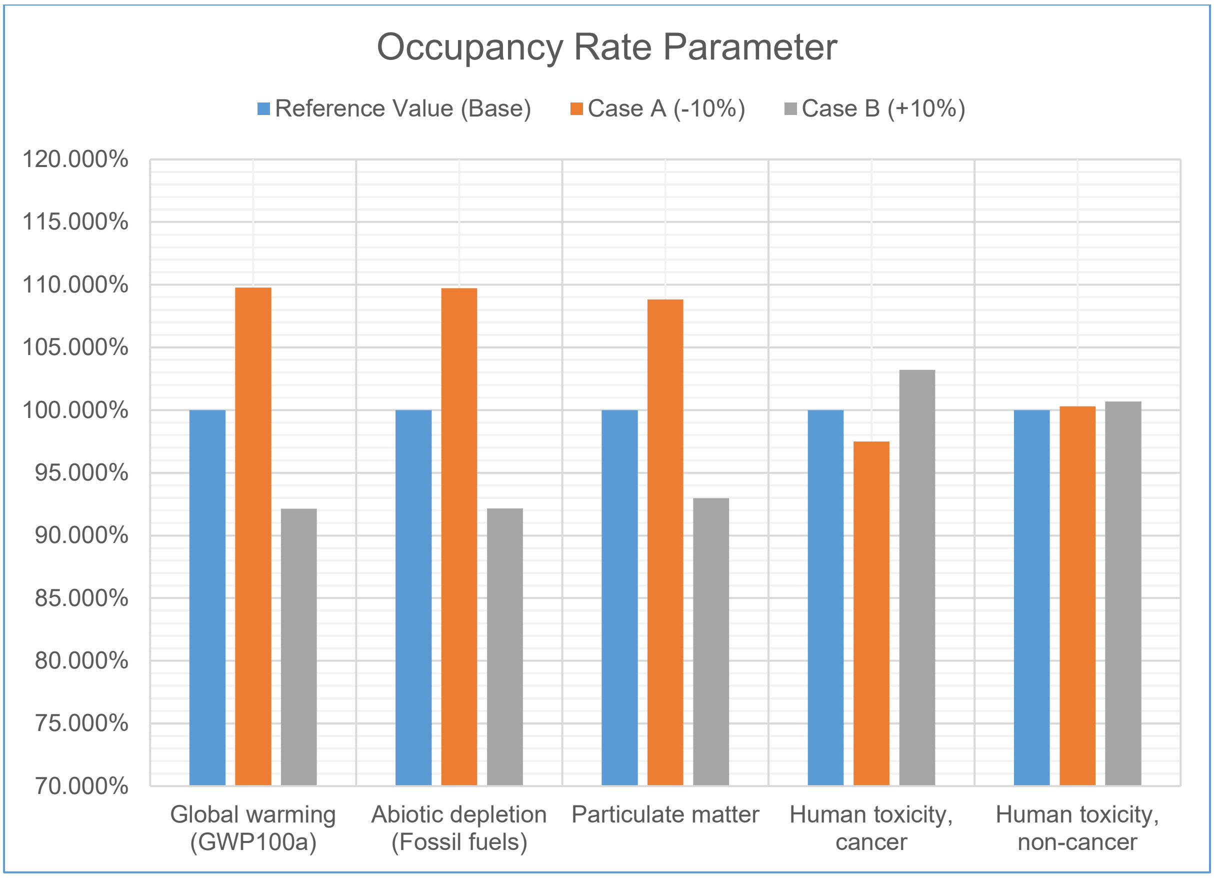


**Figure I.16: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.071493047 | 0.059244742 | 10 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.85162498 | 0.70590496 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 9.07E-06 | 7.59E-06 | 10 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.22E-10 | 1.13E-10 | 4 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.61E-10 | 6.90E-10 | 5 | -4 |

**Table I.17: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Kilometres Travelled Parameter)**

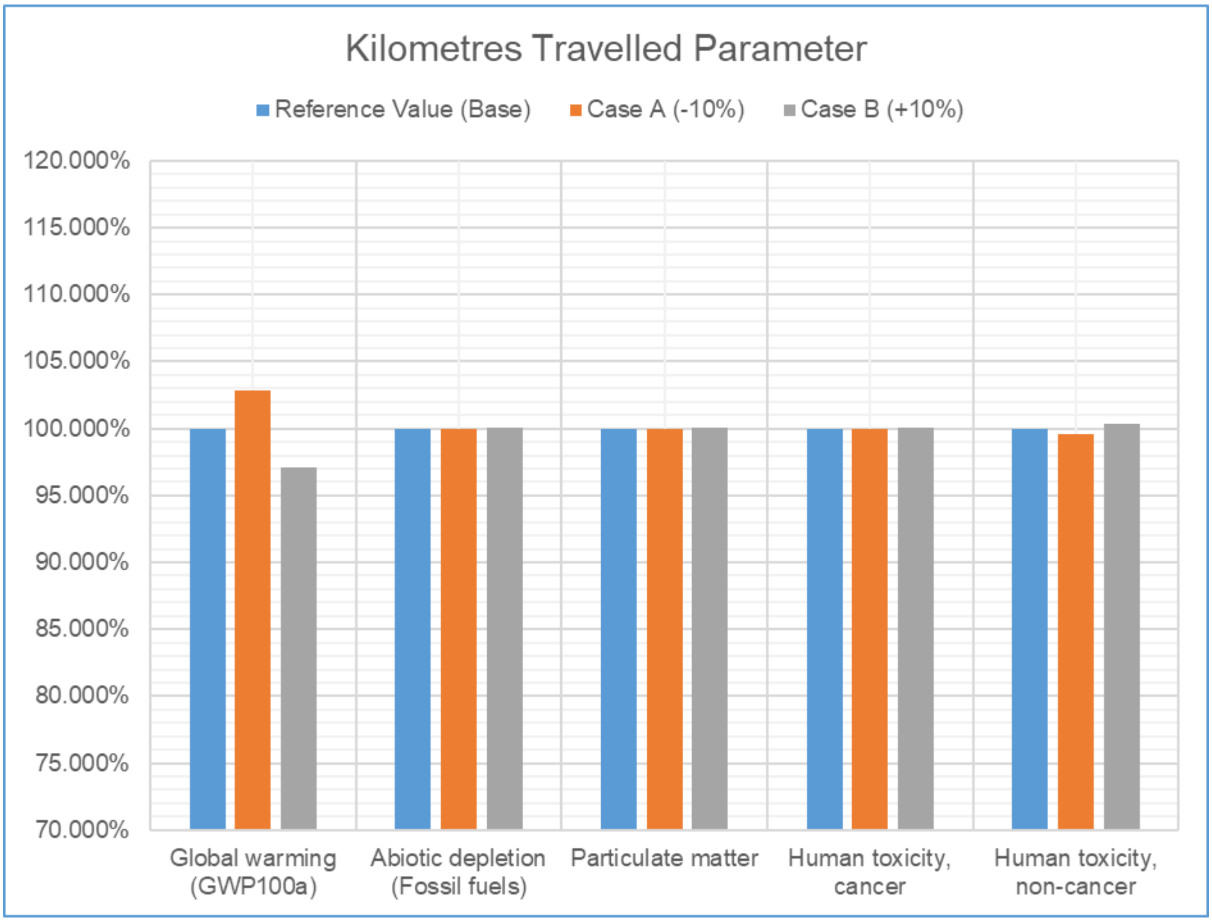


**Figure I.17: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.063841718 | 0.06567124 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.69934756 | 0.84361037 | -9 | 9 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 7.52E-06 | 8.99E-06 | -9 | 9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.13E-10 | 1.21E-10 | -4 | 4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 6.86E-10 | 7.57E-10 | -5 | 5 |

**Table I.18: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Fuel Consumption Parameter)**

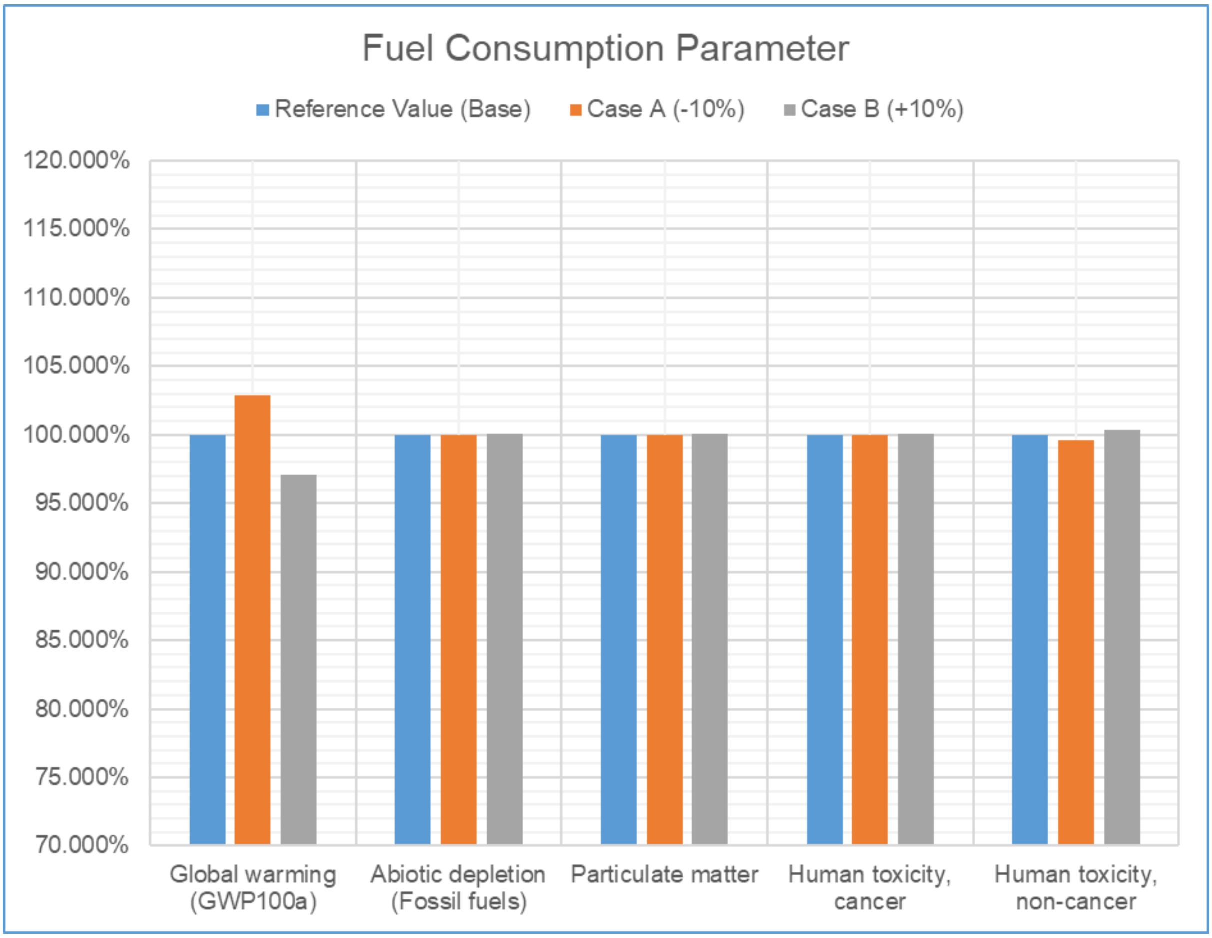


**Figure I.18: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Fuel Consumption Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.064593129 | 0.06491983 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.7694181 | 0.77353984 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 8.20E-06 | 8.32E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.10E-10 | 1.24E-10 | -6 | 6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 6.98E-10 | 7.45E-10 | -3 | 3 |

