Feasibility study of using electric vehicles for game viewing in South Africa

by

Nicolaos Dinodimos

submitted in accordance with the requirements for
the degree of

MAGISTER TECHNOLOGIAE

In the subject

ENGINEERING: ELECTRICAL

at the

University Of South Africa

Supervisor: Prof Ho Wei Hua

Co-Supervisor: Prof Du Shengzhi

October 2015

THESIS SUMMARY

The purpose of the feasibility study was to analyze the energy use of a battery electric vehicle (BEV), by using a vehicle having the parameters of a typical sedan, and with electric components hypothetically included. Its energy usage was then compared with the energy usage of other vehicle technologies presently available, and ultimately the findings were used to determine the suitability of a battery electric vehicle (BEV) for recreational use in South African game reserves.

The possible application of battery electric vehicles (BEVs) in South African game reserves, was researched in terms of energy usage and energy costs compared to other vehicle technologies. Calculations were made of the forces acting on a vehicle driving through the different routes and terrains, based on actual existing routes found in the Kruger National Park.

These forces were then translated into fuel, or energy consumption, and subsequently fuel, and energy prices. The entire exercise was performed on alternative vehicle technologies in a hypothetical scenario.

DECLARATION

Student number: **0 786 4930**

I declare that the "Feasibility study of using electric vehicles for game viewing in South Africa" is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

SIGNATURE
(Mr N Dinodimos)

DATE

ABSTRACT

The purpose of the study is to analyze the energy use of battery electric vehicles (BEVs), to compare their energy usage with other different vehicle technologies, and ultimately to determine their suitability for recreational use.

The possibility of applying such vehicles into South Africa's game reserves is researched in terms of energy costs and evaluated. Calculations were made based on actual existing routes found in the Kruger National Park, and are presently used by tourists for sightseeing and to access the different camps within the park.

Calculations were made on the forces acting on a vehicle driving through the different routes and terrains. These forces were then translated into fuel or energy consumption and subsequently into fuel and energy prices. The entire exercise was performed on alternative vehicle technologies in a hypothetical scenario.

The calculations investigated the energy consumption and efficiency of a battery electric vehicle (BEV) and other vehicle technologies such as fuel cell electric vehicle (FCEV), hybrid electric vehicle (HEV), and lastly the internal combustion engine (ICEV) vehicle.

It was found that the energy consumption of each vehicle technology revealed similar trends and ranking on most routes.

However on certain routes, the energy usage difference amongst the different vehicle technologies became more pronounced. This can be attributed to the continuous demand of energy by the vehicle to maintain forward motion.

It was found that in general, irrespective of the route profile, the route surface or its total distance, the highest energy efficiency is achieved by the battery electric vehicle (BEV), followed by the fuel cell electric vehicle (FCEV) and then by the combined hybrid electric vehicle (HEV) and lastly by the internal combustion engine (ICEV) vehicle.

However when comparing the ratio of energy demand in the different vehicle technologies, the internal combustion engine (ICEV) exhibited the largest increase in energy consumption especially in level routes where constant power to the drivetrain was required.

Lower input energy requirements, equate to lower energy costs, and this is what is achieved by the battery electric vehicle (BEV).

Theoretical projections of electrical energy costs up for a (BEV) up to 2025 together with the equivalent costs in fossil fuel for an (ICEV) reveal that electricity costs will be at least half of those of the equivalent fossil fuel required.

ACKNOWLEDGEMENTS

I would like to thank Prof Ho Wei Hua and Prof Du Shengzhi for their patience, advice, time and guidance during the process of completing my dissertation. Your support was without doubt crucial throughout this study.

I would like to thank Dr Filistea Naude for her assistance and support.

I would lastly like to express my gratitude to my family and friends for their encouragement and continued support throughout this study.

LIST OF ABBREVIATIONS

ATAC	Active Thermal Atmospheric Combustion
BEV	Battery Electric Vehicle
CIDI	Compression Ignition Direct Injection
DOD	Depth Of Discharge
4SDI	Four Stroke Direct Injection
ECE	Economic Commission Europe
EUDC	Extra Urban Driving Cycle
FCEV	Fuel Cell Electric Vehicle
FTP	Federal Test Procedure
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
ICE	Internal Combustion Engine
GHG	Greenhouse Gases
kWh	Kilowatt hour
MWh	Megawatt hour
NiMH	Nickel Metal-Hydride
Pb/A	Lead/ Acid
PEM	Polymer Electrolyte Membrane
SOC	State Of Charge
TWh	Terawatt hour

KEY TERMS AND DEFINITIONS

Electric vehicle: A vehicle that use one or more electric motors for propulsion.

Battery: A device consisting of two or more electrochemical cells that convert stored chemical energy into electrical energy.

Powertrain: The mechanism consisting of the engine or electric motor, the gearbox and the axle.

Game Park: A large area of country set aside as reserve for wild animals.

Route: A way or course taken in getting from a starting point to a destination.

Vehicle technologies: Sources of energy that an automobile utilizes for propulsion.

Energy: Energy is the capacity to perform work. Unit is the (J) joules.

Power: Power is the rate at which work is done, or energy transmitted. Unit is the (W) Watt

Force: A force is a push or a pull upon an object resulting from the object's interaction with another object.

Efficiency: A measurement of how much of the desired work or product is obtained from each unit of energy invested into that task or product.

Energy costs: Expense for generating, distributing, and using energy. include monetary and non-monetary expenses.

Energy to weight ratio: The energy stored by the battery divided by the mass of the battery.

Power to weight ratio: The power generated by the battery divided by the mass of the battery.

TABLE OF CONTENTS

ABSTRACT iii

CHAPTER 1 INTRODUCTION 1

1.1 PROBLEM STATEMENT 1

Context of the problem 1

Research gap 2

1.2 RESEARCH OBJECTIVE AND QUESTIONS 4

CHAPTER 2 LITERATURE REVIEW 6

2.1 VEHICLE TECHNOLOGIES 6

Battery Electric vehicle (BEV) 6

Life versus cycle of batteries 7

Lead acid (Pb-acid) 8

Nickel Cadmium (NiCd) 8

Nickel-Metal-Hydride (NiMH) 9

Lithium-ion (Li-ion) 9

Li-ion polymer 9

Sodium Nickel Chloride (NaNiCl) 9

How Do BEVs Compare with Conventional Vehicles 10

Potential of wide-spread adoption of electric vehicles in the future 10

Hybrid Electric Vehicle (HEV) 11

How Do HEVs Compare with Conventional Vehicle 12

Fuel Cell Electric Vehicle (FCEV) 13

Potential of hydrogen as an energy carrier 15

2.2 PRIMARY ENERGY EFFICIENCY OF ALTERNATIVE VEHICLE TECHNOLOGIES 16

2.3 POWERTRAINS 17

2.4 DESCRIPTION OF AVAILABLE VEHICLE TECHNOLOGIES 19

ICEV with a conventional powertrain 19

BEVs and the electric drivetrain 20

HEVs with internal combustion engines ... 22
FCEVs ... 23
2.5 EFFICIENCIES OF DIFFERENT POWERTRAINS ... 24
2.6 ENERGY ANALYSIS OF VEHICLE TECHNOLOGIES USING WELL-TO-WHEEL DRIVING CYCLE SIMULATIONS ... 30
2.7 MODELLING OF THE FORCES ACTING ON A VEHICLE ... 31
Projected gravity force ... 31
Aerodynamic drag ... 32
The rolling resistance ... 32
Power required ... 33
Energy required ... 34
Dynamic Analysis ... 35

CHAPTER 3 METHODOLOGY ... 37
3.1 SELECTION OF ROUTES ... 37
3.2 TOPOGRAPHICAL DATA ... 43
3.2 VEHICLE FORCES ... 44
3.3.1 Vehicle travelling up slope ... 45
3.3.2 Vehicle travelling down slope ... 47
3.4 CALCULATION OF FUEL OR ENERGY CONSUMPTION ... 48
3.5 CALCULATION OF POWERTRAIN EFFICIENCY ... 50
3.6 FUTURE ENERGY AND FUEL COSTS ... 51

CHAPTER 4 CALCULATION RESULTS AND ANALYSIS ... 52
4.1 POWERTRAIN EFFICIENCIES ... 52
4.2 ENERGY REQUIREMENTS ... 54
Present energy and fuel costs ... 66
Future energy and fuel costs ... 68
4.3 SUMMARY OF THE ENERGY LOSSES PER VEHICLE TYPE ON ALL ROUTES ... 71

CHAPTER 5 DISCUSSION **74**
5.1 ENERGY CONSUMPTION 75
5.2 TOTAL ENERGY LOSSES 75
5.3 ENERGY COSTS 76

CHAPTER 6 CONCLUSION **77**
REFERENCES 79
APPENDIX 86

LIST OF FIGURES

Figure 1 Components of a battery electric vehicle 7

Figure 2 Structure of a hybrid vehicle 12

Figure 3 Structure of a hydrogen fuel cell 14

Figure 4 Components of a fuel cell vehicle 16

Figure 5 Definitions of primary energy efficiency, vehicle efficiency, and powertrain efficiency 19

Figure 6 Road load force components 31

Figure 7 Vehicle dynamics model 35

Figure 8 Route 1 38

Figure 9 Route 2 39

Figure 10 Route 3 40

Figure 11 Route 4 41

Figure 12 Route 5 42

Figure 13 Route 6 43

Figure 14 Forces acting on a body up a slope 45

Figure 15 Forces acting on a body down a slope 47

Figure 16 The graph is a representation of the elevation profile of Route 1 displaying the height in metres vs the distance that the vehicle travelled in metres 54

Figure 17 The graph is a representation of the elevation profile of Route 2 displaying the height in metres vs the distance that the vehicle travelled in metres 54

Figure 18 The graph is a representation of the elevation profile of Route 3 displaying the height in metres vs the distance that the vehicle travelled in metres 55

Figure 19 The above graph is a representation of the elevation profile of Route 4 displaying the height in metres and the distance that the vehicle travelled in metres 56

Figure 20 The graph is a representation of the elevation profile of Route 5 displaying the height in metres vs the distance that the vehicle travelled in metres 56

Figure 21 The graph is a representation of the elevation profile of Route 6 displaying the height in metres vs the distance that the vehicle travelled in metres 56

Figure 22 Total energy losses for the different vehicles on Route 1 59

Figure 23 Total energy losses for the different vehicles on Route 2 60

Figure 24 Total energy losses for the different vehicles on Route 3 60

Figure 25 Total energy losses for the different vehicles on Route 4 61

Figure 26 Total energy losses for the different vehicles on Route 5 61

Figure 27 Total energy losses for the different vehicles on Route 6 62

Figure 28 Graph showing a breakdown of the different types of losses for each vehicle type on Route 1 63

Figure 29 Graph showing a breakdown of the different types of losses for each vehicle type on Route 2 63

Figure 30 Graph showing a breakdown of the different types of losses for each vehicle type on Route 3 64

Figure 31 Graph showing a breakdown of the different types of losses for each vehicle type on Route 4 64

Figure 32 Graph showing a breakdown of the different types of losses for each vehicle type on Route 5 65

Figure 33 Graph showing a breakdown of the different types of losses for each vehicle type on Route 6 65

Figure 34 Graph of electricity price (NERSA) 66

Figure 35 Future projected fuel and energy costs (Route 1).. 68

Figure 36 Future projected fuel and energy costs (Route 2).. 69

Figure 37 Future projected fuel and energy costs (Route 3).. 69

Figure 38 Future projected fuel and energy costs (Route 4).. 70

Figure 39 Future projected fuel and energy costs (Route 5).. 70

Figure 40 Future projected fuel and energy costs (Route 6).. 71

Figure 41 Battery electric vehicle (BEV) energy losses on all the routes 72

Figure 42 Combined hybrid electric vehicle (HEV) energy losses on all the routes...........72

Figure 43 Fuel cell electric vehicle (FCEV) energy losses on all the routes.......................73

Figure 44 Internal combustion engine vehicle (ICEV) energy losses on all the routes.......73

LIST OF TABLES

Table 1 Average distance (in km) between camps within the Kruger National park 5

Table 2 Average consumption of conventional cars and electric vehicles 11

Table 3 Assumed future possible component mean efficiencies over a normal drive schedule for the electric drivetrain...21

Table 4 Assumptions of mean primary engine energy efficiency in different configurations 23

Table 5 Assumed future PEM fuel-cell system mean efficiency...24

Table 6 Future powertrain efficiencies 26

Table 7 Vehicle efficiency calculated as consumed energy at the wheels divided by the total energy supply to vehicle, see Fig. 5 27

Table 8 Primary energy efficiency with a fossil fuel primary energy source 28

Table 9 Primary energy efficiency with biomass as primary energy source 29

Table 10 Primary energy efficiency with solar, wind or hydropower as primary energy source 30

Table 11: Characteristics of idealised vehicle used for the study...37

Table 12 Vehicle powertrain efficiency and vehicle efficiency calculations 53

Table 13 Calculated values of the input energy and fuel requirements of the (BEV-Electricity, HEV–Petrol, FCEV-Hydrogen and ICEV-Petrol) vehicles for Routes 1 to 6 58

Table 14 Average Eskom charges for electricity. 66

Table 15 Average municipal charges for electricity 67

Table 16 Present energy and fuel cost of the different technologies 67

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

<u>Context of the problem</u>

There is concern throughout the world regarding remaining energy reserves. South Africa‘s focus on industrialization together with its electrification programme into deep rural areas, has recently seen a rise in demand for electrical energy [1].The cost of oil, coal and gas as these resources become depleted, results in continuous escalation of costs.

Alternative sources of energy become an important consideration in long term sustainable living.

Investment in renewable energy, and energy efficiency, is important in reducing the negative socio-economic and environmental impacts of energy production and consumption in South Africa.

Hence investing into energy efficient technologies is the way forward to economic and social development throughout the world.

Over recent years the release of Greenhouse Gases (GHGs), and the impact that these gases are having on the Kruger National Park and other game reserves in South Africa, have led towards growing environmental consciousness, which in turn has led to the search for alternatives to petrol burning vehicles. Though electric vehicles based on conventional technologies still have some disadvantages compared with petrol vehicles, in terms of the content of energy of comparable volume units, the use of electrical vehicles for outdoor recreational purposes is becoming a feasible proposition [2].

The latest developments in battery technologies are making electric vehicles more and more attractive. From lead-acid batteries to nickel metal-hydride (NiMH) batteries, lithium-ion cell (Li-ion) technology, and the latest nanotechnology based batteries, the energy and power densities have improved drastically.

Using nanotechnology in the manufacture of batteries offers the following benefits:

- The possibility of batteries catching fire is reduced by providing less flammable electrode material.

- Nanotechnology increases the available power from a battery and decreases the time required to recharge a battery. These benefits are achieved by coating the surface of an electrode with nanoparticles. This increases the surface area of the electrode, thereby allowing more current to flow between the electrode and the chemicals inside the battery. This technique could increase the efficiency of hybrid vehicles by significantly reducing the weight of the batteries needed to provide adequate power.

- Nanotechnology increases the shelf life of a battery by using nanomaterials to separate liquids in the battery from the solid electrodes when there is no draw on the battery. This separation prevents the low level discharge that occurs in a conventional battery, which increases the shelf life of the battery dramatically.

Research gap

Electric vehicles are seen by many as the cars of the future, as they are highly efficient, produce almost no pollution, are silent, and can operate very economically compared to fossil (petrol or diesel) fuel vehicles.

Even though the internal combustion engine (ICE) is currently still the dominating source of power for vehicles [3],the rising cost of fuel and more stringent government regulations on greenhouse gas emissions have led to more active interest in hybrid and electric vehicles.

Hybrid electric vehicles (HEVs) offer a better petrol mileage than internal combustion engine (ICE) powered vehicles. Unfortunately they still have the emission problem and their dual power sources make them more complex and expensive.

Battery electric vehicles (BEVs) have zero emissions and are powered by a single source that makes their design, control, and maintenance relatively simple compared to hybrid vehicles.

In addition, the wide use of BEVs will reduce dependence on imported foreign oil, decrease the energy cost per kilometre of driving.

The main drawback for BEVs lies in the battery technology. The low energy output and power densities cause the weight of the vehicle to be too high which significantly reduces the driving range and other vehicle level performances. The initial purchasing cost of the vehicle is another factor that slows the commercialization of electric vehicles.

Conventional ICEVs like the Honda Civic, Ford Focus, and Volkswagen Golf cost between R250 000 and R280 000 compared to the Nissan Leaf BEV at R475 000 which is a price difference of some R180 000.

Since the concept of an electric game watching vehicle is quite new in South Africa, the availability of such vehicles is a rarity. The vehicles are in their experimental phase and as such are expensive. However as production of such vehicles commences it can be expected that the costs of both vehicle and parts will decrease.

Maintenance costs of these vehicles were not considered in this study as presently there are no commercially available models in the market.

While a number of electric vehicles have been designed for urban road use, there is currently development taking place in off road electric vehicle design in South Africa [4].

1.2 RESEARCH OBJECTIVE AND QUESTIONS

The research objective of this study is to investigate the usage potential of battery electric vehicles (BEVs) in game reserves in South Africa by using a vehicle having the parameters of a typical sedan and with electric components hypothetically included.

A limitation of this study is the adaptation of the different vehicle technology efficiencies from previous studies, where different assumptions were made. By combining these assumptions in the way this study was conducted would inevitably introduce uncertainties, but due to the limited time and resources available for this research, it was not possible to conduct own experiments on the efficiency of the different vehicle technologies.

This typical operation requires transporting light cargo or passengers from the different camps within the game reserves.

The vehicle will operate mostly on sandy road surfaces, as well as on tarred roads as found in South African game parks. The objective of this thesis is to answer the following questions:

- Which vehicle technology is best suited to be adapted for outdoor recreational purposes?
- How will different vehicle technologies affect the operating costs at South African game reserves?
- Which vehicle technology provides the best energy efficiency?
- Which technology is more environmentally friendly within a game park context?

The research site is the Kruger National Park in South Africa. It stretches for 352 kilometres from north to south along the Mozambique border of South Africa, and is one of the world's foremost national parks covering 19624 square kilometres and averaging 60 kilometres in width.

Each year approximately 950000 people visit the park. Popular by tourists and rangers, tarred and sand routes of varying length and gradient profile were chosen from different areas from the park. This was done so in order to create an accurate representation of the parks topography.

These routes are used to connect camping sites and game watching sites within the park.

Table 1 below shows the main tourist routes within the Kruger National Park [5].The gradient of the routes were analysed in order to calculate the forces acting on the vehicles. The calculated forces in turn were used to calculate the energy usage of the vehicles.

Table 1: Average distance (in km) between camps within the Kruger National park

Gates and Camps Distances	Berg-en-dal	Crocodile Bridge	Letaba	Lower Sabi	Malelane	Mopani	Numbi Gate	N'wanetsi	Olifants	Orpen	Pafuri Gate	Paul Kruger Gate	Phalaborwa Gate	Pretoriuskop	Punda Maria	Satara	Shingwedsi	Skukuza
Berg-en-dal	-	149	234	113	12	281	97	180	219	213	453	83	285	92	415	165	344	172
Crocodile Bridge	149	-	196	34	141	243	130	142	181	175	415	88	246	125	377	127	306	77
Letaba	234	196	-	162	226	47	216	94	32	117	218	173	51	211	176	69	109	162
Lower Sabi	113	34	162	-	105	209	95	108	147	141	380	53	213	90	342	93	271	43
Malelane	12	141	226	105	-	272	94	170	210	204	444	74	277	85	408	156	333	64
Mopani	281	234	47	209	272	-	263	141	86	164	172	220	74	258	130	116	63	209
Numbi Gate	97	130	216	95	94	263	-	162	201	195	434	65	267	9	396	147	325	54
N'wanetsi	180	142	94	108	170	141	162	-	79	63	312	119	145	156	274	25	203	108
Olifants	219	181	32	147	210	86	201	79	-	102	250	158	83	195	212	54	141	147
Orpen	213	175	117	141	204	164	195	63	102	-	335	152	167	184	297	48	226	137
Pafuri Gate	453	415	218	380	444	172	434	312	250	335	-	392	246	438	76	287	109	380
Paul Kruger Gate	83	88	173	53	74	220	65	119	158	152	392	-	224	60	354	104	283	12
Phalaborwa Gate	285	246	51	213	277	74	267	145	83	167	246	224	-	261	201	119	137	213
Pretoriuskop	92	125	21	90	85	258	9	156	195	184	438	60	261	-	389	140	318	49
Punda Maria	415	377	176	342	408	130	396	274	212	297	76	354	201	389	-	254	71	342
Satara	165	127	69	93	156	116	147	25	54	48	287	104	119	140	245	-	178	93
Shingwedsi	344	306	109	27	333	63	325	203	141	226	109	283	137	318	71	178	-	271
Skukuza	72	77	162	43	64	209	54	108	147	137	380	12	213	49	342	93	271	-

South Africans account for 80 per cent of all visitors visiting the park. Most of these visitors make use of their own ICE vehicles to travel between camps and to go on game drives. Such drives can last up to 2 hours [5].

CHAPTER 2 LITERATURE REVIEW

2.1 VEHICLE TECHNOLOGIES

In this section, an introduction is carried out into the different types of vehicle technologies, the different battery technologies, the primary energy efficiency of the different vehicle technologies, and the modelling methodology of the forces acting on the vehicle.

Battery Electric vehicle (BEV)

Battery Electric vehicles (BEVs) run on electrical power. They are propelled by an electric motor (or motors) powered by rechargeable battery packs. Figure 1 shows the components of a battery electric vehicle (BEV). They can be powered up by a wide variety of primary energy sources, thus reducing oil dependency and improving security of energy supply. Well-to-wheel efficiency analysis also shows that electric vehicles are more energy-efficient than ICEVs over a wider range of primary energy sources [6].

The driving range presently for a medium sized car is 100-200 km due to limits in battery capacity. This range is expected to increase to 150-250 km in the medium term with a battery recharging time of several hours [6].

BEVs are ideally suited to smaller sized cars and shorter trips as in urban driving and including new transportation models such as car sharing.

BEVs have a shorter driving range than FCEVs, HEVs and ICEVs. On average, considering a medium sized BEV with maximum battery loading of 30 kWh battery pack at a weight of 220 kg achievable by the year 2020, will not be able to have a driving range of further than 150 km at a speed of 120 km/hour on the highway in real life driving conditions and taking into consideration the expected improvements until 2020 into account [6].

BEVs have significantly longer charging times. It can take up to 6-8 hours to charge a battery pack using normal charging equipment. Fast charging may become widespread in the near future, but it is unclear what the impact of over time of quick charging has on the battery performance and its subsequent degradation, and the impact that charging has on the power grid stability [6].

The energy density in vehicle batteries of the latest technology (Lithium-ion) is by a factor of 50 lower than in conventional liquid fuels. Even with a factor of 3 in higher energy efficiency, a factor of 15 in larger weight would be required for onboard storage of the electric energy required to match the same range with an electric vehicle as with an internal combustion engine vehicle. A factor of 3 meaning 3 times as much and so on [7].The high cost and payload of the battery restrict the maximum amount of energy that can be stored which in turn affects the driving range of the vehicle. The electricity charge-out capacity of a battery has also to be limited to ensure durability.

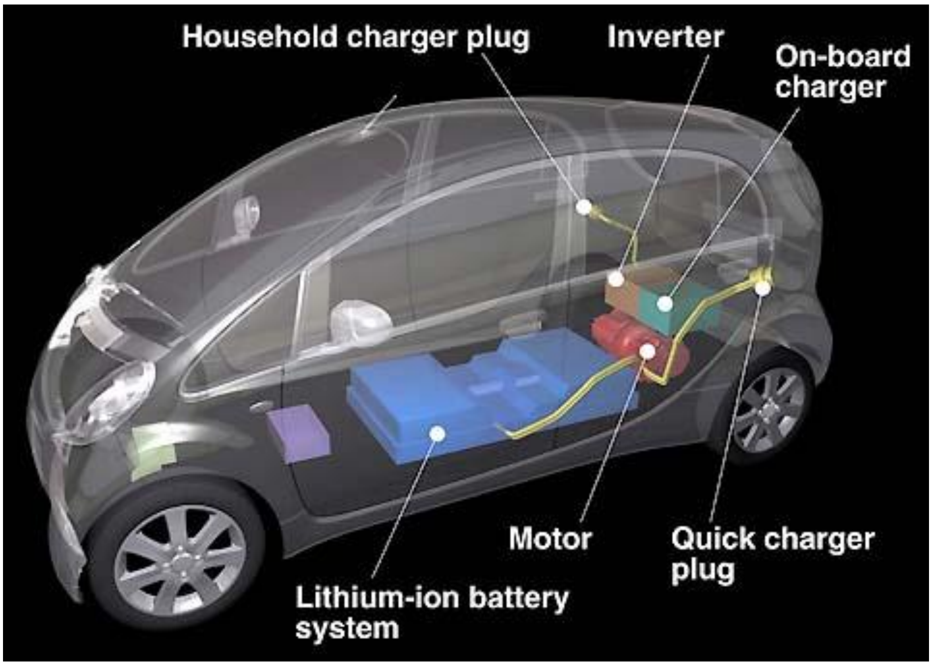

Figure 1 Components of a battery electric vehicle [8]

<u>Life versus cycle of batteries</u>

The number of cycles expected from a battery during its life is of course very dependent on the usage profile. A BEV requires deep discharge cycling, that is, using the maximum available energy stored during one charge, whereas a HEV only uses a small part of its energy, being constantly recharged by the internal combustion engine (ICE).

In the first case, the battery is generally charged overnight for utilization over the next day. Therefore, the number of cycles required corresponds to more or less one cycle/day of use up to 80% of the stored energy, and 3500 such cycles would represent about a 10-year life.

The total cumulated driving distance depends on the battery size and energy density determining the car range. Nickel Cadmium (NiCd) batteries, used in commercially available BEV’s during the last 25 years, usually provided a 70 km average range, leading to a cumulated driving distance of more than 200 000 km, that is, an 8-year daily utilization of approximately 3000 cycles, while generally less than 1000 cycles were obtained with lead acid batteries.

The required cycle life of advanced BEV(Li-ion) batteries, at 80% depth of discharge (DOD), is usually around 3000 cycles, which represents as much as 360 000 km for an average 120 km range. It can be seen from these figures that the life requirement of a BEV battery is more demanding than that of most of the conventional ICE cars.

In the case of hybrid electric vehicles (HEVs), the battery is subjected to thousands of very short cycles per day, using a very small amount of the total battery energy at 50% state of charge (SOC).Because the energy involved in each cycle (corresponding to each power peak required from the electric power train) may largely vary, average values have been set to define a cycle life. A typical requirement for a full hybrid car battery is approximately 300 000 cycles of 25 Wh, representing 8% of a 0.33kWh battery [9].

Lead acid (Pb-acid)

Lead-acid batteries are the oldest type of rechargeable battery and have a very low energy-to-weight and energy-to-volume ratio.

This means that lead acid batteries take up significant amounts of space within vehicles, and add significant amounts of weight. However, they can maintain a relatively large power-to-weight ratio and are low cost, making them ideal for use in road vehicles [10].

Nickel Cadmium (NiCd)

Nickel Cadmium give the longest cycle life of any currently available battery (over 1500 cycles) but has low energy density compared to some other battery types. Cadmium is also toxic to both humans and animals, so its use is in domestic applications is being superseded by Li-ion and NiMH types of batteries [10].

Nickel-Metal-Hydride (NiMH)

The Nickel Metal Hydride battery technology is similar to a NiCd battery in design, except cadmium is replaced making it less detrimental to the environment. NiMH batteries can also have 2-3 times the capacity of an equivalent size NiCd, with much less significant memory effect. Compared to lithium ion batteries, energy capacity is lower and self-discharge is higher. Applications include hybrid vehicles such as the Toyota Prius, the Toyota RAV4 BEV and consumer electronics [10].