**Table I.19: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Vehicle Manufacture Parameter)**

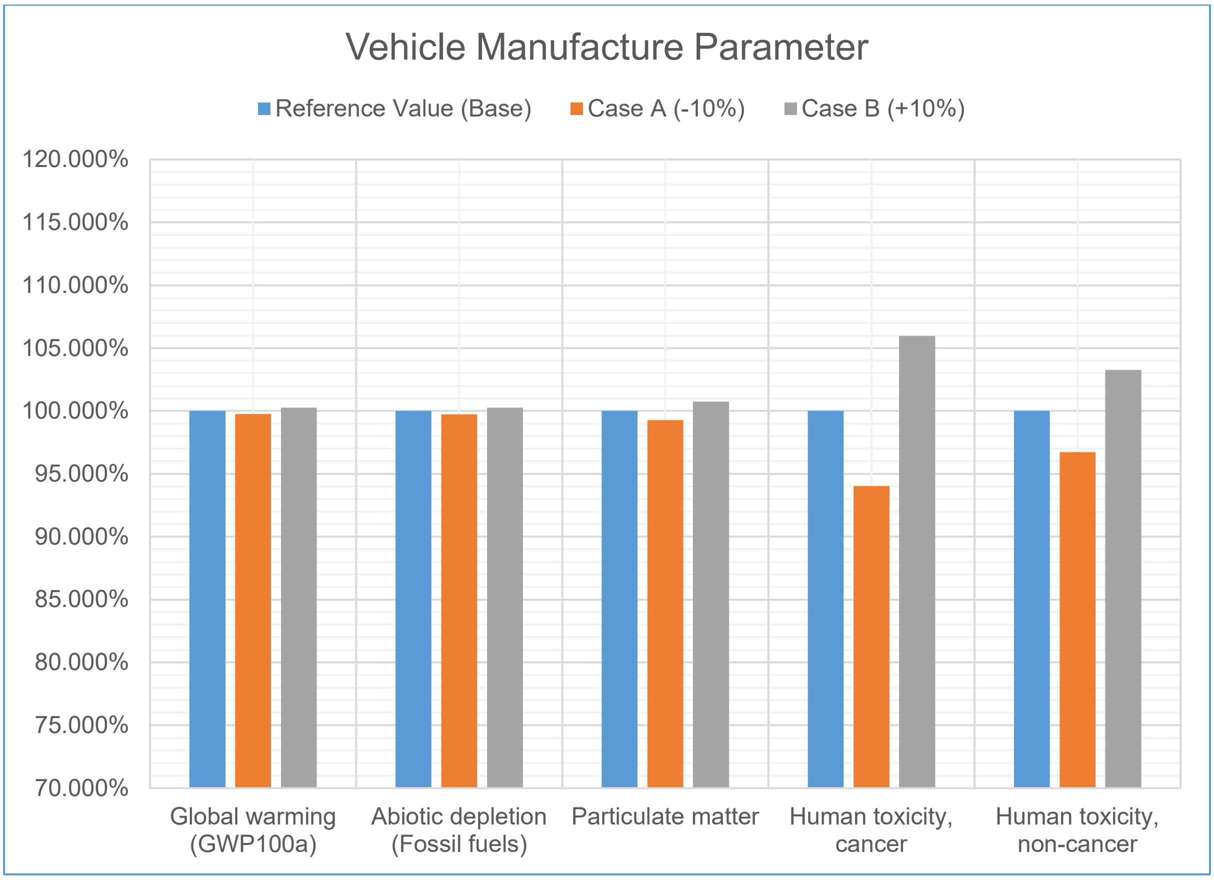


**Figure I.19: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.064701752 | 0.064811206 | -0.1 | 0.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.75331199 | 0.78964595 | -2.4 | 2.4 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 8.23E-06 | 8.28E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.17E-10 | -0.1 | 0.1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.20E-10 | 7.23E-10 | -0.3 | 0.3 |

**Table I.20: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Crude Oil Extraction Parameter)**

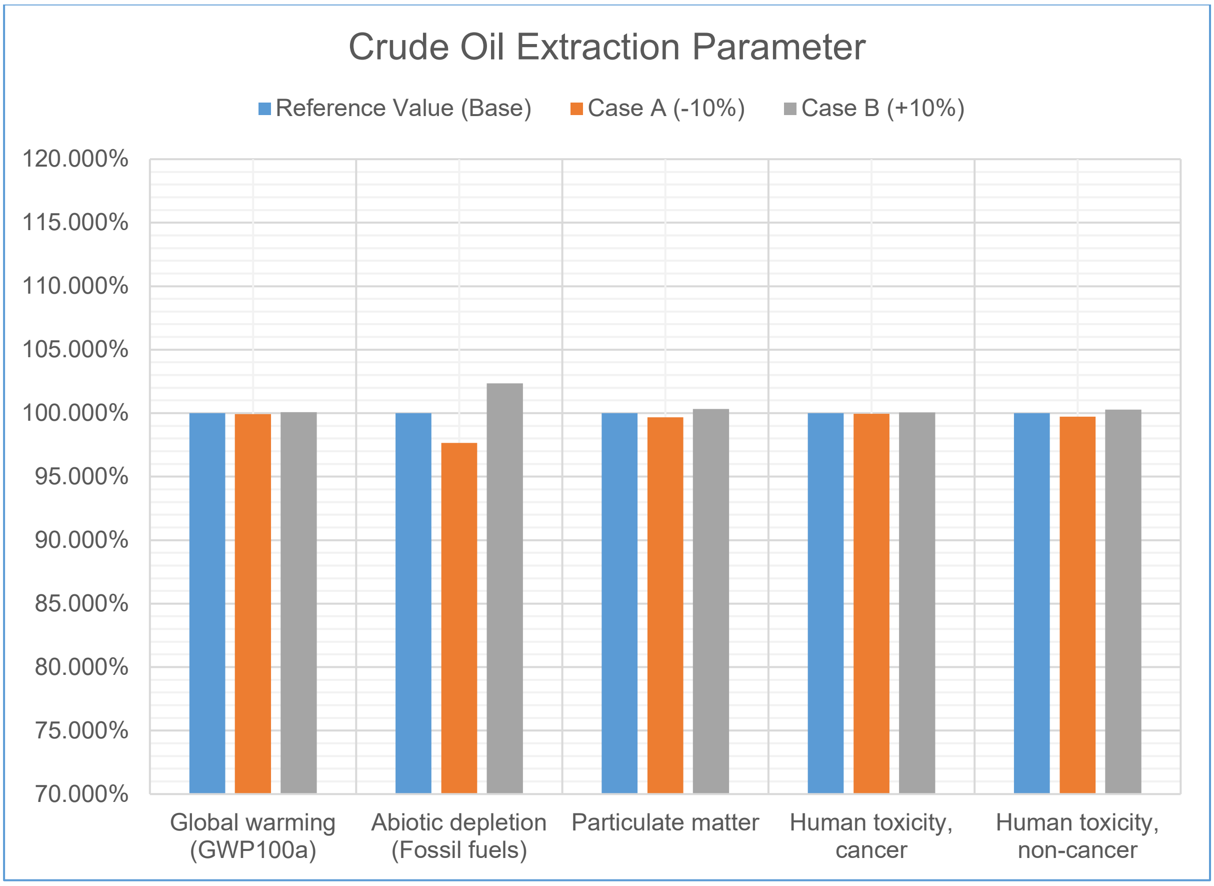


**Figure I.20: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Crude Oil Extraction Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.064319136 | 0.065193822 | -0.7 | 0.7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.70897228 | 0.83398566 | -8.1 | 8.1 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 7.91E-06 | 8.60E-06 | -4.2 | 4.2 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.14E-10 | 1.20E-10 | -2.5 | 2.5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.01E-10 | 7.42E-10 | -2.9 | 2.9 |

**Table I.21: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Crude Oil Refining Parameter)**

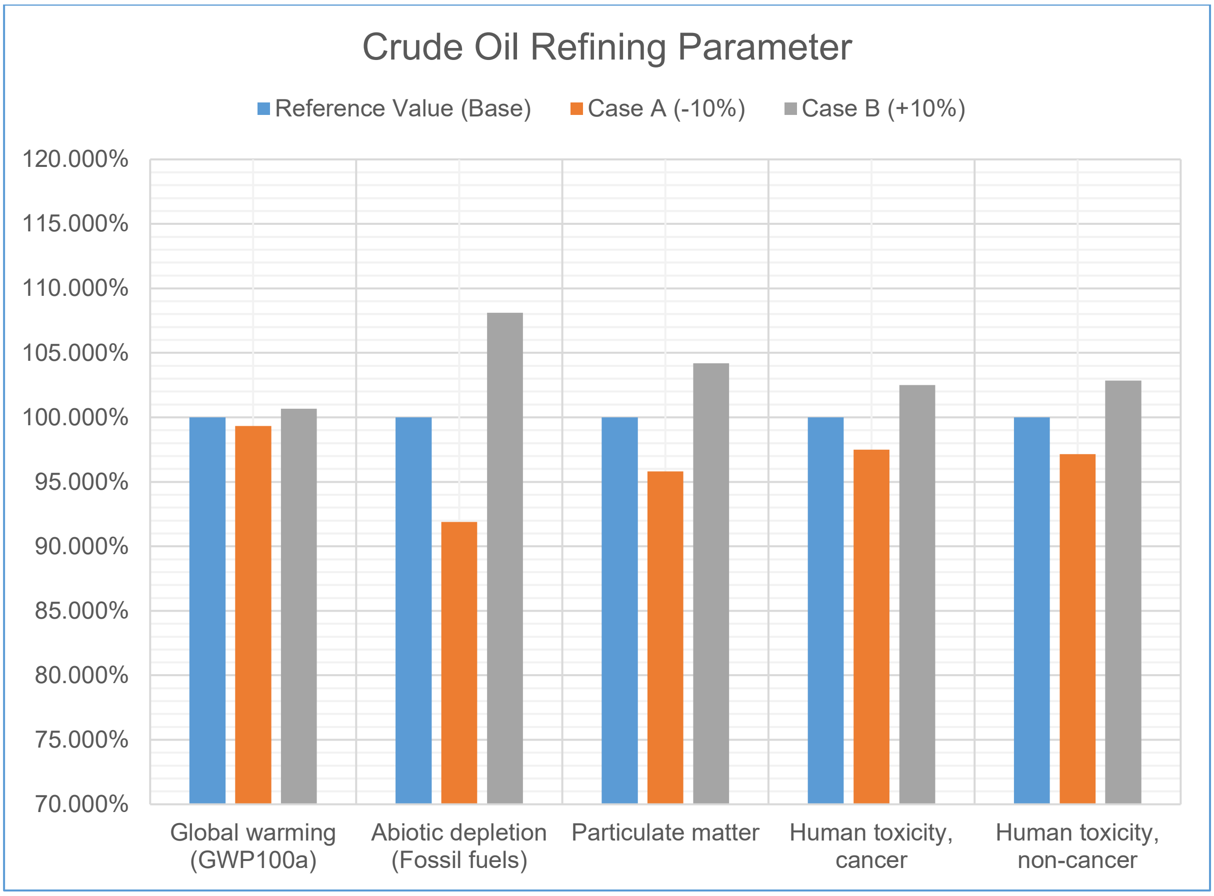


**Figure I.21: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.064511401 | 0.065001558 | -0.4 | 0.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.76852494 | 0.774433 | -0.4 | 0.4 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 8.23E-06 | 8.28E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.18E-10 | -0.5 | 0.5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.08E-10 | 7.35E-10 | -1.8 | 1.8 |