Lithium-ion (Li-ion)

The relatively modern lithium-ion battery technology is very light and has a very high charge density. Current limitations include volatility, the potential for overheating, high cost, and limited shelf and cycle life. The technology currently has widespread use in consumer electronics as in mobile phones, but has only recently begun to be used in vehicle applications (e.g. the Tesla Roadster and Toyota Prius electric cars). General motors and Toyota are now also moving towards using more Lithium-ion batteries [10].

Li-ion polymer

This is a similar technology to Li-ion, but typically has slightly lower charge density, greater life cycle degradation rate and an ultra-slim design (as little as 1 mm thick). Disadvantages include the high instability of overcharged batteries, and if the battery discharges below a certain voltage it may never be able to hold a charge again [10].

Sodium Nickel Chloride (NaNiCl)

Sodium Nickel Chloride, also known as the Zebra battery, belongs to the class of molten salt batteries. These use molten salts as an electrolyte, offering both a higher energy density, as well as a higher power density making rechargeable molten salt batteries, a promising technology for powering electric vehicles. However, the normal operating temperature range is 270–350^{o}C, which places more stringent requirements on the rest of the battery components, and can bring problems of thermal management and safety. Furthermore, there are also significant thermal losses when the battery is not in use [10].

Electric on-board equipment, such as air-conditioning further limits the effective driving range.

Partial recharging of the battery takes 15-30 minutes [6].Battery swapping reduces charging time and it is expected to be feasible if used once every two months or less. This can be implemented provided that battery standards are adopted by the majority of car manufacturers. BEVs are therefore ideally suited to smaller cars and urban driving, potentially achieving~80% CO_2 reduction by the year 2030 compared to today.

Electric motors are standard industrial products, available in all sizes as required for road vehicles. Batteries, on the other hand, are the main issue for the lack of a broad market introduction of electric vehicles due to their low energy density and high cost.

How Do BEVs Compare with Conventional Vehicles

Electric vehicles produce zero emissions while driving, which significantly improves air quality and they can be almost CO_2-free, depending on the primary energy source used. Zero emission powertrains, therefore go hand-in-hand with the decarbonisation of energy supply, with the potential to remove most emissions completely in the near future.

Electric vehicles can be fuelled by a wide variety of primary energy sources such gas,coal, oil, biomass, wind, solar and nuclear energy, thus reducing the need of oil, and enhancing energy security by stabilising an increasingly volatile power grid.

Potential of wide-spread adoption of electric vehicles in the future

Electricity as an energy carrier can be produced from all primary energy sources. Supply potential therefore is not an issue of availability of primary energy sources but of production capacity from power generation plants, and of power distribution infrastructure, with renewable energy also increasingly becoming more an issue of energy storage capacity.

A mid-size electric vehicle annual energy consumption is of order 3 MWh assuming it travels 15,000 km/year and an average energy consumption of 20 kWh/100 km). The consumption of 1 million electric vehicles is then of order 3 TWh/year, corresponding to 0.1 % of present total annual EU electricity production (3362 TWh in 2007) [11].

Summation of the different national and regional targets set out today would result in about 5 million electric vehicles in the EU by 2020, with a total electricity consumption of about 0.5 % of present EU electricity production [12].

In-depth studies show that, taking into account the energy efficiency at production and distribution level, the consumption figures of BEV versus ICEV are as follows on Table 2:

Table 2: Average consumption of conventional cars and electric vehicles [13]

Vehicle Type	ICEV		BEV
	Fuel consumption / 100 km	Electricity equivalent	Electricity consumption
Car	8,5 l petrol	909 Wh / km	488 Wh / km
Van	12, l petrol	1283 Wh / km	600 Wh / km
Small truck	16, l diesel	1910 Wh / km	1000 Wh / k

The figures show that battery electric cars (BEV)’s, vans or small trucks, respectively consume 54%, 47% and 52% of the primary energy needed by internal combustion engine vehicles (ICEV)’s. It is clear that BEV’s are much more energy efficient. This advantage can increase when it will be possible to recharge vehicles by connecting them directly to electricity production sources with a total output efficiency exceeding 50% such as plants with combined gas/steam cycle, fuel cells, buffer batteries, etc.

Hybrid Electric Vehicle (HEV)

HEVs have an electric motor and a battery pack in addition to the internal combustion engine (ICE) found in traditional vehicles. In figure 2 the internal structure of an HEV is shown. The batteries in HEVs are lighter and smaller than those in non hybrid electric vehicles because the internal combustion engine (ICE) produces most of the power to operate the vehicle. The ICE can be designed to run on petrol, diesel, or any other alternative fuel. The battery pack or capacitor can also store excess energy generated from braking to use for quick acceleration and to recharge the batteries [14].

HEVs have a similar performance and distance to ICEVs, though electric driving only applies to shorter distances. They represent a plausible solution for reducing CO2 emissions considerably compared to ICEVs.

There are two types of HEV's namely parallel and series types. In parallel HEVs, the petrol tank supplies fuel for the ICE and the batteries provide power to the motor and the transmission, which turns the wheels. In series HEVs, the ICE does not directly power the vehicle but instead turns a generator, which provides electrical power to either the motor or the batteries.

The main idea behind HEVs is the extra flexibility offered by the electric motor, which allows the engine to operate more efficiently. At low speeds and low energy demand, the electric motor drives the vehicle using battery power. The ICE engages when needed to drive the car at a faster speed or when the battery needs recharging. At full acceleration, the battery also adds power. When the vehicle idles, the ICE shuts off to conserve energy [14]**.**

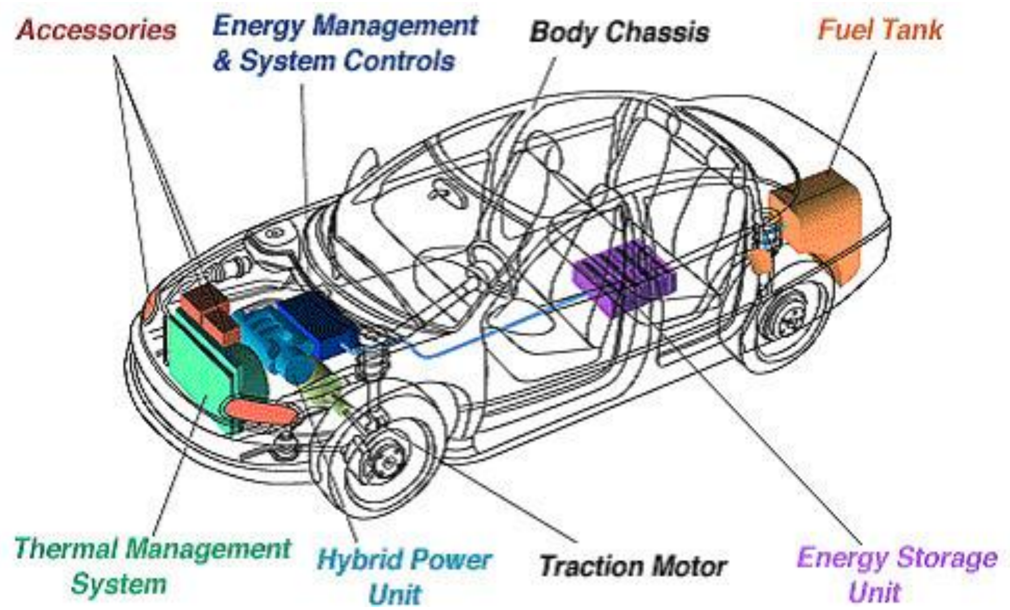

Figure 2 Structure of a hybrid vehicle [13]

<u>How Do HEVs Compare with Conventional Vehicle</u>

They require fewer refuellings and are more economical to run.

They have typical driving ranges of twice that of conventional vehicles and six times that of electric vehicles.

HEVs also emit fewer tailpipe pollutants because of their electric powertrains and efficient ICEs. In conventional vehicles, ICEs are designed to meet peak power needs as when the vehicle needs to climb a hill or accelerate.

In HEVs, the engines are smaller much lighter and cleaner-running. They are designed to operate efficiently when meeting average power needs because the battery kicks in when extra energy is required, and the batteries are recharged automatically.

Five-year maintenance costs for HEVs have been lower than those for ICE vehicles.

A great deal of progress has been made in improving the battery quality so they will last for a vehicle lifetime of 250 000 kilometres or more.

The main disadvantage of HEVs is their purchase price. Manufacturers are working towards making HEVs commercially feasible.

Fuel Cell Electric Vehicle (FCEV)

The operation of a fuel cell powered electric vehicle (FCEV) involves the use of a fuel cell that generates onboard the electricity needed to power the electric drive. The components of fuel cell vehicle are shown in Figure 4. The fuel cell is fed with hydrogen, either coming from a tank filled with hydrogen produced elsewhere, or produced onboard through a dedicated fuel processor, using petrol, bio-ethanol or other liquid fuels; the fuel cell electric vehicle (FCEV) is based on the polymer electrolyte membrane (PEM) technology [15].

Polymer Electrolyte Membrane (PEM) fuel cells used in FCEVs are also called Proton Exchange Membrane fuel cells as they make use of hydrogen fuel and oxygen from the air to produce electricity. Hydrogen gas is combined with oxygen gas in a fuel cell on board a vehicle. The resulting electrochemical reaction produces electricity and heat. Water vapour is given out as exhaust gas in a process inverse to the electrolysis of water. The energy which first had to be used to produce hydrogen is recovered in this recombination process.

Energy losses do occur in the several energy conversion processes, from the primary energy source to the final electricity production on board the vehicle, and its use for propulsion through an electric motor. Nevertheless, the energy efficiency of the final stage on board the vehicle can be at least a factor 2 higher than with the internal combustion engine.

Most fuel cells designed for use in vehicles produce less than 1.16 volts of electricity, a voltage that is far from enough to power a vehicle. Therefore, to produce the correct voltage multiple cells must be assembled into a fuel cell stack. The potential power generated by a fuel cell stack depends on the number and size of the individual fuel cells that comprise the stack and the surface area of the PEM. Figure 3 below shows how a PEM fuel cell works [16].

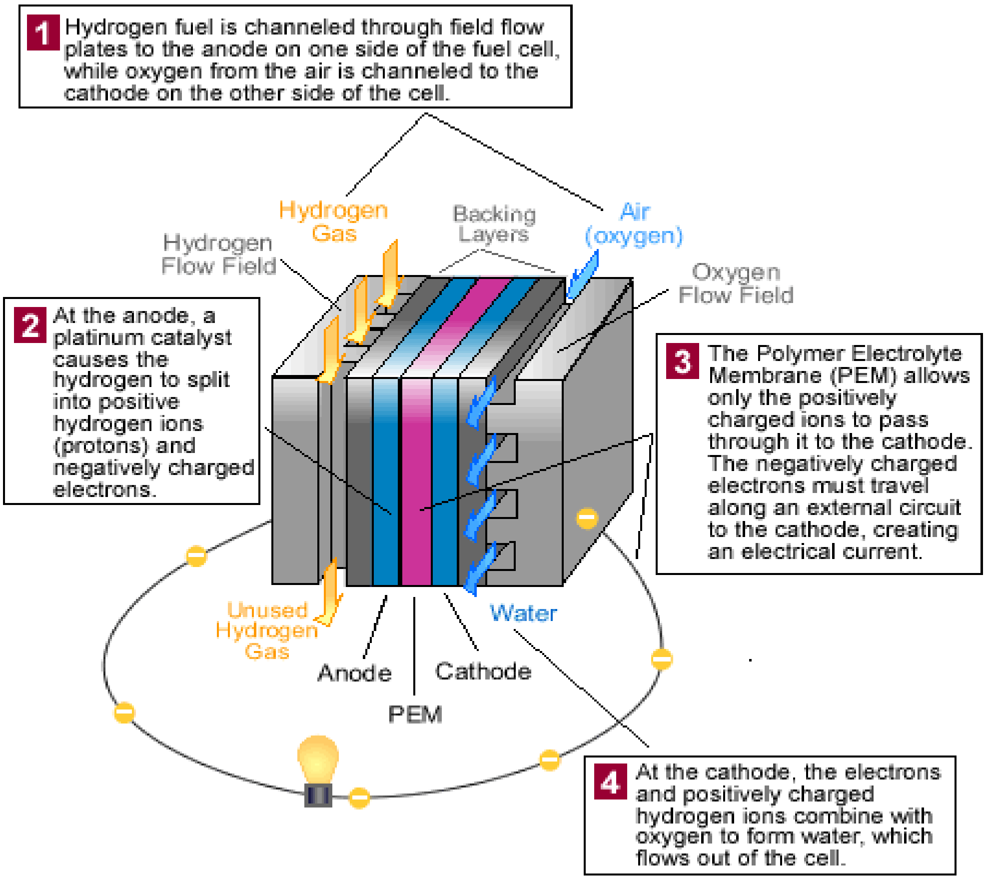

Figure 3 Structure of a hydrogen fuel cell [13]

Potential of hydrogen as an energy carrier

The FCEV has the greatest potential usage in the medium to larger car-segment including buses. This segment represents more than 70% of the current car fleet.

Hydrogen has as an energy carrier like electricity, the same reasoning with regards to the potential of primary supply, production and distribution capacities. Hydrogen has been produced in large quantities for about a century mainly for industrial applications.

At worldwide level, oil refining is the most hydrogen-intensive sector (51%), due to fossil fuel quality requirements followed by the manufacture of ammonia (34%), and the production of other specialty chemicals (14%) [12].

FCEVs driving performance such as acceleration, having a range of around 600 km and refueling time of less than 5 minutes, is comparable to ICEV's [6]. They are therefore a feasible low-carbon substitute for ICEVs for medium to larger cars and longer trips, potentially capable of achieving 80% CO2 reduction by 2030 compared to today [6].

With a driving range and comparable performance to ICEVs, FCEVs are the lowest carbon solution for medium to larger cars and longer trips. This car segments account for 50% of all cars and 75% of CO2 emissions, and hence replacing one ICEV with one FCEV achieves a relatively high CO2 reduction [6].

The FCEV technology is ready for market entry. All technological problems such as heat management, efficiency, storage, platinum size all have been resolved. To date over 400 FCEVs, ranging from the small A segment to the large J-class segment (SUV), have driven more than 15 million km with over 80 000 fuelling procedures, and a study [9] shows that further production could reduce the cost of fuel cells by 90% by the year 2020, by innovations in design, different use of materials for example reducing platinum use and further innovations in production technology and economies of scale [12].

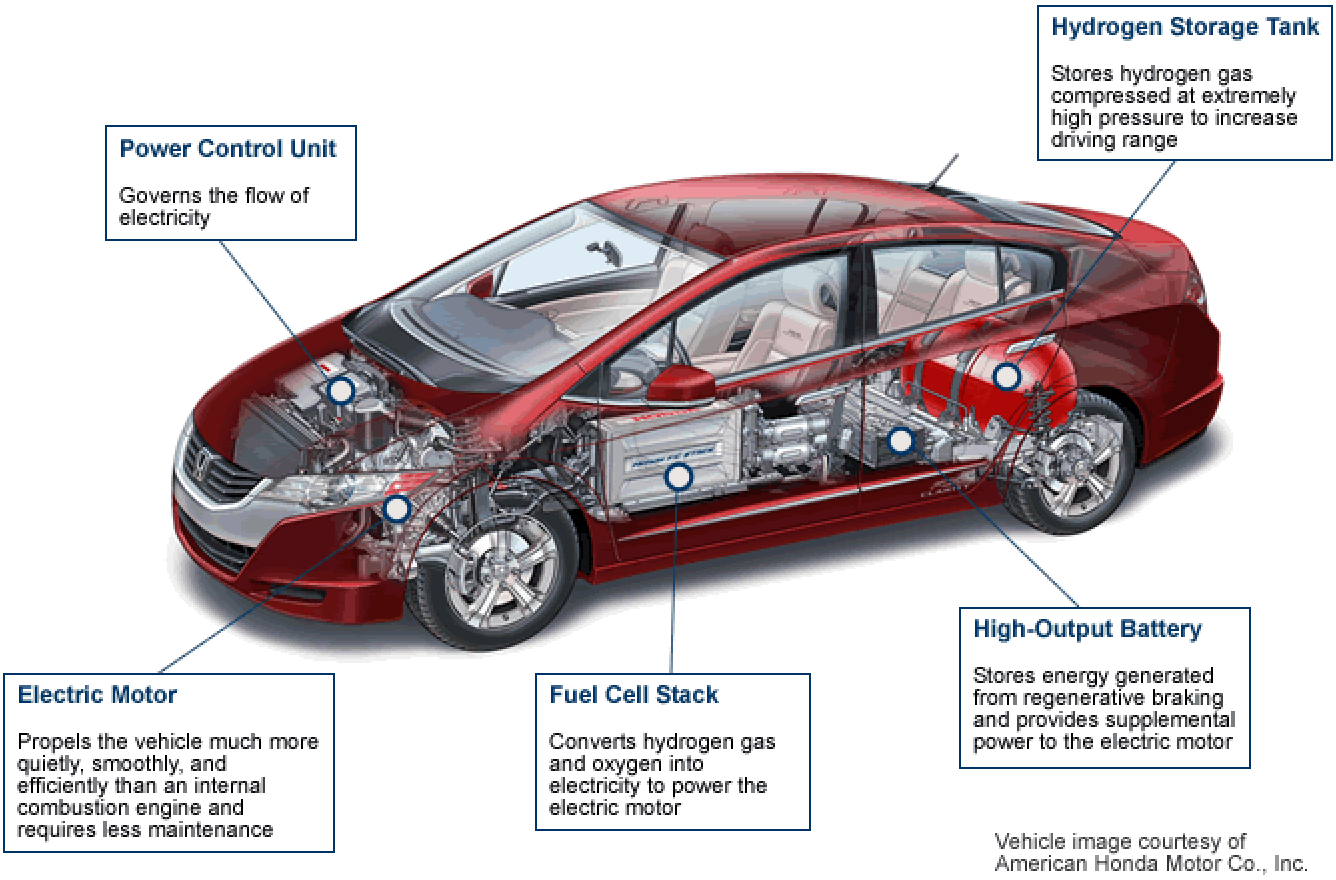

Figure 4 Components of a fuel cell vehicle (American Honda Motor Co)

2.2 PRIMARY ENERGY EFFICIENCY OF ALTERNATIVE VEHICLE TECHNOLOGIES

To compare the efficiency of different technologies of vehicles that use different energy sources, the primary energy efficiency was used as a measure for comparison. Primary energy efficiency takes into account all energy use from the well to the wheel (WTW). The primary energy efficiency for energy chains based on fossil fuels, biomass, and primary electricity from renewable sources, were compared.

Future efficiencies stated are assumed possible, if developments and improvements of key technologies are successful, and energy efficiency has high priority in such developments.

Other studies conducted have compared alternative powertrains with conventional vehicles and analysed the potential benefits regarding energy efficiency.

Most of the studies conducted, have compared only one of the alternatives vehicle technologies with the conventional internal combustion vehicle drivetrain.

The battery-powered electric vehicle (BEV) is compared with the internal combustion vehicle (ICEV) [17, 21]. The hybrid electric vehicle (HEV) and the fuel-cell vehicle (FCEV) are compared with the conventional ICEV [22-25].

When comparing powertrains there is no need to consider the primary energy efficiency [22,23] when using the same energy carrier (such as petrol). When different energy carriers that exhibit varying degrees of energy losses during fuel production and distribution are used, primary energy efficiency analysis becomes necessary [17–19]. Some studies do not include renewable energy sources in their assessments [18]and other studies do not include all the alternative powertrain technologies relevant today in their comparisons. [17,19,25].

The focus is on primary energy efficiency both from fossil and renewable energy resources, and included are all of the currently most feasible alternative powertrains.

2.3 POWERTRAINS

The term powertrain typically refers to the engine, transmission system, and output shaft to drive the road wheels. In the term alternative powertrain we include both the electric drivetrain, energy storage (e.g. batteries and hydrogen storage), and, possibly, a prime mover (ICEV or fuel-cell).

The powertrains studied included electric drivetrains in BEVs, HEVs with an internal combustion engine (ICE) and FCEVs. These vehicles are probable future alternatives to present day ICEVs. The focus is on powertrain technology that could be potentially available within 10–20 years. The time frame is set to enable an assessment of potential without considering the time needed for the development of possibly more advanced powertrains. The future development and possible improvement of the ICEV was also assessed and compared with the alternative powertrains.

The primary energy efficiency calculations by Ahman were based on the three different resources such as fossil fuels, biomass and primary electricity from wind, solar or hydro electric power. The definitions of powertrain efficiency, vehicle efficiency and primary energy efficiency are shown in Figure 5.

W_D is the primary energy, W_C is the energy supplied to the vehicle, W_B is the energy supplied to the powertrain, and W_A is the useful energy at the wheels.

Powertrain efficiency, $\eta_{powertrain} = W_A/W_B$

Vehicle efficiency, $\eta_{vehicle} = W_A/W_C$

Primary energy efficiency, $\eta_{primary} = W_A/W_D$

Using the efficiencies of the different components included in the powertrain, the overall powertrain efficiency was calculated. The component efficiencies are assumed future mean efficiencies achieved over a normal drive schedule.

To calculate the vehicle efficiency, the powertrain efficiency was adjusted to compensate for losses due to the power required for heating and for the benefits when no energy is required as during idling and the use of regenerative braking. The primary energy efficiency included the energy used for energy extraction, conversion, distribution and storage.

The energy incorporated in vehicles was not included. Incorporated energy typically accounts for only 7–8% of total life-cycle energy use today [26]. However, for future fuel efficient vehicles this percentage could increase to between 14 and 18% for the different vehicle alternatives [26]. For electricity, a minor approach was used, which means that the efficiency of the electricity supply was calculated as the efficiency of the supplementary electricity production required by the system to supply the energy for the vehicles.

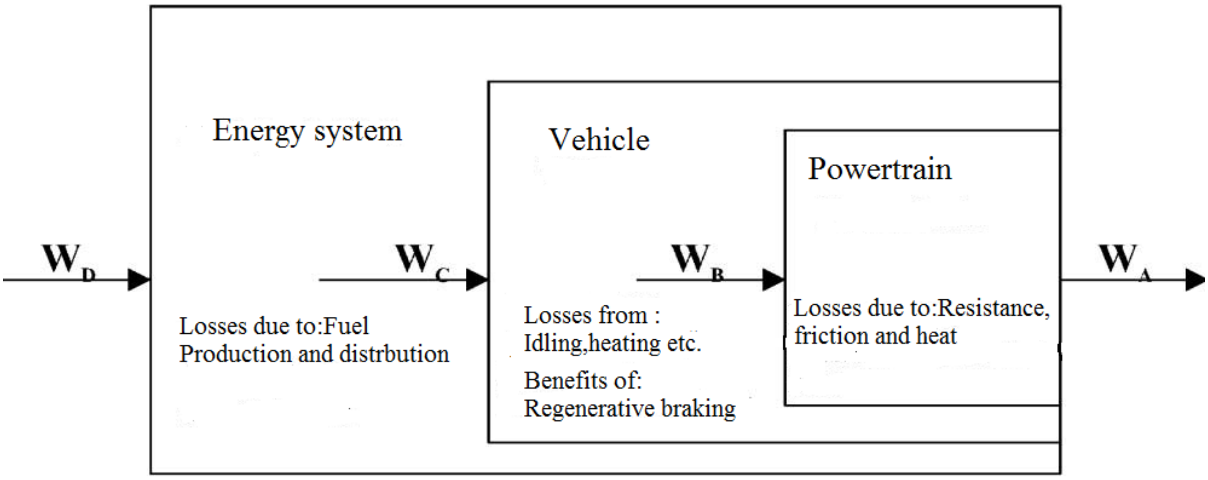

Figure 5 Definitions of primary energy efficiency, vehicle efficiency, and powertrain efficiency.

The new vehicle alternatives are assumed to have the same performance, comfort and size as a conventional vehicle today. Looking at efficiency will, however, not give all the answers as the future weight may differ between the alternatives (notably for the BEV).

2.4 DESCRIPTION OF AVAILABLE VEHICLE TECHNOLOGIES

ICEV with a conventional powertrain

The powertrain of the ICEV consists of a fuel tank, an internal combustion engine (petrol or diesel), coupled to a transmission.

A characteristic of the internal combustion engine is that its maximum efficiency is achieved near the maximum load point. This makes the mean efficiency of the engine relatively low since maximum power is very seldom achieved under normal driving conditions. The mean power required in a US Federal Test Procedure (FTP) schedule is below 10 kW [27], while the maximum power required for an ICEV is between 60 and 90 kW or more, depending on the size of the vehicle.

The mean efficiency is thus low, around 18% in an FTP schedule [17], compared with the maximum efficiency, which is between 35 and 40% in a new engine today.

There are possible options for improving the mean efficiency in the conventional power-train such as variable valve timing, shutting off the engine during idling in traffic, introducing higher compression ratios, turbo charging, and a continuously variable transmission [28].

BEVs and the electric drivetrain

The electric drivetrains of BEVs, HEVs, and FCEVs consist of an electric generator, an electric motor, coupled to a transmission.

A BEVs main drawback is its battery. As a result of the low energy storage capacity of the battery, the driving range of BEVs is restricted compared with the high energy potential of a petrol vehicle. A BEV battery should store up to 30 kWh to afford the vehicle an acceptable driving range. In order to make BEVs commercially viable, the United States Advanced Battery Consortium (USABC) recommends that a BEV battery should be able to store at least 150 Wh/kg [29]. The batteries used are lead/acid (Pb/A), nickel–metal hydride (NiMH), and lithium batteries capable of storing 80–100 Wh/kg [30]. The only battery believed to have the long-term potential to reach the USABC goal of 150 Wh/kg, is the lithium–polymer battery, see, for example [30,31].

The cost of batteries is a major obstacle today. A NiMH battery costs between 500 and 550 US$/kWh [30], which means between 15 000 and 15 500 US$ for a BEV battery package of 30 kWh. Pb/A batteries were the dominating type of batteries in early BEVs and HEVs, but the current BEVs are making use of NiMH or lithium battery.

There has been a great improvement in the efficiency of both generators and electric motors over the past 20 years. Due to the development of advanced electronic control systems, the mean energy efficiency over a normal drive schedule has increased both for generators and electric motors, see, for example [33–35]. Today, only a one-speed reduction-gear is needed to manage all possible power and speed requirements for an electric motor with an advanced control system [33–35]. The general assumption is that the variations in load and speed will, be handled by the electric drivetrain in an efficient manner.

The potential energy efficiency of an electric drivetrain ranges between 65 and 75% (see Table 3). Current efficiencies are lower, around 57%.

Future improvements in efficiency will result from the implementation of an advanced energy control system together with a modern efficient generator and electric motor. The advancement in technology of lithium–polymer batteries could also improve the electric drivetrain efficiency substantially in the future. The electric drivetrain in HEVs may be more efficient than in BEVs due to the potential for more efficient batteries.

Table 3 Assumed future possible component mean efficiencies over a normal drive schedule for the electric drivetrain

Electric drivetrain technologies	Generator (%)	Battery (%)	Electric motor and control system (%)	Transmission (%)	Total energy efficiency for the drivetrain (%)[h]
BEV (NiMH battery) today	85a	80a	86b	98g	57
BEV (NiMH battery) potential	92b	81c	89f	98g	65
HEV (Pb/A battery)potential	92b	90d	89f	98g	72
BEV/HEV (Li-ion battery)potential	92b	95e	89f	98g	76

a The efficiencies of vehicles on the market today differ widely between manufacturers due to rapid development. Assumptions based on [20,36].
b Assumption based on: [37].
c Assumption based on [30,38].
d Pb/A batteries, which are efficient and easy to use in HEVs [23,30].
e The performance of lithium–polymer batteries is difficult to validate because there is basically only one advanced manufacturer, 3M/Hydro-Quebec. Adapted from [31, 39, 40].
f Assumptions based on [33–35].
g Assumed mean efficiency of a reduction gear. Based on: [20,23]. A reduction gear is also assumed in the electric drivetrain in parallel HEVs in the future.
h Multiplying these mean efficiencies is a simplification for calculating the system mean efficiency, but given the uncertainties the figures represent good indicators on future possible mean efficiency.