**Table I.22: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Vehicle Maintenance Parameter)**

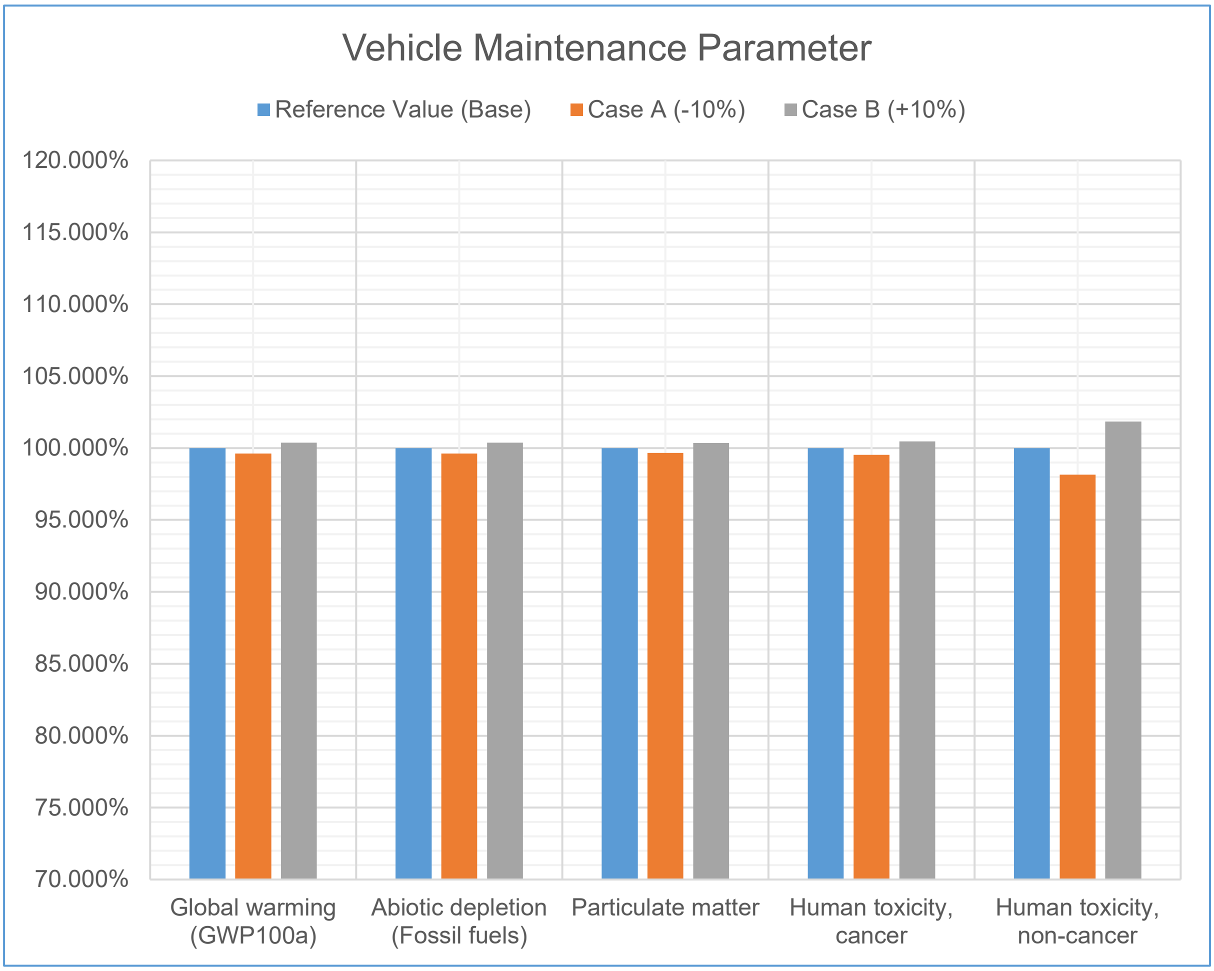


**Figure I.22: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.064756479 | 0.064752171 | 0.064760788 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.77147897 | 0.77147738 | 0.77148056 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 8.26E-06 | 8.26E-06 | 8.26E-06 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.17E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.22E-10 | 7.21E-10 | 7.22E-10 | -0.01 | 0.01 |

**Table I.23: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Vehicle Disposal Parameter)**

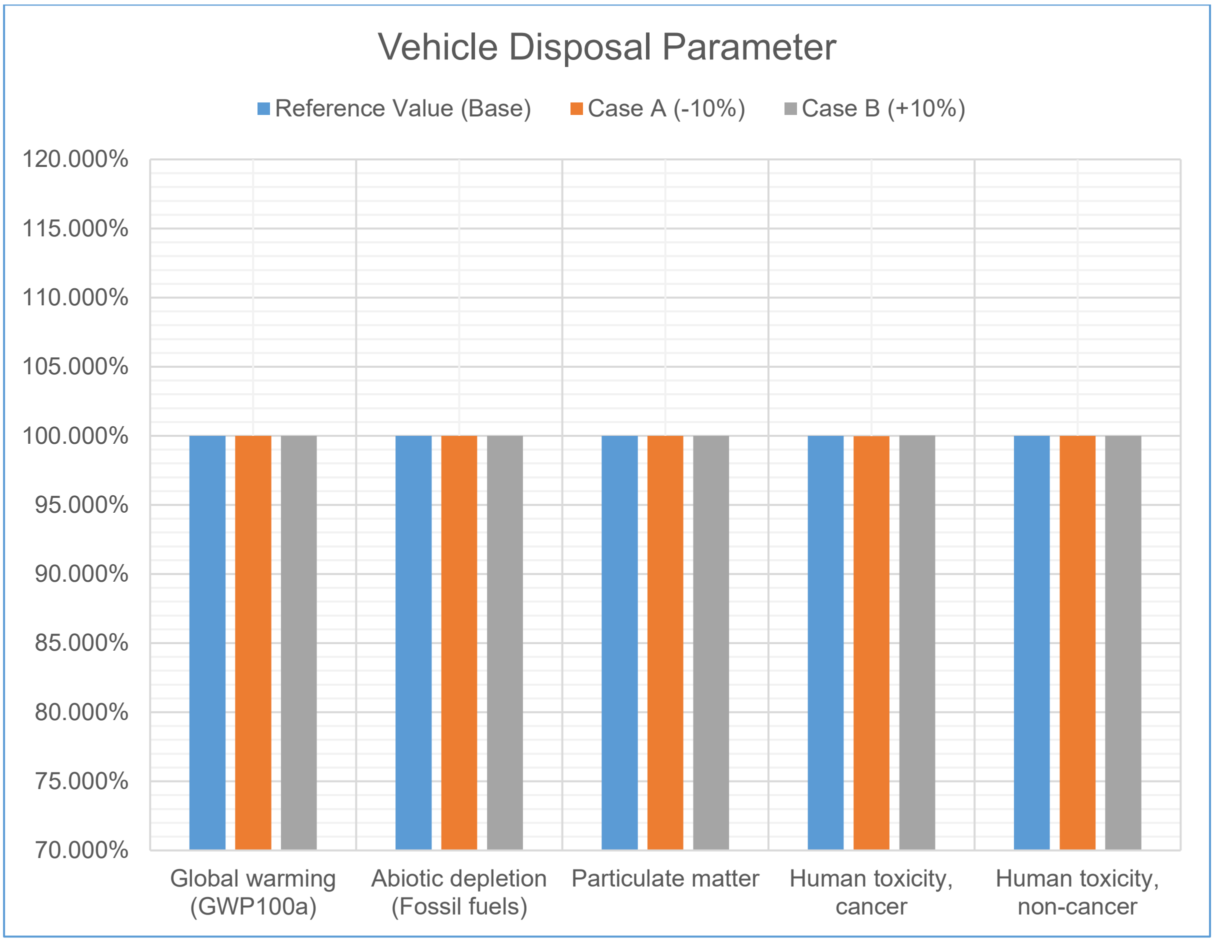


**Figure I.23: Sensitivity Analysis for LCA of 2450/LSD Scania Buses (Vehicle Disposal Parameter)**

## 2451/ Volvo LSD Buses

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.07013933 | 0.058887586 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.8355137 | 0.7018439 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 8.87E-06 | 7.58E-06 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.14E-10 | 1.20E-10 | -3 | 3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 7.18E-10 | 7.22E-10 | 0 | 1 |

**Table I.24: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Occupancy Rate Parameter)**

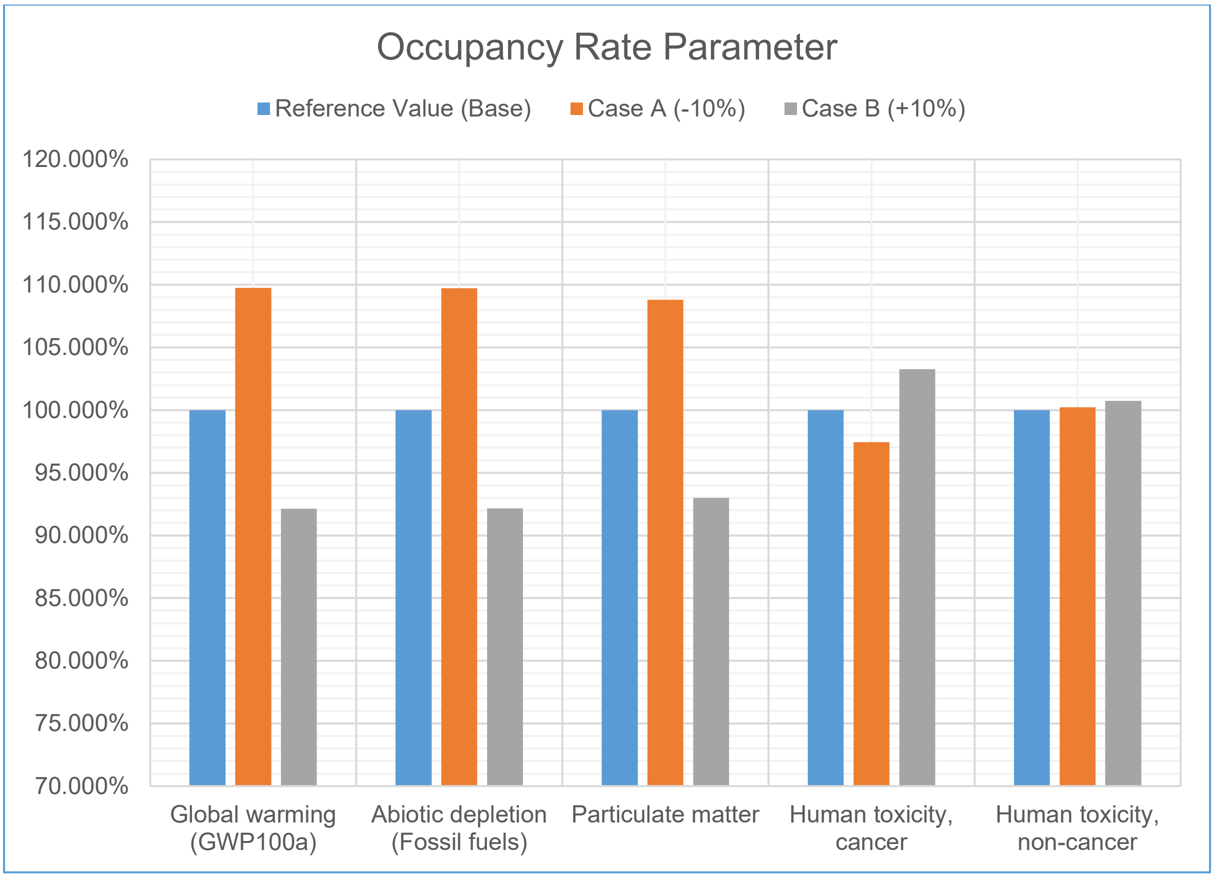


**Figure I.24: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Occupancy Rate Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.070552067 | 0.058474849 | 10 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.84053019 | 0.69682741 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 8.96E-06 | 7.49E-06 | 10 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.21E-10 | 1.13E-10 | 4 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 7.55E-10 | 6.85E-10 | 5 | -4 |