HEVs with internal combustion engines

Analysis of the hybrid powertrain, reveals an electric motor and a battery which are combined with an internal combustion engine and a fuel tank. The internal combustion engine also referred to as the, primary engine, can charge the battery, or take over the driving from the electric drivetrain when the battery is discharged.

The electric drivetrain are either used in series or in parallel with the primary engine. In a series configuration, all the energy must go through the electric drivetrain. In a parallel configuration, part of the energy passes a mechanical drivetrain. The HEVs sold today are not pure series or parallel configurations, but have increasingly integrated or combined configurations.

Today, ICEs dominate as primary engines, see, for example Toyota Prius and Honda Insight. With hybridisation, the ICE can be designed for the mean power of a normal driving schedule instead of the maximum power required. This allows the engine to operate closer to its maximum efficiency. We have not considered gas turbines or Stirling engines, as the potential for high energy efficiency in passenger-car-sized engines seems to be low, see, for example [41,42].

The mean efficiency of the ICE in a hybrid configuration is shown in Table 4. The ICE usually used is a four-stroke direct injection (4SDI) engine, and the assumed ICE developed for future use is either a compression ignition direct injection (CIDI) engine or a new engine type, combining both CIDI and 4SDI features, e.g. the active thermal atmospheric combustion (ATAC) engine. The parallel configuration assumed in this study is a genuine parallel configuration with as small battery pack as possible.

Table 4 Assumptions of mean primary engine energy efficiency in different configurations

Mean engine efficiency over a normal drive schedule	HEV series configuration (%)	HEV parallel configuration (%)	ICEV (%)
ICE, today (4SDI)	–	–	18a
ICE, future (CIDI or developed 4SDI)	40b	36b	24c

a Efficiency today. Adopted from [17].
b Adapted from [23] assuming a diesel engine with 43% maximum efficiency and a 55%FUDS/45%FHDS. The parallel engine will have to deal with greater variation in load and thus have a lower mean efficiency than the series hybrid. Future engines will probably have the same efficiency, even if they are of another type (e.g. ATAC, 4SDI, GDI).
c Adapted from [28] assuming variable valve timing, idle shut-off, higher compression ratio.

FCEVs

Fuel-cell technology for automotive application today is the proton exchange membrane (PEM) fuel cell. The advantage of this fuel cell is its potential for high energy efficiency and zero emissions.

One disadvantage of the fuel-cell system is the requirement of pure hydrogen for fuel in the cell. Hydrogen can be stored on board the vehicle, either as a liquid, in nanofibres or in hydrides.

Liquid storage of hydrogen is the most energy-consuming alternative. About 50% of the energy content is used to liquefy the hydrogen gas [62,43,44]. The energy efficiency of compressing hydrogen gas to 350 bars is about 70–90% [47]. Another alternative is to use a "hydrogen carrier", such as methanol or petrol, which is used to provide the hydrogen for the cell. Methanol and petrol are easy to store with current vehicle technology, but this solution lowers the fuel-cell system efficiency (see Table 5).

The PEM fuel cell has different efficiency features, compared with the ICE, making hybridisation less interesting. The maximum efficiency of a fuel cell is achieved at 25–50% of maximum load [50], which gives no benefit from reducing maximum power with hybridisation. However, there are other advantages in hybridisation of fuel-cell systems.

The most obvious ones are the possibility to use electricity from the battery during idling and to help FCEVs to start cold, and the possibility of utilising regenerative braking [51,54].

Assumptions regarding the efficiency of a PEM fuel-cell system are given in Table 5.

Table 5 Assumed future PEM fuel-cell system mean efficiency

Mean fuel efficiency, hybrid configuration (%)	Hydrogen gaseous (%)	Hydrogen liquid (%)	Methanol (%)	Petrol (%)
PEM fuel-cell system[a]	47	47	47	47
Reformer efficiency[b]	–	–	85	80
Total fuel-cell system energy efficiency	47	47	40	38

a   Adapted from [39,42,51] with an assumed maximum efficiency of 55% and the efficiency curve in [50].
b   Adopted from [42].

2.5 **EFFICIENCIES OF DIFFERENT POWERTRAINS**

Table 6 shows a summary of the calculated efficiencies for the powertrains of the various types of vehicles. It is provided here to allow for easy cross-comparisons. The highest efficiency is achieved by the battery-powered electric vehicle. The two hybrid powertrains and the fuel-cell powertrain fuelled with methanol have approximately the same efficiency. The fuel-cell powertrain fuelled with pure hydrogen gas has about 20% higher efficiency than when it is fuelled with methanol. Furthermore, there is a considerable potential for improvement in the ICE powertrain.

The electric drivetrain offers the benefits of zero fuel use during idling and the possible use of regenerative braking. However, there is also a disadvantage in that electric power is needed for heating, since the heat losses from the electric motor are too small to cover the demand for interior heating of the vehicle. All these features influence the total vehicle efficiency (see

Table 7). In order to calculate the effects on vehicle efficiency, the energy sinks for braking, idling and heating were estimated according to Amann [22] and DeCicco and Ross [28].

The calculated difference between vehicle and powertrain efficiency is small. However a small relative improvement for vehicles using electric drivetrains compared with vehicles using ICE powertrains can be identified in Table 7.

In addition to powertrain efficiencies, it is also useful to look at primary energy efficiencies which takes into account the electricity generation and transmission losses.

The primary energy efficiencies, when fossil energy sources are used, are given in Table 8. The fossil fuels originate from crude oil or natural gas. Minimal fossil based electricity generation from coal was assumed in the short term and, in the long term, minimal electricity from natural-gas plants was assumed. The reason for this is that power from new natural-gas plants is produced at a lower cost than in new coal-fired plants [52].

When considering electricity production, based on natural gas, the BEV has the highest primary energy efficiency. The advantage with regard to the emission of CO2 is even higher due to lower carbon content per unit energy than in coal or oil. If the electricity is generated from coal, the primary energy efficiency for BEVs is lower than for HEVs and FCEVs.

HEVs with advanced heat engines are twice as efficient as current vehicles today [53] FCEVs have lower efficiencies than HEVs due to high conversion losses from natural gas to hydrogen or methanol. An important option for CO2 reduction is the use of biomass as a renewable energy carrier [52].

The primary energy efficiencies for vehicles using energy carriers based on biomass are given in Table 9. The BEV has the highest potential for primary energy efficiency. One reason for this, apart from the high vehicle efficiency, is the fact that liquid and gaseous fuels are produced from biomass with relatively low efficiency. The various HEVs and FCEVs all have similar efficiencies.

Finally, the primary energy efficiencies for vehicles using primary electricity from solar, wind, or hydro power are given in Table 10. In this case, only BEVs and FCEVs were considered. Hydrogen for the fuel cell is produced through the electrolysis of water. The efficiency of producing primary electricity is set to 100% for all the alternatives.

There is a substantial energy loss when converting electricity to hydrogen and back to electricity again in the FCEV. For this reason, the most efficient alternative would be to use the electricity directly in a BEV. Hydrogen is, however, easier to store than electricity and is a practical energy carrier, however hydrogen is a highly combustible gas which could be dangerous when used in vehicles. .

Table 6 Future powertrain efficiencies

Powertrain efficiency	Primary engine(%)[a]	5 speed transmission(%)	Electric drivetrain(%)[b]	Powertrain total energy efficiency
Battery powered powertrain	-	-	65	65
Hybrid powertrain parallel	36	92	68[c]	30[d]
Hybrid powertrain series	40	-	72	29
Methanol fuel cell powertrain	40	-	72	29
Hydrogen fuel cell powertrain	47	-	72	34
ICE powertrain current	24	92	-	22
ICE powertrain improved	18	92	-	16

a Based on Table 4.
b Based on Table 3.
c Adapted from Table 3 with the exception that the transmission is assumed to be mechanical.
d Assuming a 55% city driving schedule with electric drivetrain and 45% highway driving schedule with a mechanical drivetrain.

Table 7 Vehicle efficiency calculated as consumed energy at the wheels divided by the total energy supply to vehicle, see Fig. 5

Vehicle	Consumed energy at the wheels (%)	Energy out from powertrain[a] (%)	Energy to powertrain[b] (%)	Energy required for extra loads[c] (%)	Energy losses due to idling[d] (%)	Total energy supplied to the vehicle (%)	Vehicle efficiency (%)
BEV	100	95	146	17	0	163	61
HEV parallel	100	95	327	14	0	340	29
HEV series	100	95	327	14	0	340	29
FCEV methanol	100	95	327	14	0	340	29
FCEV hydrogen	100	95	279	14	0	293	34
ICEV improved	100	100	452	10	27[e]	489	20
ICEV current	100	100	625	10	75	700	14

a 5% of consumed energy at the wheels is saved due to regenerative braking which assumes that 25% of the braking energy is regenerated. This relatively low figure is due to traffic safety.
b Calculated as (energy out from powertrain)/(powertrain efficiency based on Table 6).
c Assumed to be 10% of the useful energy at the wheels according to [28]. Consideration taken of the fact that some heat losses can be used for heating for the FCEV and the HEV.
d Energy during idling assumed to be 12% of "energy to powertrain". Adapted from [22,28].
e 50% of energy used during idling can be saved, according to [28].
f Calculated as (consumed energy at the wheels)/(total energy supplied to vehicle).

Table 8 Primary energy efficiency with a fossil fuel primary energy source

Vehicle	Primary energy	Energy carrier	Primary energy to energy carrier[a] (%)	Distribution[b] (%)	Vehicle efficiency[e] (%)	Primary energy efficiency
BEV	Coal	Electricity	40[c]	93	61	23
BEV	Natural gas future	Electricity	55[d]	93	61	31
HEV parallel	Crude oil	Diesel	95.3	99.8	30	28
HEV series	Crude oil	Diesel	95.3	99.8	29	28
FCEV	Natural gas	Hydrogen (350 bar)	85	86	34	25
FCEV	Natural gas	Methanol	72	99.6	29	21
ICEV future	Crude oil	Petrol	91.5	99.8	20	19
ICEV today	Crude oil	Petrol	91.5	99.8	14	13

a Adopted from [55,63].
b Adopted from [55,63].
c Relates to Danish coal power with an efficiency ranging between 36% and 47%.
d Adopted from [64].
e From Table 7.

Table 9 Primary energy efficiency with biomass as primary energy source

Vehicle	Primary energy	Energy carrier	Primary energy to energy carrier[a] (%)	Distribution[b] (%)	Vehicle efficiency[e] (%)	Primary energy efficiency
BEV	Biomass	Electricity	45[c]	93	61	25
HEV parallel	Biomass	Methanol	63	99.6	30	19
HEV series	Biomass	Methanol	63	99.6	29	18
FCEV	Biomass	Hydrogen (350 bar)	69	86	34	20
FCEV	Biomass	Methanol	63	99.6	29	18
ICEV future	Biomass	Methanol	63	99.6	22[d]	14
ICEV today	Biomass	Methanol	63	99.6	15[e]	10

a   Adopted from [55,63].
b   Adopted from [66].
c   Adopted from [55,63].
d   Efficiency is assumed to be 10% higher than for petrol. Source: [65].
e   Efficiency is assumed to be 6% higher than for petrol. Source: [65].
f   From Table 7.

Table 10 Primary energy efficiency with solar, wind or hydropower as primary energy source

Vehicle	Primary energy	Energy carrier	Primary energy to energy carrier[a] (%)	Distribution[b] (%)	Vehicle efficiency[e] (%)	Primary energy efficiency
BEV	Solar, wind or hydropower	Electricity	100	93[a]	61	57
FCEV	Solar, wind or hydropower	Hydrogen (350 bar)	90[c]	86[b]	34	26

a Adopted from [63].
b Adopted from [55].
c Adopted from Ogden and Nitsch [56] who assumed that the efficiency today (1994) of 70–75% can be increased to 85–90% in the future.
d From Table 7.

2.6 ENERGY ANALYSIS OF VEHICLE TECHNOLOGIES USING WELL-TO-WHEEL DRIVING CYCLE SIMULATIONS

After the preliminary WTW analysis carried out under nominal operating conditions, the focus should be on the simulation of the vehicles energy consumption when following standardized ECE-EUDC driving cycle.

The analysis is carried out considering different hypothesis about the vehicle driving range, the maximum speed requirements and the possibility to sustain more aggressive driving cycles. The analysis shows interesting conclusions, with best results achieved by BEVs only for very limited driving range requirements, while the fuel cell solutions yield best performances for more extended driving ranges where the battery weight becomes too high.

Results are finally compared to those of conventional internal combustion engine vehicles, showing the potential advantages of the different vehicle technologies.

2.7 MODELLING OF THE FORCES ACTING ON A VEHICLE

In Requirement Development for Electrical Vehicles Using Simulation Tools by Zhan, McDermott, Zoghi, and Hasan is shown that the energy required to move a vehicle is determined by the distance it travels and the force it has to overcome. The road load force the vehicle must overcome in order to move the given distance consists of three components [58, 61], as illustrated in Figure 6:

1. The component of the gravity force in the direction of travel, if it is a sloped path.

2. The aerodynamic drag.

3. The rolling resistance.

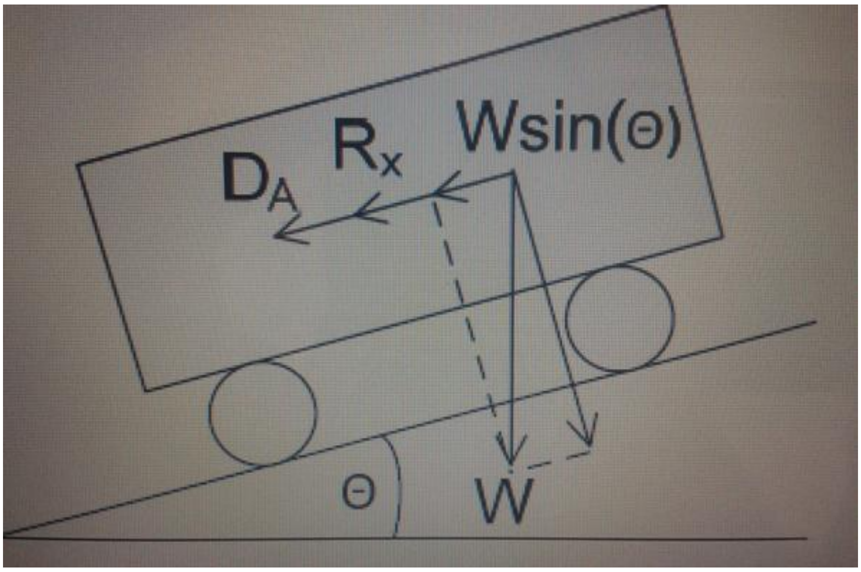

Figure 6 Road load force components

<u>Projected gravity force</u>

The force of gravity consists of two components, one in the direction of travel, and the other in the direction perpendicular to the surface. In order to move the vehicle up the slope surface, the vehicle must overcome the force of gravity component in the direction of travel.