**Table I.25: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Kilometres Travelled Parameter)**

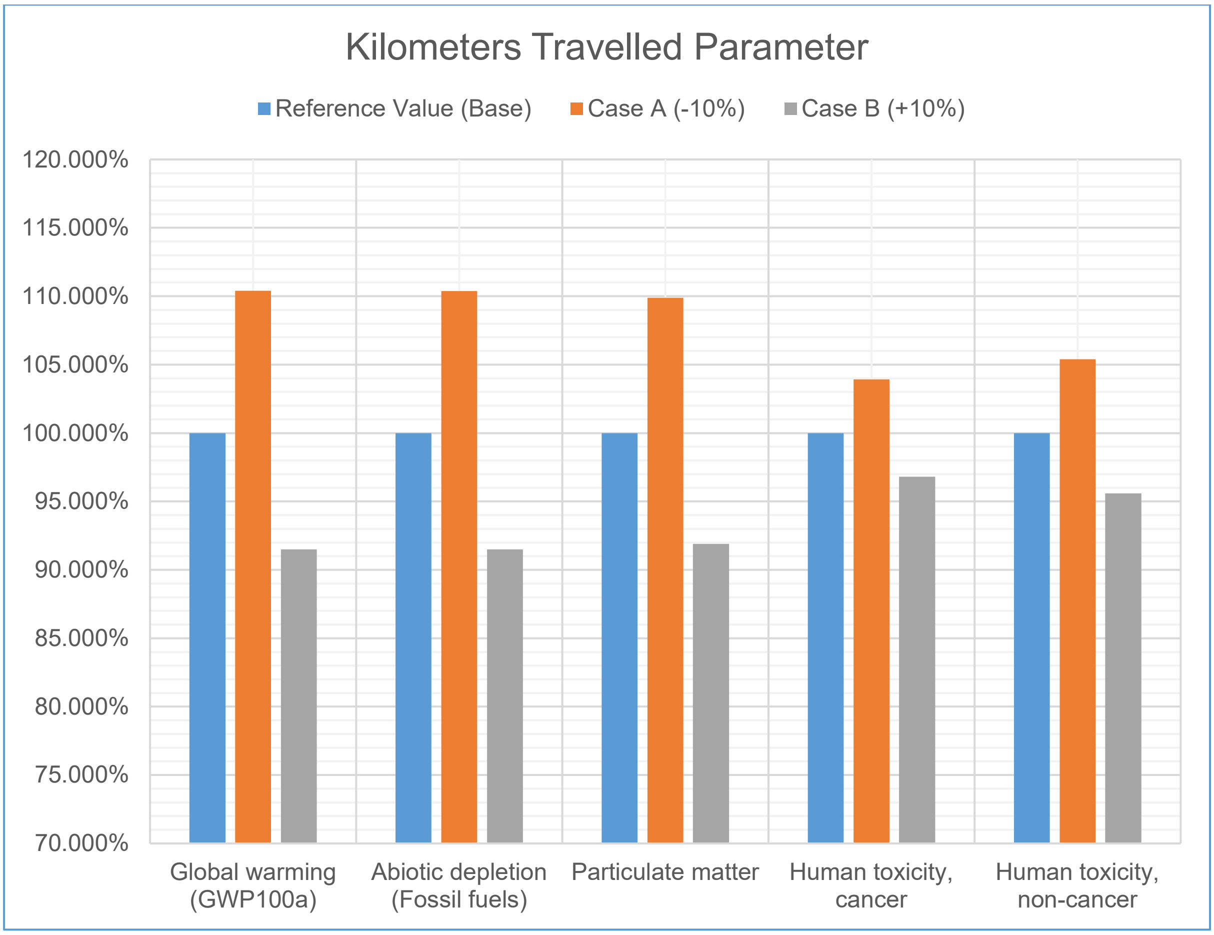


**Figure I.25: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Kilometres Travelled Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.063007499 | 0.064811695 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.69036079 | 0.83262654 | -9 | 9 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 7.43E-06 | 8.88E-06 | -9 | 9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.13E-10 | 1.21E-10 | -4 | 4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 6.82E-10 | 7.51E-10 | -5 | 5 |

**Table I.26: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Fuel Consumption Parameter)**

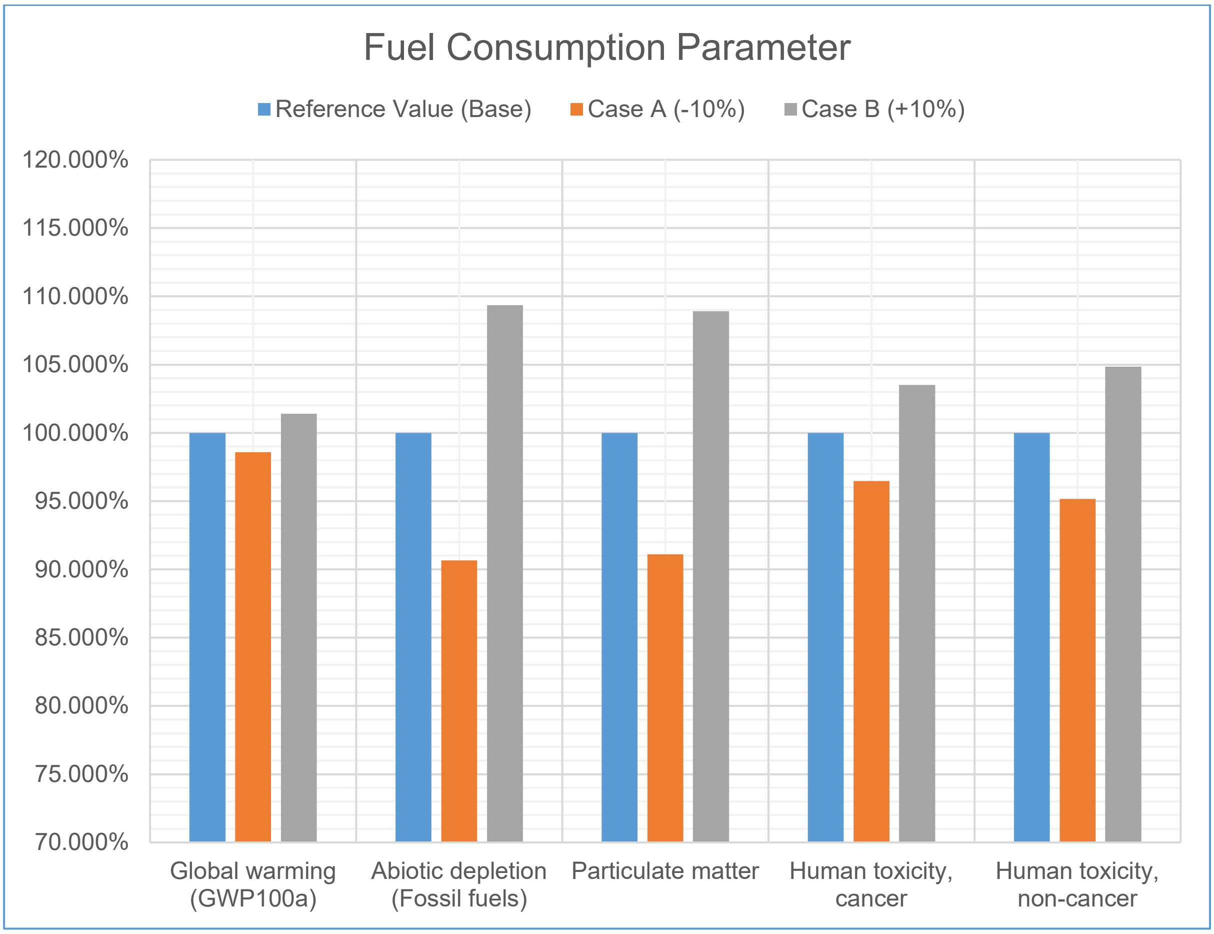


**Figure I.26: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.063746247 | 0.064072947 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.7594328 | 0.76355453 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 8.09E-06 | 8.22E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.10E-10 | 1.24E-10 | -6 | 6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 6.93E-10 | 7.40E-10 | -3 | 3 |

**Table I.27: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Vehicle Manufacture Parameter)**

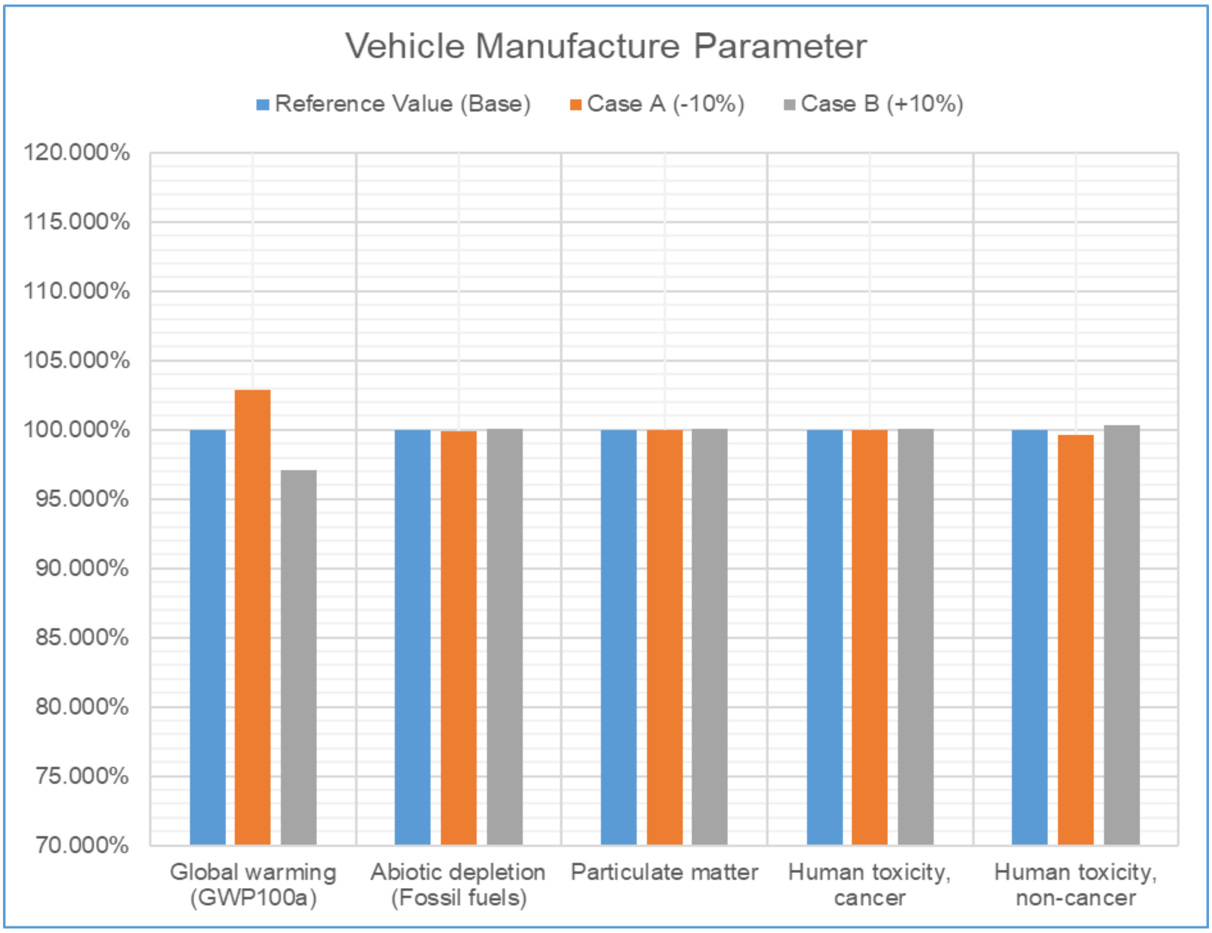


**Figure I.27: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Vehicle Manufacture Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.063664519 | 0.064154675 | -0.4 | 0.4 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.75853963 | 0.7644477 | -0.4 | 0.4 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 8.13E-06 | 8.18E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.16E-10 | 1.17E-10 | -0.5 | 0.5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 7.03E-10 | 7.30E-10 | -1.9 | 1.9 |