This is given by

$$\mathbf{Wx = Wsin(\theta)} \qquad \mathbf{(1)}$$

where W is the gravity force, θ is the angle of the inclined surface, and Wx is the component of the force of gravity in the direction of travel.

On a flat surface, the force of gravity is perpendicular to the direction of travel, and will not directly contribute to the energy required to move the vehicle.

The force of gravity also has an indirect impact on the amount of energy required to move a vehicle, since the weight has an influence on the rolling resistance of the vehicle.

Aerodynamic drag

The drag is a function of speed for any given vehicle. At low speed the drag force is negligible. At high speed, the drag becomes a significant factor. For simplicity, a semi-empirical model is used here [46].

$$\mathbf{D_A = \frac{1}{2}\rho V^2 C_D A} \qquad \mathbf{(2)}$$

where V is the vehicle speed (m/s), A is the frontal area of the vehicle (2), CD is the aerodynamic drag coefficient, DA is the aerodynamic drag (N), ρ is the air density ($kg.m^{-3}$).

The rolling resistance

Rolling resistance of the tyres is a major vehicle resistance force. It is the dominant motion resistance force at low speed (<80 Km/h). The rolling resistance can be modelled as the vehicle static weight W multiplied by the coefficient of rolling resistance fr,

$$\mathbf{Rx = frW} \qquad \mathbf{(3)}$$

The coefficient of rolling resistance is affected by tyre construction, tyre temperature, vehicle speed, road surface, and tyre pressure. For instance, the rolling resistance coefficient changes as the temperature changes. To simplify our analysis, we make the following assumptions [67]:

- The tyre pressure is maintained at the value specified by the OEM.
- The tyre temperature is above 10^oC.
- The vehicle is driven on a dry concrete surface at a speed below 96.56 Km/h.

With these assumptions, the coefficient of rolling resistance can be assumed constant. Typical values for the coefficient of rolling resistance fr are between 0.01 and 0.02 under the above assumptions. We use 0.015 as the nominal value [67]. :

Dynamic weight transfer and the aerodynamic lift force have negligible effects on the coefficient of rolling resistance.

Power required

Based on the above analysis, the power required to drive the vehicle at a given speed V (mph) is given by the total road load forces multiplied by the vehicle speed, i.e.,

$$\mathbf{HP = 0.00267(D_A + Rx + Wx)\ V} \qquad \mathbf{(4)}$$

where Wx can be calculated using (1), DA is given by (2), Rx can be calculated using (3) with fr = 0.015, and 0.00267 is the conversion factor to horsepower, HP. To calculate these quantities, we need the following inputs:

- vehicle speed (km/h).
- vehicle weight (including trailer if there is one) (kgs).
- frontal area of the vehicle, (including trailer if there is one) (m^2).
- aerodynamic drag coefficient.
- coefficient of rolling resistance.
- surface slope angle (degree).

Energy required

Energy is power integrated over time. If the total distance travelled is long enough, the initial acceleration and final deceleration have negligible effect on the total energy calculation. Also, since this is a steady state analysis the aerodynamic drag is constant.

Noting that Wx = Wsin (θ) and

V = dx/dt, it follows that

$$\int Wx\ \frac{dx}{dt}dt = \int Wsin(\Theta)dx = \int \sin(\Theta)\,dx = W\Delta h$$

where Δh is the change in elevation between the starting and ending points. Thus, the energy required to move a vehicle for a distance of d (miles) at a speed V (mph) with a change in

elevation of Δh (miles) is given by:

E (kWh) = 0.00267[(DA+Rx)d + W Δh] × 0.746 (kW)/Hp

= 0.002 [(DA +Rx)d + WΔh]. (5)

Define θ* as the average slope; i.e.

sin θ* = Δh/d

and

Wx* = W sin θ*

Then the trip energy becomes

E (kWh) = 0.002(DA +Rx + Wx*)d. (6)

At first glance, the energy calculation in (6) appears to be independent of the speed. A closer look reveals that the energy is dependent on the speed since the aerodynamic drag *DA* is dependent on the vehicle speed. If speed is not constant, equations (5, 6) do not apply and the power consumed to overcome drag must be evaluated as an integral.

The energy calculations in (6) can be converted to MJ (1kWh = 3.6 MJ):

$$E\ (MJ) = 0.0072(DA + Rx + Wx^*)d. \qquad \textbf{(7)}$$

Dynamic Analysis

When the vehicle is driven over a short period of time or the time spent in accelerating/decelerating is a significant portion of the total time, steady state analysis is not adequate. Instead, dynamic analysis is needed.

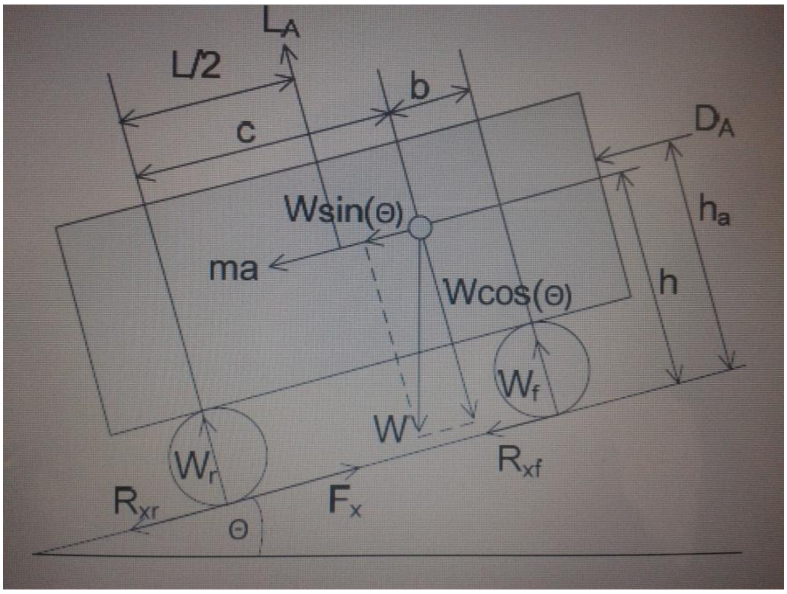

Figure 7 **Vehicle dynamics model**

The forces acting on the vehicle are illustrated in Fig. 7
.

- W is the gravity force.
- Rxf and Rxr are front and rear rolling resistant forces and Rxf +Rxr = Rx.
- Wf and Wr are front and rear normal forces.
- DA is the aerodynamic drag.
- LA is the aerodynamic lift.
- Fx is the tractive force (rear wheel drive is assumed).

Compared to the vehicle forces and inertia, the dynamics of the motor and wheels are not significant and hence not considered here. Newton's Second Law is applied in the direction of the vehicle movement and the direction perpendicular to the road surface.

$$\mathrm{Fx} - \mathrm{W}\sin\theta - \mathrm{DA} - \frac{\mathrm{w}}{\mathrm{y}}\mathrm{a} - \mathrm{Rx} = 0 \qquad \textbf{(8)}$$

$$\mathrm{Wf} + \mathrm{Wr} + \mathrm{LA} - \mathrm{W}\cos\theta = 0 \qquad \textbf{(9)}$$

where the aerodynamic lift force is given by

$$\mathrm{LA} = \frac{1}{2}\boldsymbol{\rho}\mathbf{V}^{2}\mathbf{C}_{\mathbf{L}}\,\mathbf{A} \qquad \textbf{(10)}$$

Typical values for aerodynamic lift coefficient is CL = 0.3-0.5 [47]. The lift force is applied at the centre of the wheel base.

CHAPTER 3 METHODOLOGY

The methodology used in the conduct of this study consist of a few different stages, namely selection of routes, extraction of topographical data, calculation of vehicle forces, calculation of fuel or energy consumption and estimation of cost of fuel or energy. The entire exercise was performed on characteristics of a typical sedan car. Table gives the information about the vehicle used for this study.

Table 11 Characteristics of idealised vehicle used for the study

Hyundai Accent 1.6	
Car Length	4.28 m
Gross Vehicle Mass (GVM)	1580 kg
Coefficient of drag	0.30
Wheel rim diameter	14 inch

3.1 SELECTION OF ROUTES

Several popular game viewing routes in the Kruger National Park were selected in order to cover a range of driving conditions. The parameters used for the selection were the road surface, overall gradients and route length. For this study, 6 routes were chosen and are shown below. Figures 8 to 13 give a visual of each route and were generated by using Google earth.

3.1.1 Route 1

This route is a section of the Olifants camp road leading to the Olifants rest camp. The route surface consists of sand and has a length of 8.884 Km and displays repeated uphill and downhill sections. The route runs in a west to east direction through rugged veld terrain and is situated centrally in the Kruger national park. It has a minimum elevation of 204 m and a maximum elevation of 266 m.

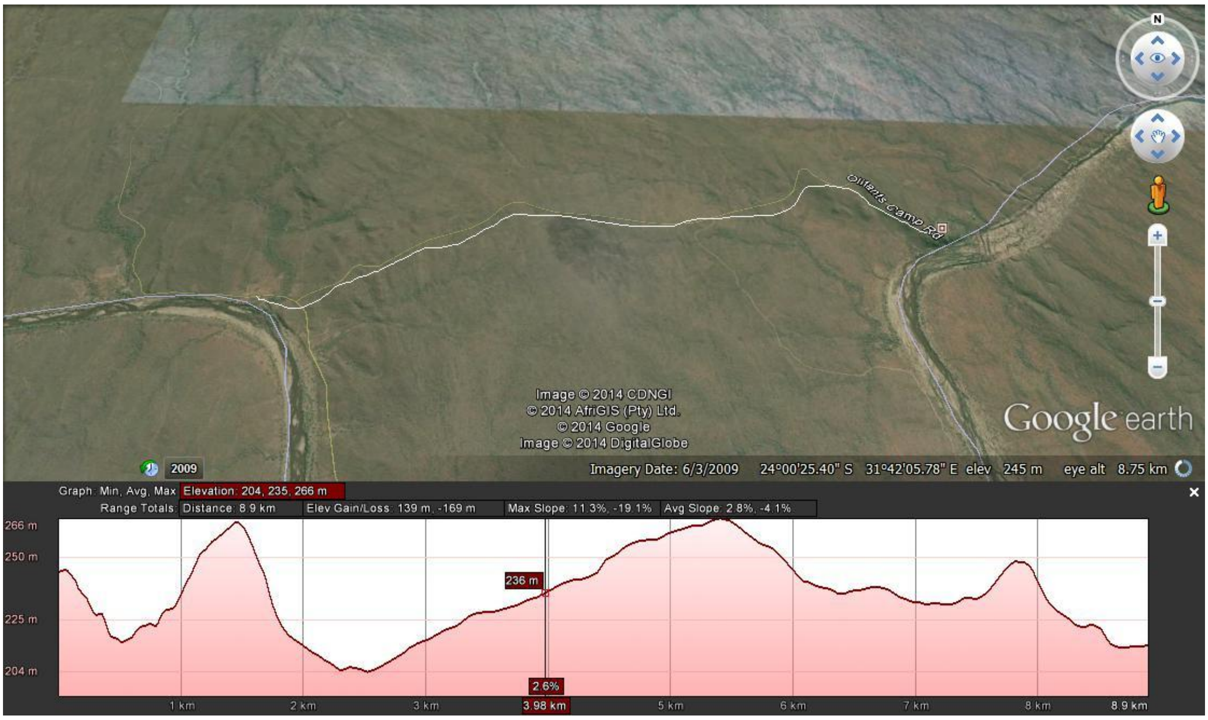

Figure 8 Route 1

3.1.2 Route 2

The route represents a section of road connecting the Berg-en-Dal rest camp to the Malelane Skukuza road. The route runs from a westerly to a north easterly direction through mountainous bushveld in the southern tip of the Kruger Park. The route surface is sand. It has a length of 14.644 Km. The route displays small up hills and down hills with more pronounced up hills towards the end. The route has a minimal elevation of 332 m and a maximum elevation of 491 m.