**Table I.28: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Vehicle Maintenance Parameter)**

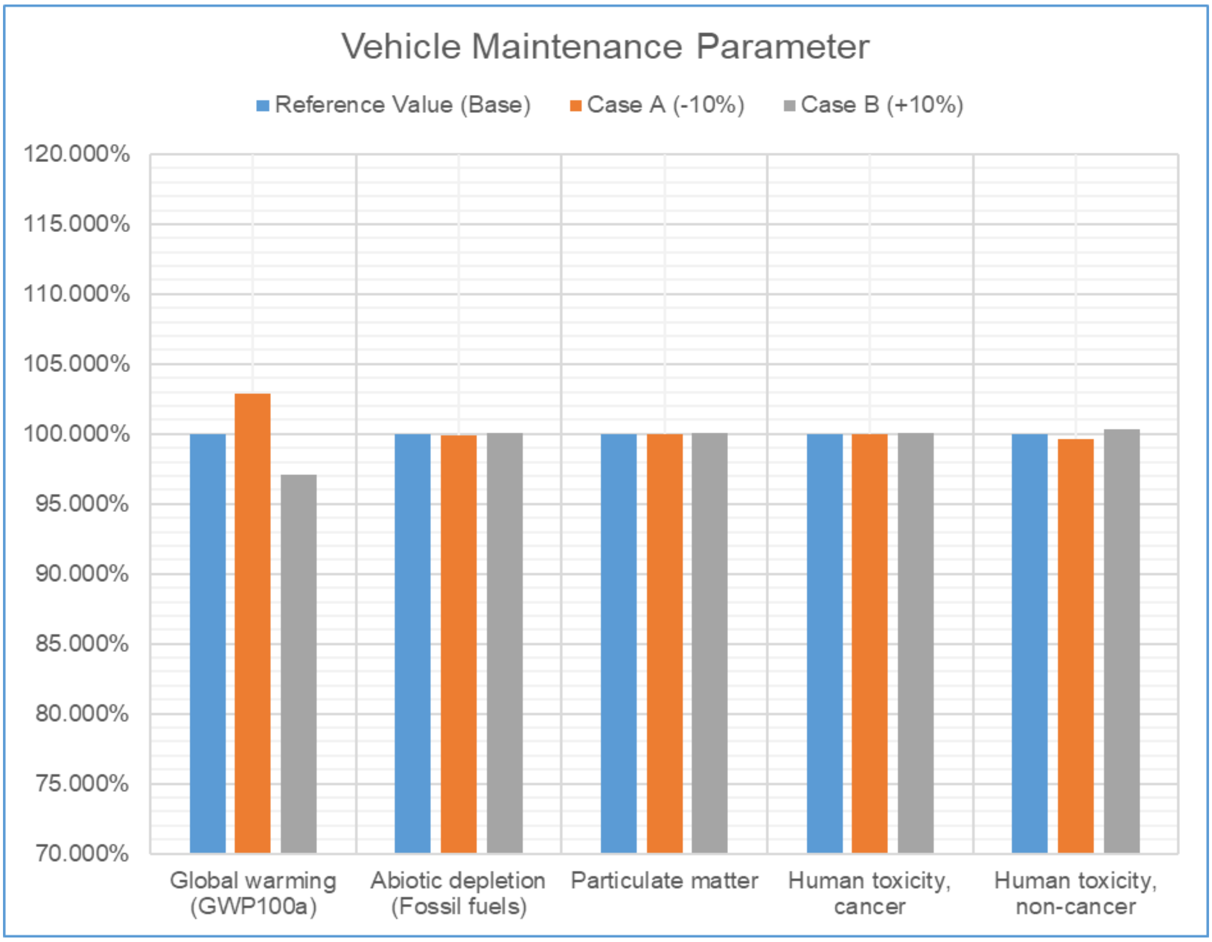


**Figure I.28: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.063478308 | 0.064340886 | -0.7 | 0.7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.69985227 | 0.82313506 | -8.1 | 8.1 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 7.81E-06 | 8.50E-06 | -4.2 | 4.2 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.14E-10 | 1.20E-10 | -2.5 | 2.5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 6.96E-10 | 7.37E-10 | -2.8 | 2.8 |

**Table I.29: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Crude Oil Refining Parameter)**

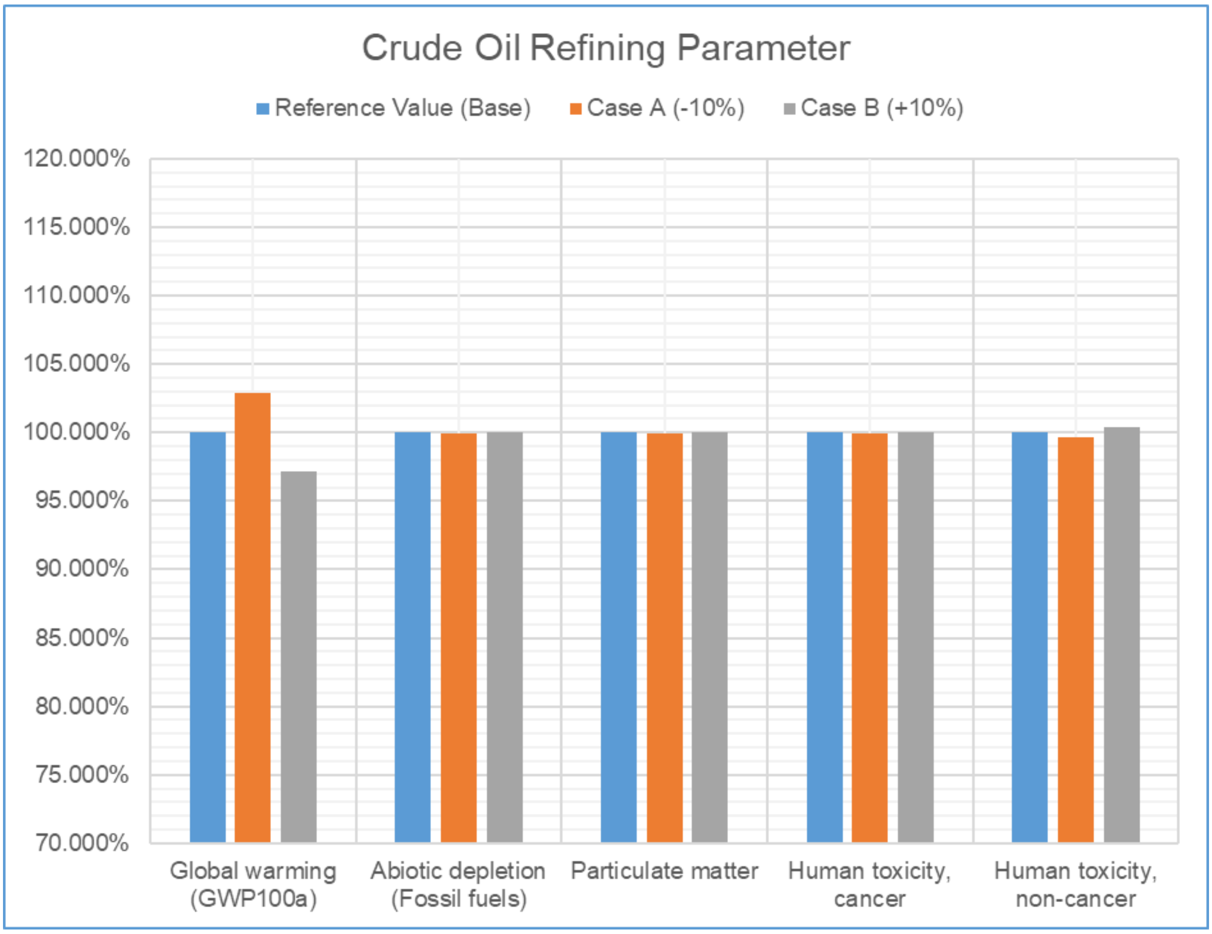


**Figure I.29: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Crude Oil Refining Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.063905289 | 0.063913905 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.76149208 | 0.76149525 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 8.15E-06 | 8.15E-06 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.17E-10 | -0.02 | 0.02 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 7.17E-10 | 7.17E-10 | -0.01 | 0.01 |

**Table I.30: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Vehicle Disposal Parameter)**

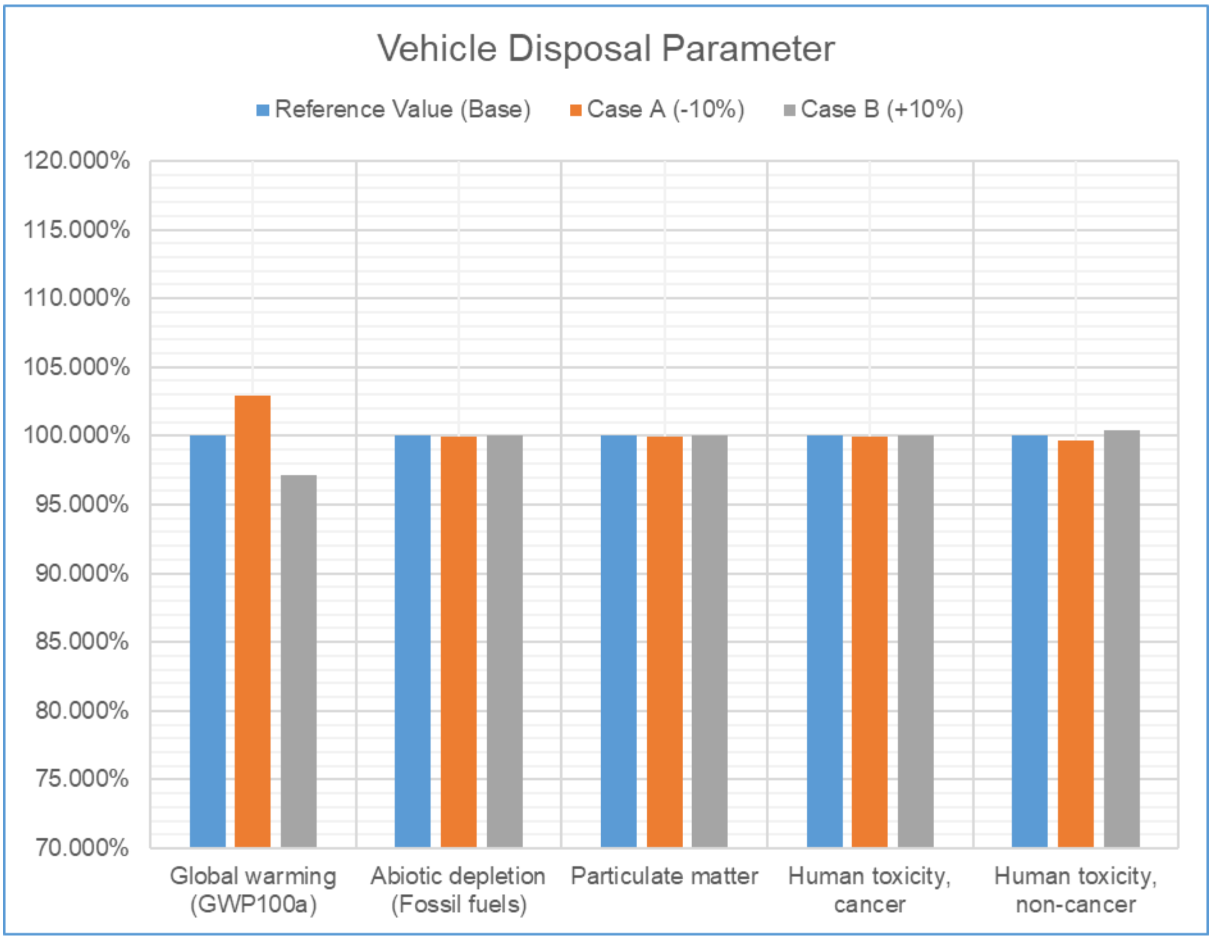


**Figure I.30: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Vehicle Disposal Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg /pkm)** | 0.063909597 | 0.063855627 | 0.063963567 | -0.1 | 0.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.76149366 | 0.74357817 | 0.77940915 | -2.4 | 2.4 |
| **Particulate Matter (kg/pkm)** | 8.15E-06 | 8.13E-06 | 8.18E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.17E-10 | 1.17E-10 | 1.17E-10 | -0.1 | 0.1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.17E-10 | 7.15E-10 | 7.19E-10 | -0.3 | 0.3 |

**Table I.31: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Crude Oil Extraction Parameter)**

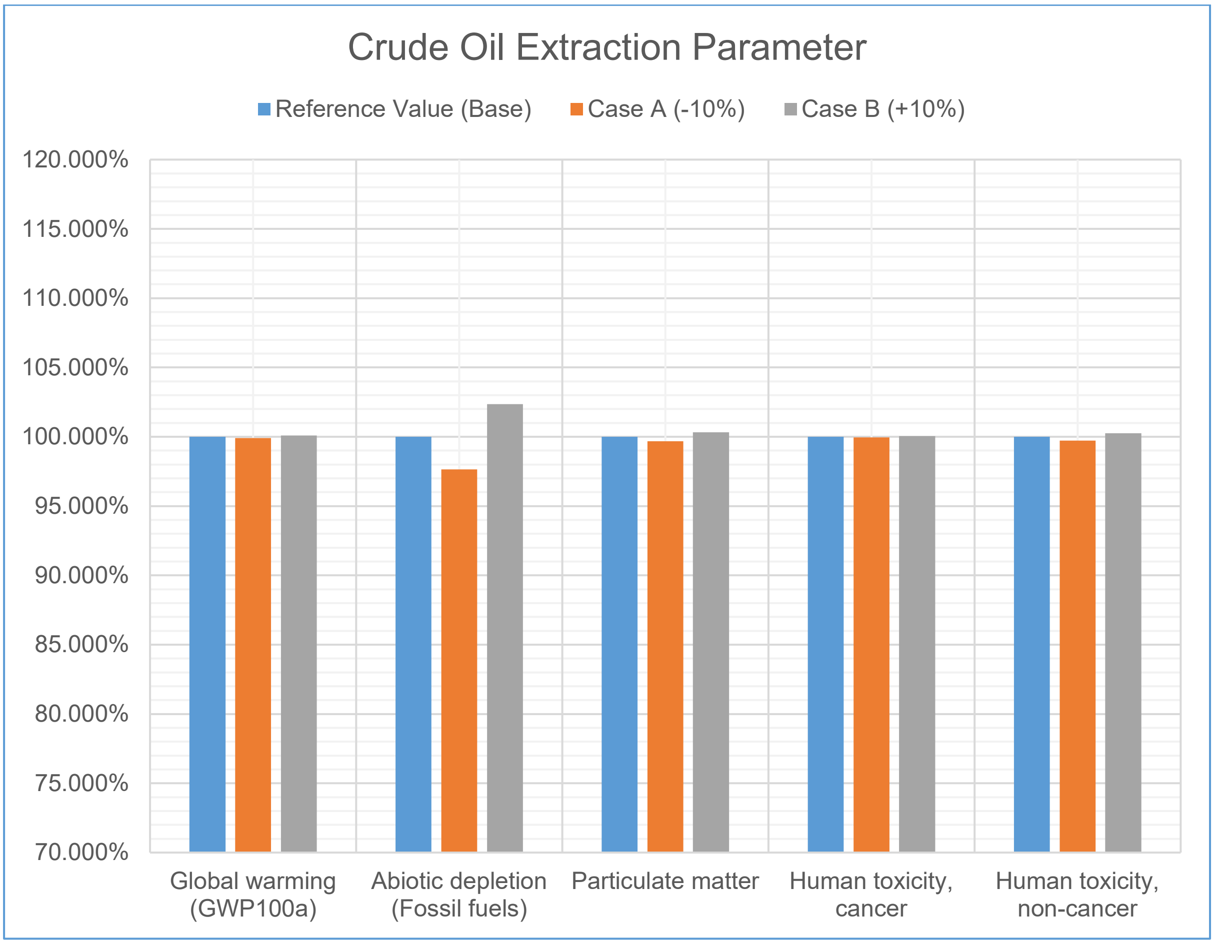


**Figure I.31: Sensitivity Analysis for LCA of 2451/ LSD Volvo Buses (Crude Oil Extraction Parameter)**

### 2452/Mercedes LSD Buses

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.077391427 | 0.064821121 | 10 | -8 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.92353639 | 0.77386247 | 10 | -8 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 9.77E-06 | 8.32E-06 | 9 | -7 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.19E-10 | 1.25E-10 | -2 | 3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.61E-10 | 7.57E-10 | 1 | 0 |

**Table I.32: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Occupancy Rate Parameter)**

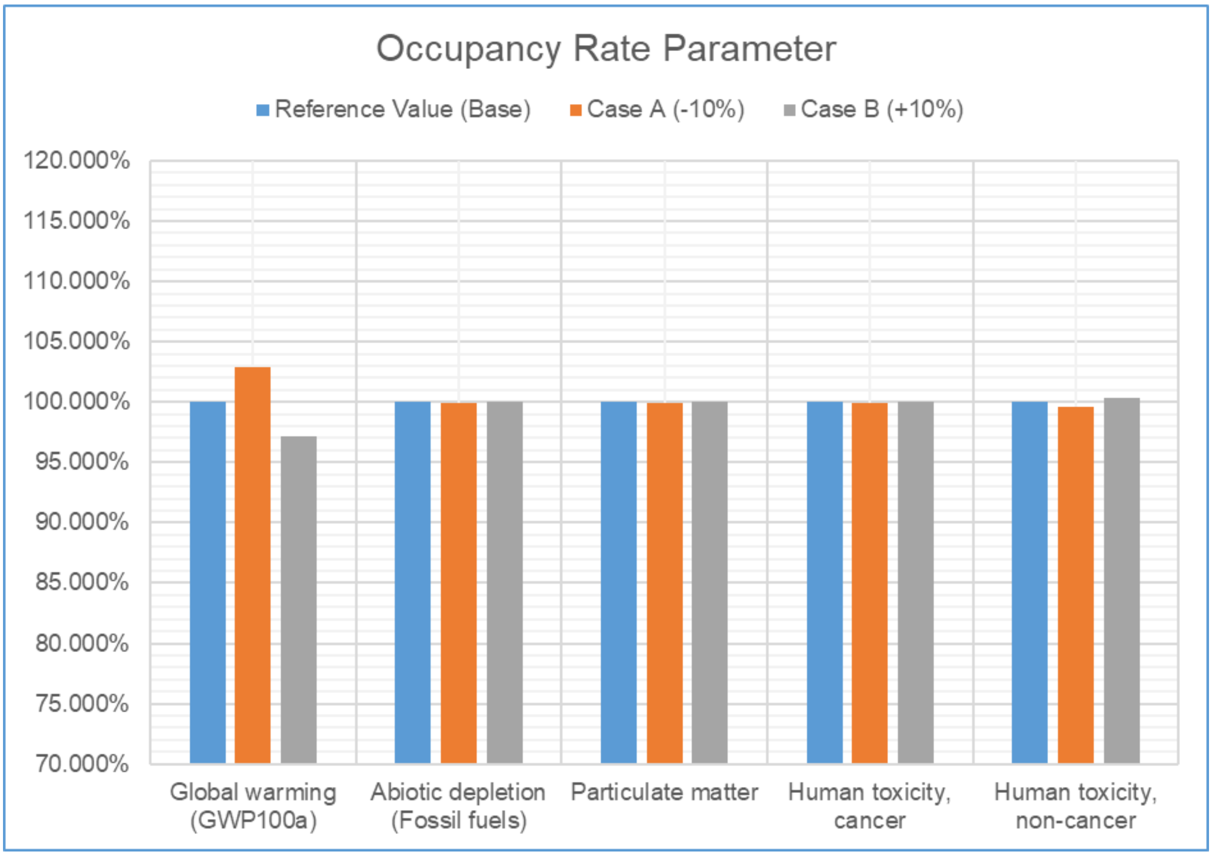


**Figure I.32: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Occupancy Rate Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.070273135 | 0.070599835 | 0 | 0 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.83865322 | 0.84277495 | 0 | 0 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 8.90E-06 | 9.02E-06 | -1 | 1 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.14E-10 | 1.28E-10 | -6 | 6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.32E-10 | 7.79E-10 | -3 | 3 |

**Table I.33: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Vehicle Manufacture Parameter)**

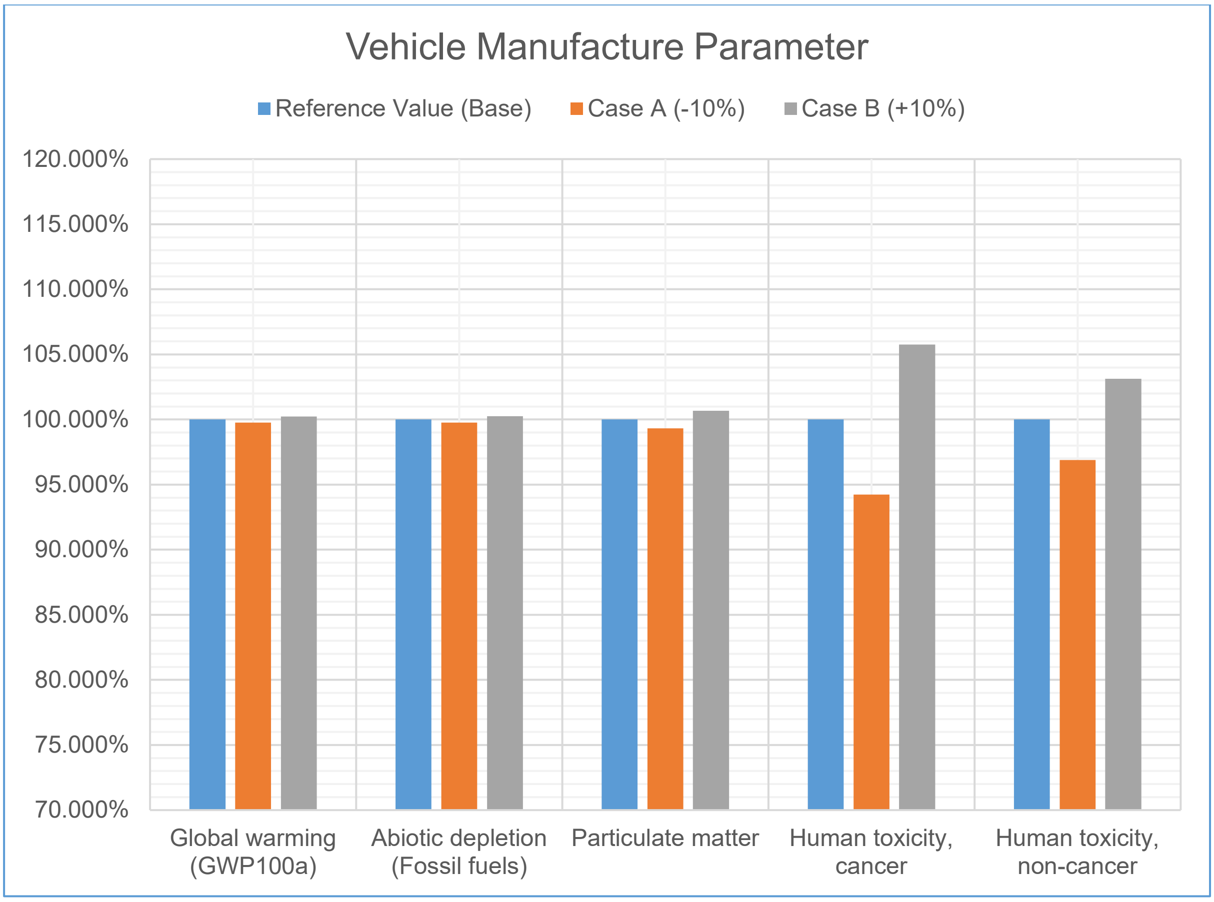


**Figure I.33: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Vehicle Manufacture Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.077804164 | 0.064408384 | 10 | -9 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.92855288 | 0.76884598 | 10 | -9 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 9.86E-06 | 8.23E-06 | 10 | -8 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.26E-10 | 1.17E-10 | 4 | -3 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.98E-10 | 7.20E-10 | 6 | -5 |