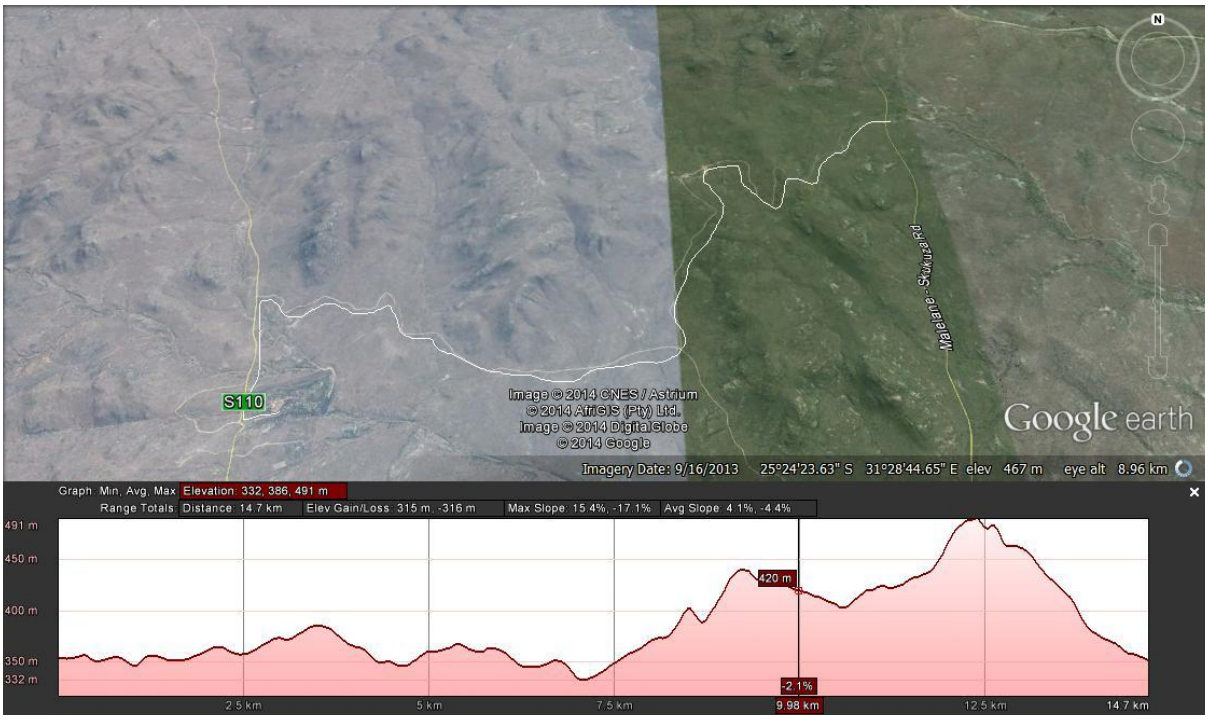

Figure 9 Route 2

3.1.3 Route 3

The route represents the section of road linking the Skukuza rest camp to the Tshokwane picnic site. The route runs from the south to north easterly direction through thorn thicket bushveld terrain in the south part of the Kruger Park. The route surface is tar and the length of the route is 13.264 Km. The route displays small uphills with larger down hills. It has a minimum elevation of 249 m and a maximum elevation of 290 m.

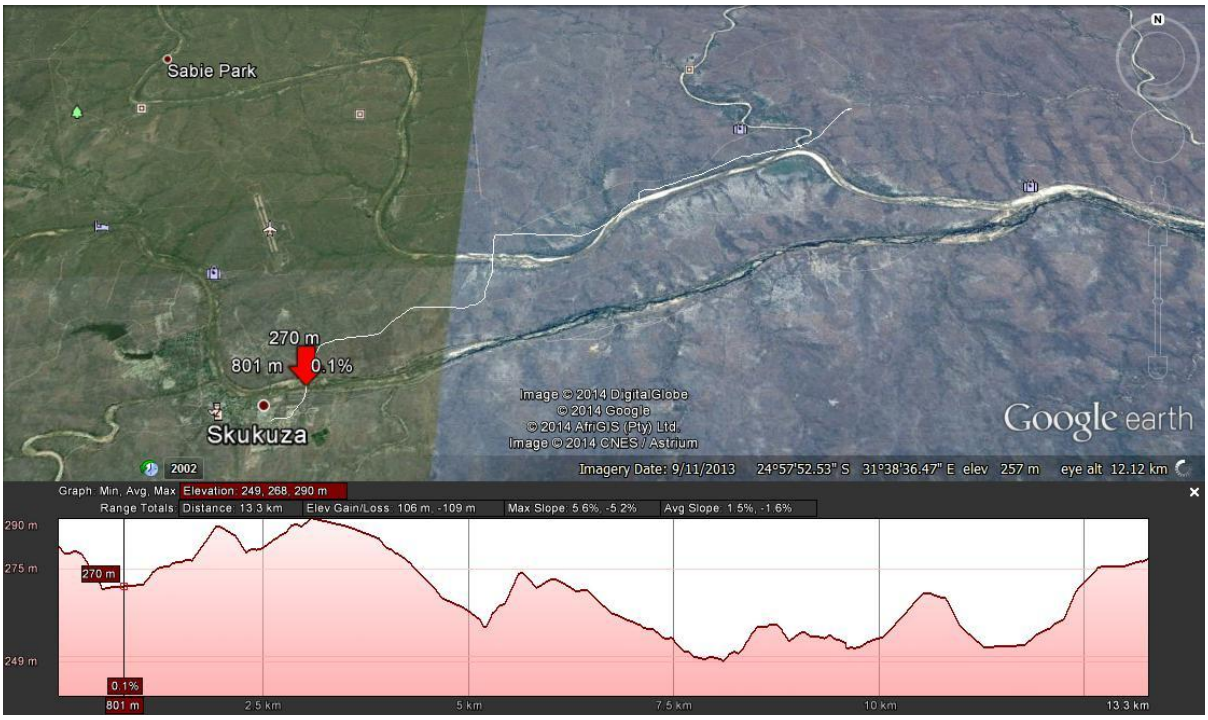

Figure 10 Route 3

3.1.4 Route 4

The route represents the section of road linking the Phalaborwa gate to the Letaba rest camp. The route runs from the west to the east through bush willow woodland terrain in the central part of the Kruger Park. The route surface is tar and the length of the route is 13.746 Km. The route displays small up hills with larger down hills. It has a minimum elevation of 390 m and a maximum elevation of 427 m.

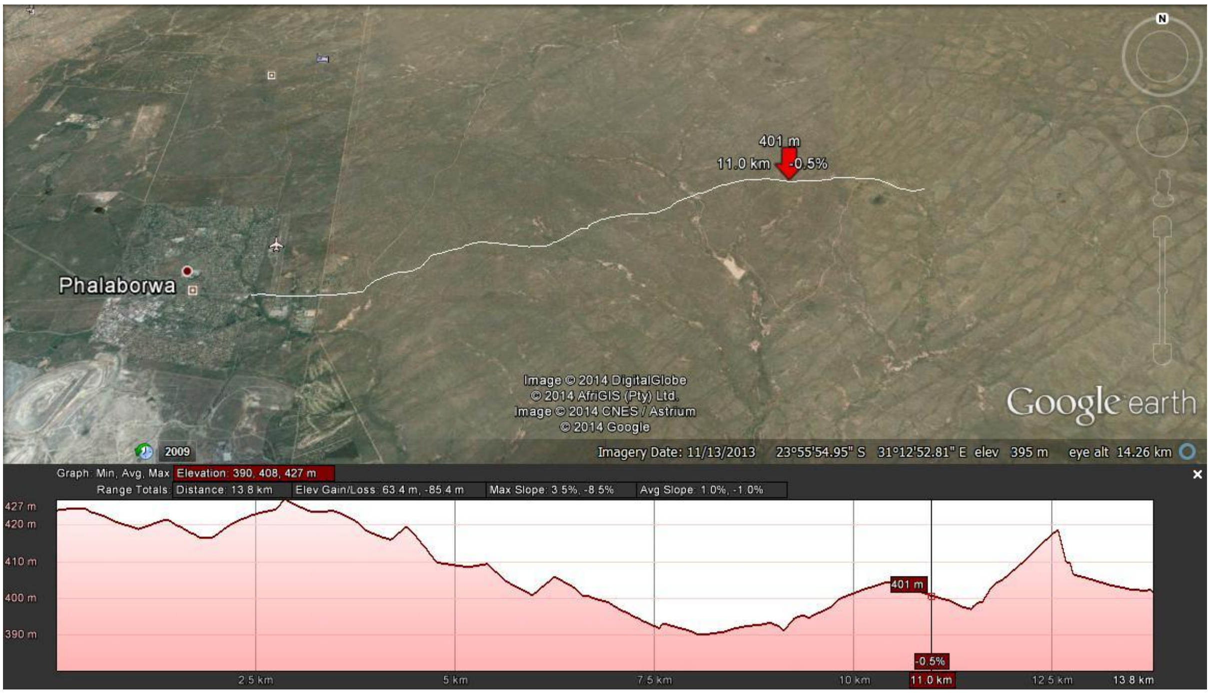

Figure 11 Route 4

3.1.5 Route 5

The route represents the section of road linking the Honeyguide tent camp to the Talamati bush camp. The route runs from the west to the east through bushveld terrain in the central part of the Kruger Park. The route surface is sand and the length of the route is 17.341 Km. The route displays mainly down hills. It has a minimum elevation of 369 m and a maximum elevation of 443 m.

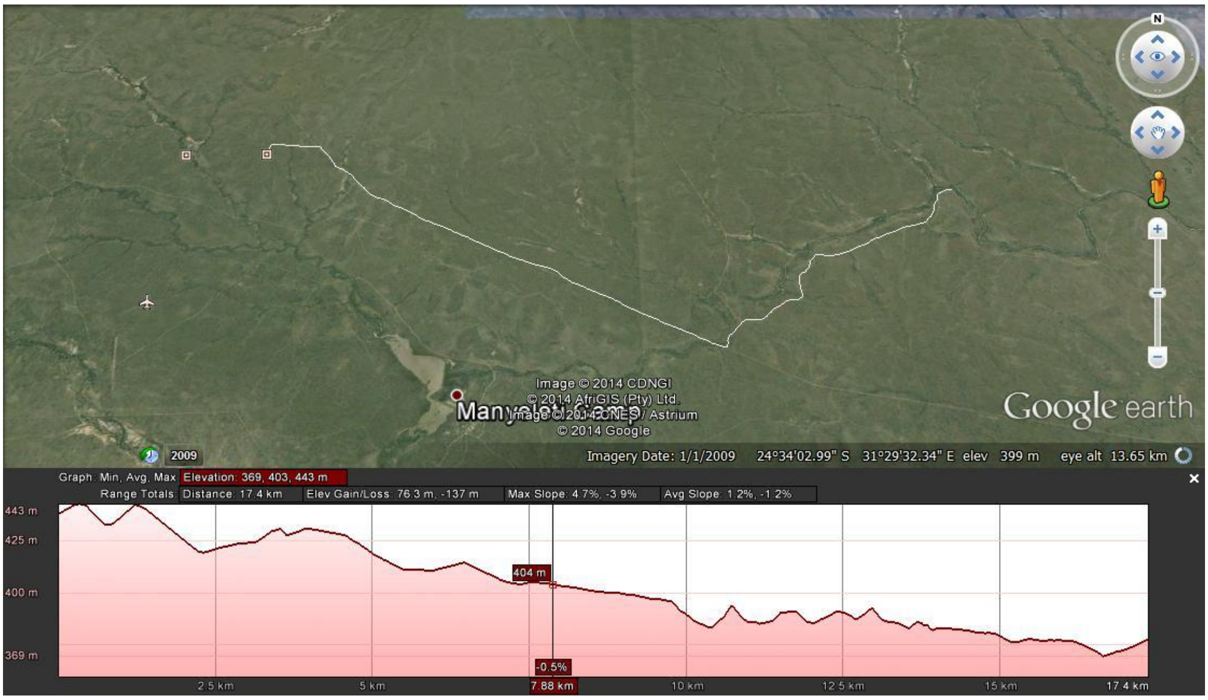

Figure 12 Route 5

3.1.6 Route 6

The route represents the section of road linking the Lower Sabie rest camp to the Tshokwane picnic site. The route runs from a southerly to a northerly direction through Maroela veld terrain in the southern part of the Kruger Park. The route surface is tar and the length of the route is 13.609 Km. The route displays mainly up hill. It has a minimum elevation of 168 m and a maximum elevation of 241 m.

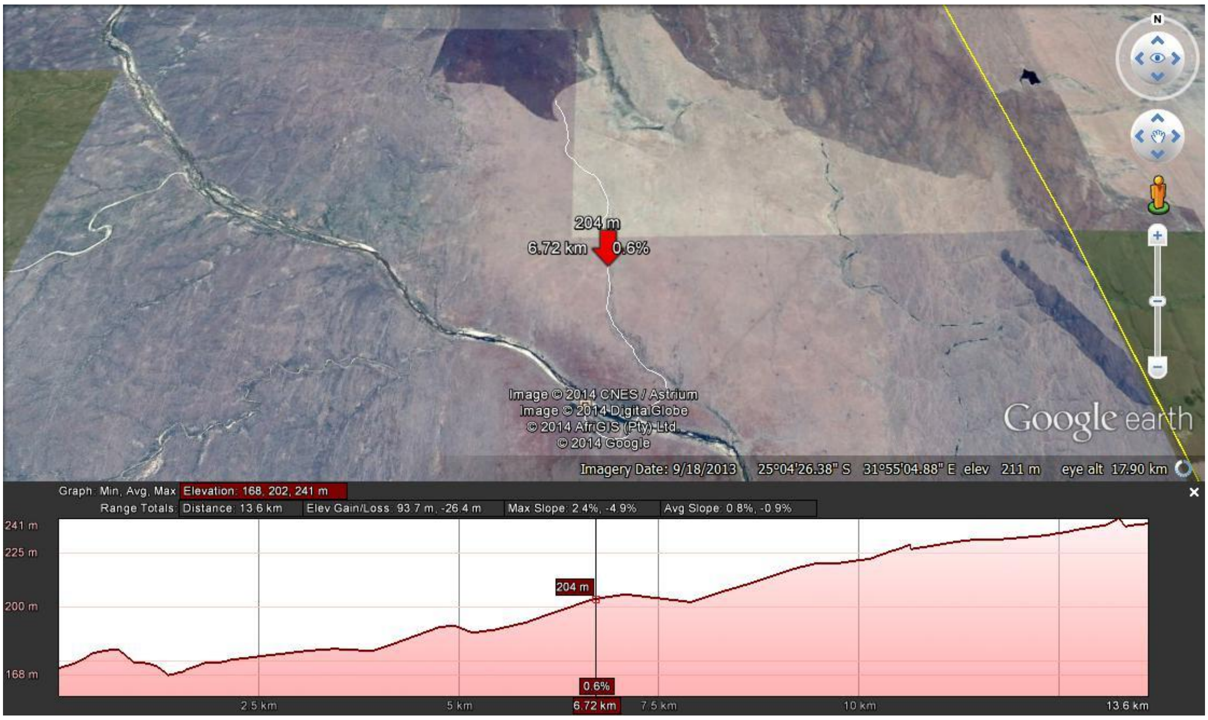

Figure 13 Route 6

3.2 TOPOGRAPHICAL DATA

Due to budget and practical limitations, actual data collection in situ using surveying techniques were not used. Instead, the free software Google Earth was used for the selection of routes as well as for gathering of topographical data.