**Figure I.34: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Kilometres Travelled Parameter)**

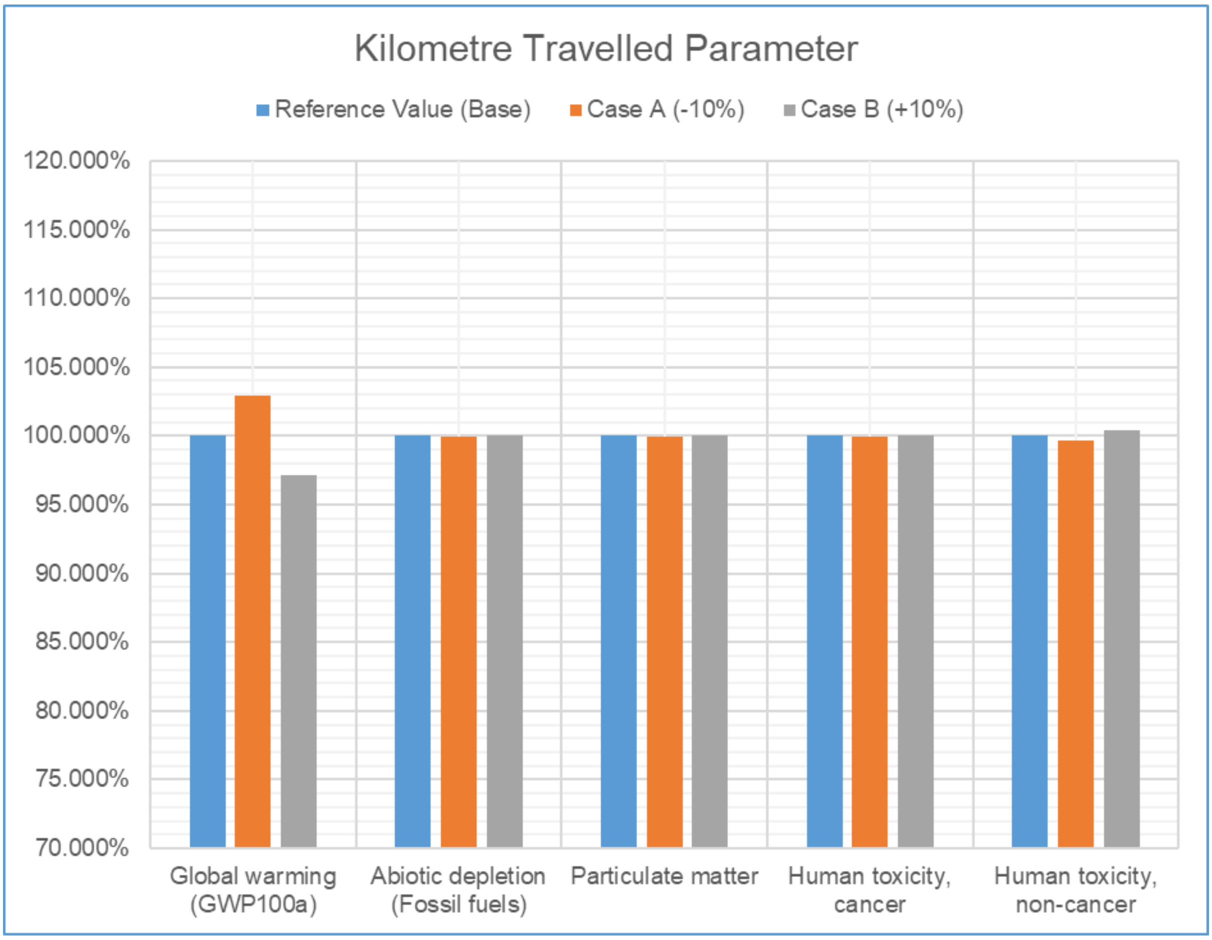


**Figure I.34: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Kilometres Travelled Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.069433921 | 0.071439049 | -1 | 1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.76165917 | 0.919769 | -9 | 9 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 8.16E-06 | 9.77E-06 | -9 | 9 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.17E-10 | 1.26E-10 | -4 | 4 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.17E-10 | 7.94E-10 | -5 | 5 |

**Figure I.35: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Fuel Consumption Parameter)**

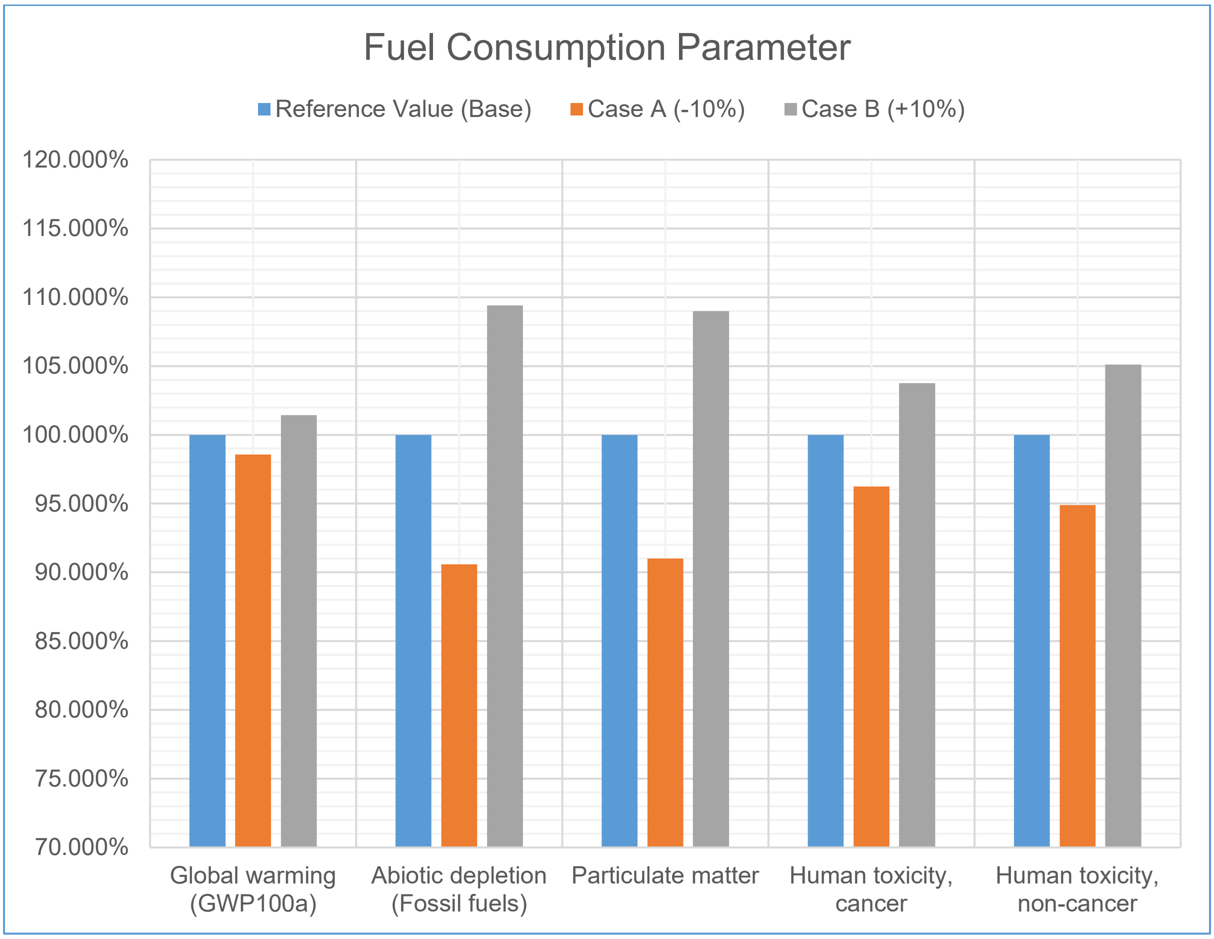


**Figure I.35: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Fuel Consumption Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.070191406 | 0.070681563 | -0.3 | 0.3 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.83776005 | 0.84366812 | -0.4 | 0.4 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 8.93E-06 | 8.99E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.21E-10 | 1.22E-10 | -0.5 | 0.5 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.42E-10 | 7.69E-10 | -1.8 | 1.8 |

**Figure I.36: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Vehicle Maintenance Parameter)**

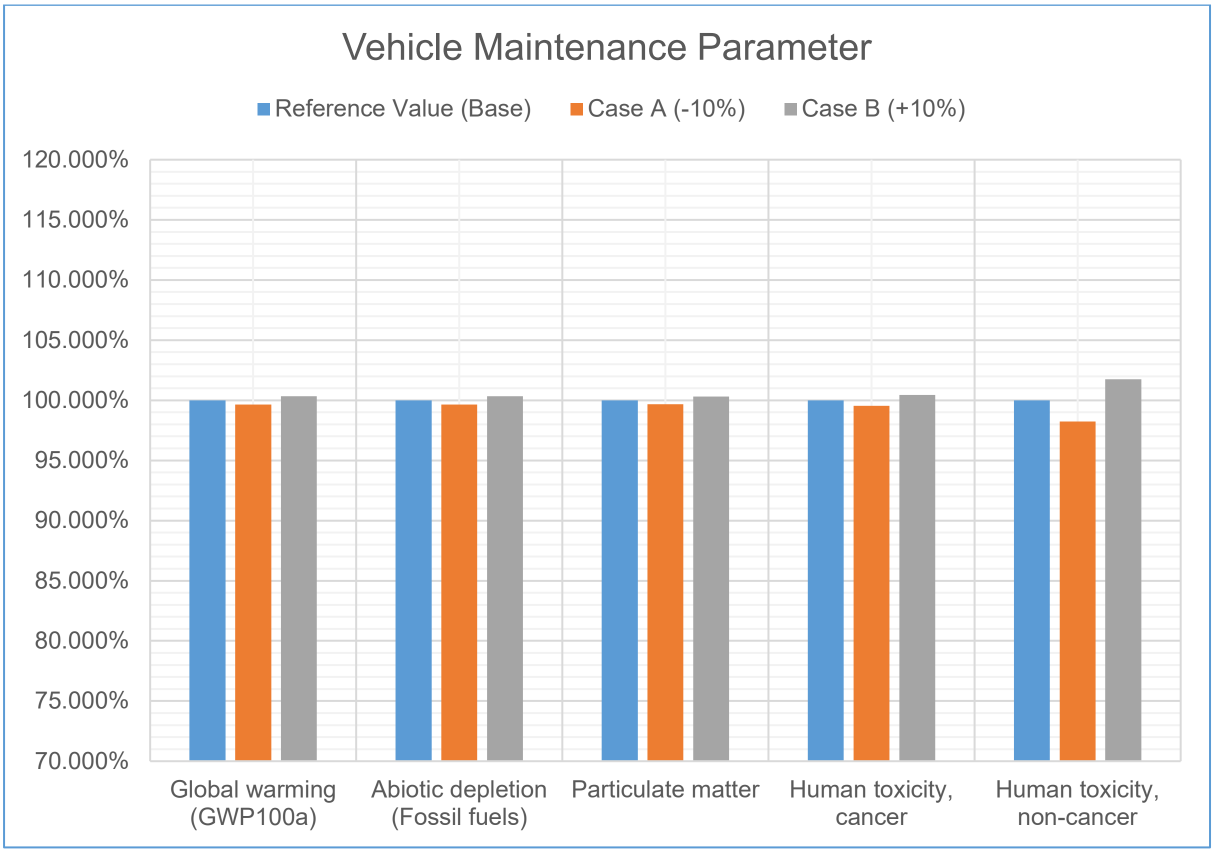


**Figure I.36: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Vehicle Maintenance Parameter)**

| Impact Category | Reference Value (Base) | Case A (-10%) | Case B (+10%) | Case A % Diff wrt Base | Case B % Diff wrt Base |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.070376505 | 0.070496465 | -0.1 | 0.1 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.82080335 | 0.86062482 | -2.4 | 2.4 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 8.93E-06 | 8.99E-06 | -0.3 | 0.3 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.21E-10 | 1.21E-10 | -0.1 | 0.1 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.53E-10 | 7.57E-10 | -0.3 | 0.3 |

**Table I.37: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Crude Oil Extraction Parameter)**

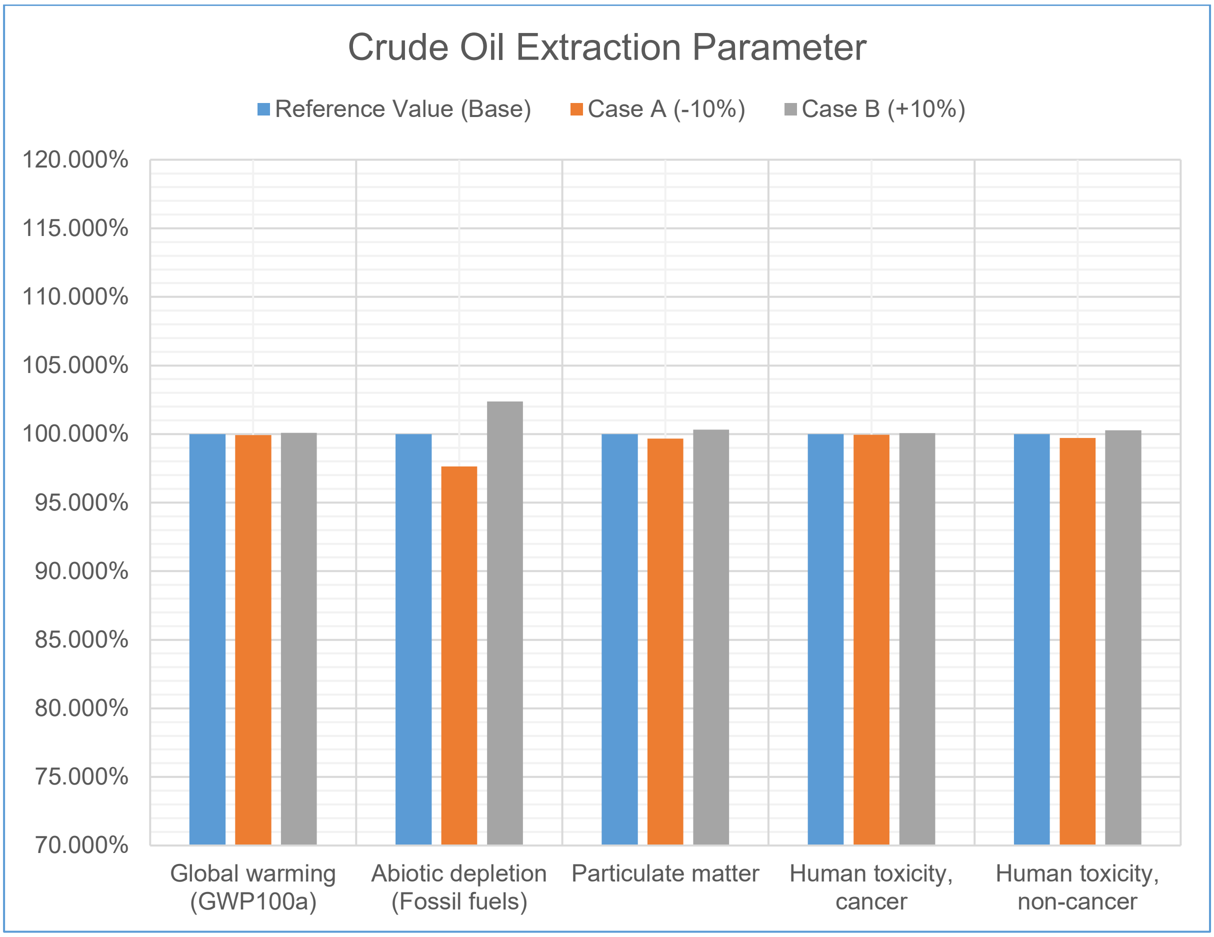


**Figure I.37: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Crude Oil Extraction Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.070432176 | 0.070440793 | -0.01 | 0.01 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.8407125 | 0.84071567 | 0.00 | 0.00 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 8.96E-06 | 8.96E-06 | 0.00 | 0.00 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.21E-10 | 1.21E-10 | -0.01 | 0.01 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.55E-10 | 7.55E-10 | -0.01 | 0.01 |

**Table I.38: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Vehicle Disposal Parameter)**

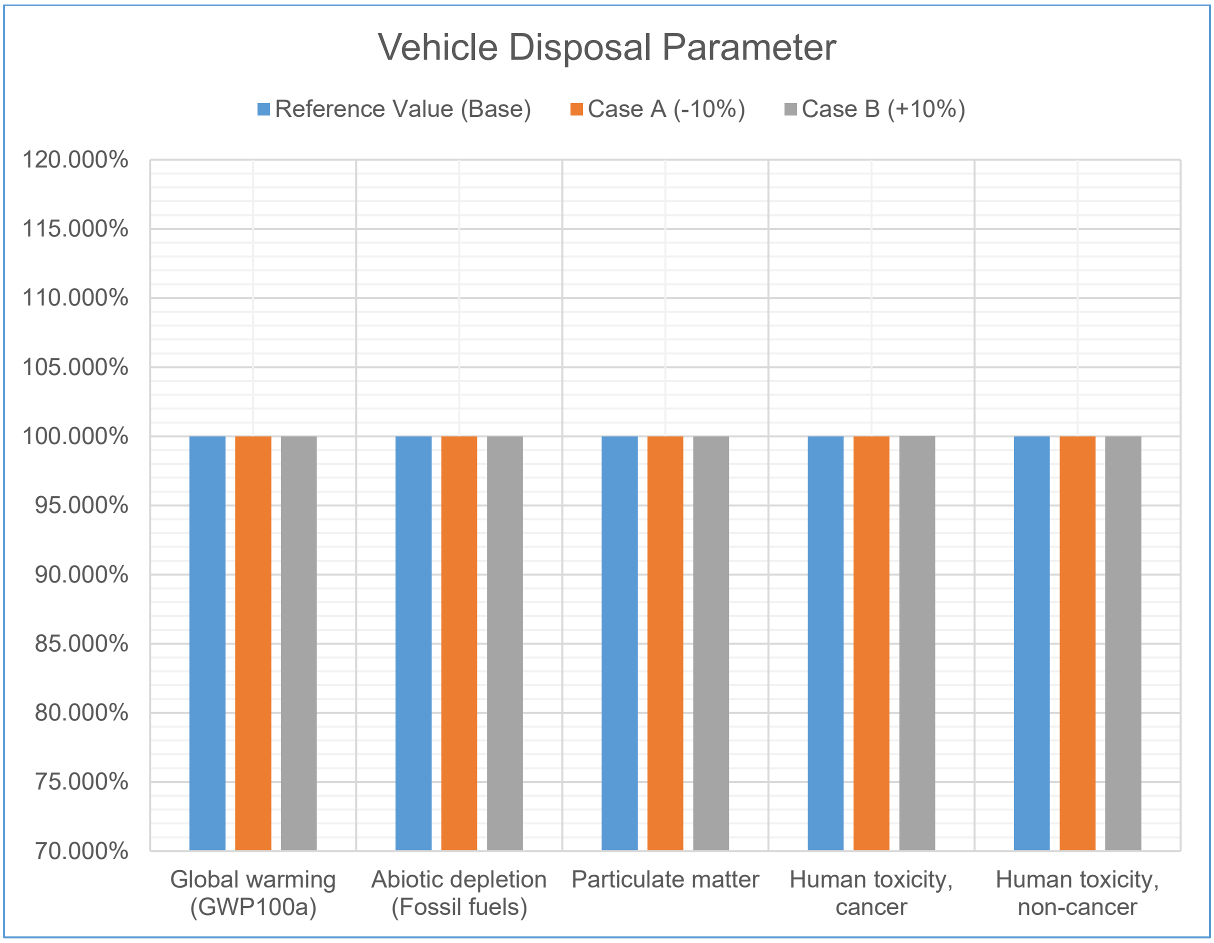


**Figure I.38: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Vehicle Disposal Parameter)**

| **Impact Category** | **Reference Value (Base)** | **Case A (-10%)** | **Case B (+10%)** | **Case A % Diff wrt Base** | **Case B % Diff wrt Base** |
|---|---|---|---|---|---|
| **Global Warming (GWP100a) (kg/pkm)** | 0.070436485 | 0.069957164 | 0.070915806 | -0.7 | 0.7 |
| **Abiotic Depletion (Fossil Fuels) (MJ/pkm)** | 0.84071409 | 0.77220771 | 0.90922046 | -8.1 | 8.1 |
| **Particulate Matter (kg/pkm)** | 8.96E-06 | 8.58E-06 | 9.34E-06 | -4.2 | 4.2 |
| **Human Toxicity, Cancer (kg/pkm)** | 1.21E-10 | 1.18E-10 | 1.24E-10 | -2.6 | 2.6 |
| **Human Toxicity, Non-Cancer (kg/pkm)** | 7.55E-10 | 7.33E-10 | 7.78E-10 | -3.0 | 3.0 |

**Table I.39: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Crude Oil Refining Parameter)**

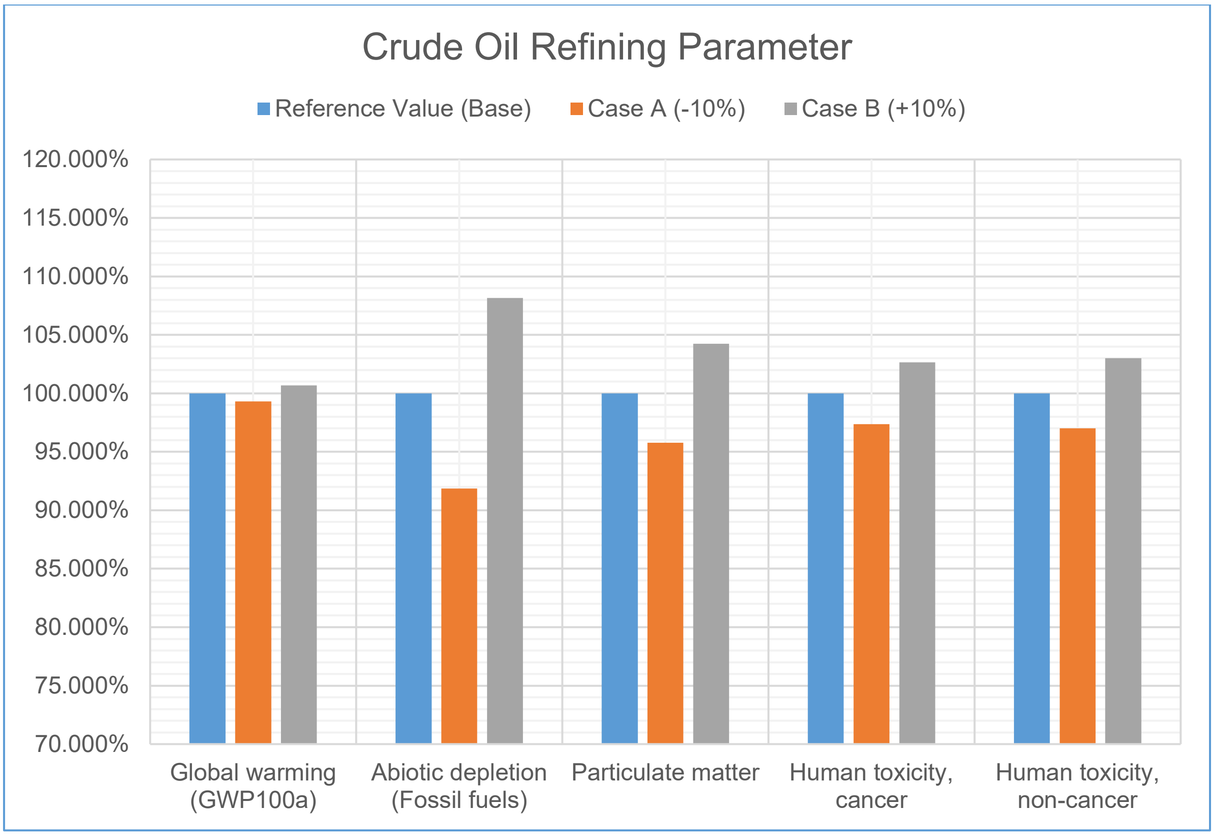


**Figure I.39: Sensitivity Analysis for LCA of 2452/LSD Mercedes Buses (Crude Oil Refining Parameter)**