After the routes were selected, each route was saved as a KML file which is a proprietary file format used to store and display the geographical data in either Google Earth or Google Maps. KML uses a tag-based structure with nested elements based on the XML standard.

The KML file is then imported to the Geocontext-Profiler program [68].

The program Geocontext-Profiler, creates topographic profiles anywhere on earth as well as in the seabed and ocean floor. The program, with its advanced options allows you to create a profile along the road and it measures the slope angle.

The program can import KML, KMZ and GPX files from GPS devices. It then outputs the topographical data in a comma separated value (CSV) format file.

The Geocontext-Profiler extracts data at a minimum interval of 1 metre. For the purpose of this study, we require data at 1 metre intervals. Spline interpolation in Matlab was used to get data at the required interval. See appendix for the spline interpolation code.

3.2 VEHICLE FORCES

A positive gradient indicates that the vehicle is travelling upslope and a negative gradient indicates that it is travelling downslope. A zero value gradient indicates that the vehicle is travelling on a level section of the route. The gradient is expressed in terms of an angle in radians.

A force calculating exercise is conducted with a mass simulating a car and it is used to calculate the driving force required for each of the routes at 1 metre intervals. A speed of 30km/h (speed limit of game parks) was selected for this and deeming the aerodynamic drag experienced by the vehicle negligible due to the low speed. The details of these calculations are as follows:

3.3.1 Vehicle travelling up slope

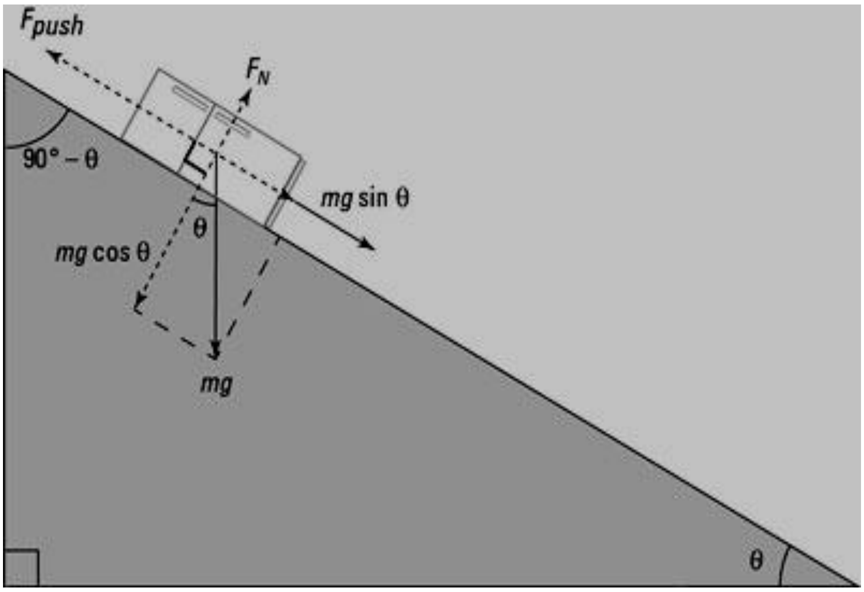

Figure 14 Forces acting on a body up a slope

Normal force (F_N) is the force that pushes up against a vehicle, perpendicular to the surface of the road that the vehicle is resting on. The normal force isn't necessarily equal to the force due to gravity; it's the force perpendicular to the surface a vehicle is moving on.

A vehicle must battle gravity and friction to move up a slope.

The minimum force needed to push the vehicle up the ramp has a magnitude F_{push}, and it has to counter the component of the weight of the vehicle acting along the ramp and the force due to friction.

The first step in this is to resolve the weight of the vehicle into components parallel and perpendicular to the ramp. Taking a look at figure 14, it shows the vehicle and the forces acting on it. The component of the weight of the vehicle along the slope which either assists or hampers the locomotion is

$$\mathbf{F\ weight\ assist = mg\sin\theta} \qquad \mathbf{(11)}$$

Where m is the mass of the vehicle, g is the gravitational acceleration, θ is the angle of the inclined surface.

The component of the vehicle’s weight perpendicular to the slope together with the acceleration due to gravity is

$$\mathbf{F_N = mg\cos\theta} \qquad \mathbf{(12)}$$

When the component of the weight along the slope is known, the minimum force required to push the vehicle up the ramp can be worked out. The minimum force has to overcome the static force of friction acting down the slope and the component of the vehicle’s weight acting down the slope, so the minimum force is

$$\boldsymbol{F_{push}} \mathbf{= mg\sin\theta + FF} \qquad \mathbf{(13)}$$

After the vehicle starts moving, you can keep it moving with less force. The force of friction is:

$$\mathbf{FFriction = C_{rr}F_N} \qquad \mathbf{(14)}$$

Where C_{rr} is the coefficient of rolling resistance, F_N is the normal force.

The **normal force (F_N)** is needed to continue motion. F_N is equal and opposite to the component of the vehicle’s weight acting perpendicularly to the slope.

Now as we have already seen the **normal force (F_N)** acting on the vehicle is given by:

$$\mathbf{F_N = mg\cos\theta}$$

This can be verified this by letting theta go to zero, which means that F_N becomes *mg*, as it should.

The **force of friction (F_F)** is then given by:

$$\mathbf{FFriction = C_{rr}mg\cos\theta} \qquad \mathbf{(15)}$$

The **minimum force** required to overcome the component of the weight acting along the slope and the static force of friction is given by:

$$F\ push \geq C_{rr} mg\cos\theta + mg\sin\theta \qquad (16)$$

3.3.2 Vehicle travelling down slope

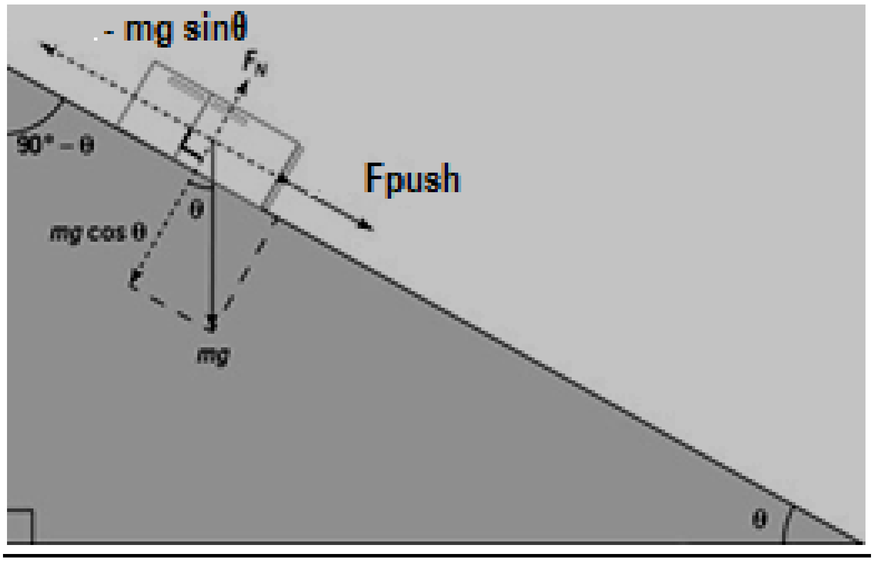

Figure 15 Forces acting on a body down a slope

Similarly by using the different force formulas shown previously, the minimum forces can be calculated at 1 metre intervals, when the vehicle is moving down a slope.

The minimum forces were calculated at 1 metre intervals which are then summed up to calculate the total force required by the vehicle to travel the entire route. The total force can then be converted into power which in turn can be converted into the energy requirements of the vehicle. These calculations are shown in section 3.4.

3.4 CALCULATION OF FUEL OR ENERGY CONSUMPTION

A speed of 30km/h was chosen as the average speed the vehicle is travelling at, and it has to be taken into consideration when calculating the total energy consumption because the higher the speed the vehicle is travelling, the higher the energy consumption. The speed of the vehicle has to be converted from km/h to m/s. This is given by:

Speed in m/s = speed in km/h x 1000m ÷ 3600s

The power required by the vehicle to travel 1m of the route is given by :

Power (Kw)= F_{push} (N) x speed (m/s) ÷1000

After determining the vehicle power requirements of the particular route, this power can easily be expressed in terms of energy usage.

We need to find out how long does it take for the vehicle to travel 1m at the current speed. This is given by:

$$\text{Time(S)} = \frac{\textbf{Distance (m)}}{\textbf{Speed (ms}-\textbf{1)}} \qquad (17)$$

To calculate the energy consumption at 1m length intervals along the route, is given by:

Energy (J) =Power (w) x time(s) **(18)**

The above formula calculates the energy required by the vehicle in order to be able to travel this particular route. However the input energy that must be supplied to the vehicle is much larger as power trains losses must be taken into account. To calculate the input energy to the vehicle is given by:

Input Energy = Energy x % powertrain efficiency

The input energy of the vehicle must be expressed in different units for different types of vehicle technologies

For an electric vehicle (1kWh = 3600kJ)

The kwh usage is given by :

kWh =Input Energy ÷3600

For a HEV vehicle (1 litre of petrol = 34MJ) [69].

The amount of litres of fuel used is given by:

Litres of fuel = Input Energy ÷34000

For an FCEV (1 kg of Hydrogen= 120 MJ)[70].

The amount of hydrogen gas in kilograms used is given by:

H_2(kg) =Input Energy ÷120000

For an ICEV vehicle (1 litre of petrol = 34MJ)

The amount of litres of fuel used is given by:

Litres of fuel = Input Energy ÷34000

Estimation of cost of fuel or energy

The fuel or energy costs of the vehicle travelling on a route can be calculated as follows:

For a BEV the energy costs for a route in Rands is given by:

Cost of KWh in Rands = kWh consumed x price of kWh unit

For a HEV the fuel cost for a route is given by:

Cost of Litres of fuel in Rands = Litres of Fuel x price of fuel per litre

For a FCEV the cost of hydrogen fuel for a route is given by:

Cost of Hydrogen gas in Rands = H_2 (Kgs) x price per kg

For an ICEV the fuel cost for a route is given by:

Cost of Litres of fuel in Rands = Litres of Fuel x price of fuel per litre

3.5 CALCULATION OF POWERTRAIN EFFICIENCY

A fraction of the energy derived from fuel is actually used by a conventional vehicle for propulsion. The rest of the energy is lost to engine and driveline inefficiencies or used to power accessories.

Data on energy losses experienced, such as engine losses, parasitic losses and drivetrain losses on the different vehicle technologies were extracted from the US Department of Energy website [71], with the provided estimates based on analysis of over 100 vehicles by the Oak Ridge National Laboratory in the United States and are shown in Table 12.

This data was used to calculate the powertrain efficiencies, and vehicle efficiencies of the different vehicle technologies.

To calculate the % powertrain efficiency (η) is given by:

% of Powertrain efficiency (η) = % of Useful Energy at the wheels (WA) -% of Engine losses - % of Parasitic losses - % of Drivetrain losses

To calculate the % vehicle efficiency (η) is given by:

% of Energy supplied to the powertrain (WB) = % of Energy output from powertrain ÷ % of Powertrain efficiency

% of Total Energy supplied to the Vehicle (WC) = % of Energy supplied to powertrain (WB) + % of Idling energy losses

% of Vehicle efficiency (η) = % of Useful Energy at the wheels (WA) ÷ % of Total Energy supplied to the Vehicle (WC)

3.6 FUTURE ENERGY AND FUEL COSTS

A future energy cost forecast was also performed in order to calculate the cost of fuel in the next 10 years. Forecasting crude oil prices has never been an easy task, though it is important for so many economic sectors. Looking ahead, there are several issues that can inform the process of making assumptions for future price paths. These include: the behaviour of futures markets and the expected future demand and supply balances and lastly the impact of geopolitics. For the purpose of this study the projections of crude oil price per barrel as forecasted by the World Bank can been used to calculate the price of crude oil up to the year 2025.

We calculate the future price of a litre of fuel as follows:

To determine the price of a gallon of fuel:

Estimated price of barrel of Brent Crude in US Dollars ÷ 42 (number of gallons in a barrel) to determine the price per gallon

To calculate the average price of a gallon of fuel:

Price of gallon ÷2 x 3 = (Average cost of gallon of fuel in US Dollars)

To determine the amount of litres in a gallon of fuel:

Gallons of fuel ÷ 3.785 = litres of fuel

Price of fuel in South African Rands:

Litres of fuel x price of US Dollar in Rands

Final price of litre of fuel in South African Rands

Price of litre of fuel x 1.3656 (Fuel tax component)

All the formulas and calculations of the forces acting on a vehicle, as well as energy and fuel costs calculations were done on an Excel spreadsheet.

CHAPTER 4 CALCULATION RESULTS AND ANALYSIS

The overall aim of this project was to investigate the energy efficiency of different vehicle technologies by using six different route tests. The calculations investigated the energy consumptions, and efficiency, of the different types of vehicles. The following section presents the data collected during the simulated test drives of the six routes.

The powertrain efficiencies, total energy consumption and operating costs will be presented for all the routes.

4.1 POWERTRAIN EFFICIENCIES

Powertrain efficiencies are calculated for all the different types of vehicles and are given in Table 11. The highest efficiency is shown for the battery electric vehicle (BEV). The fuel cell electric vehicle (FCEV) comes second best when powered with hydrogen gas. This is followed by the hybrid electric vehicle (HEV), with the internal combustion engine vehicle (ICEV) being the least efficient.

The electric powertrain of the BEV, FCEV and HEV has no losses due to idling, and it has the potential to recover energy by means of regenerative breaking. However, the BEV requires additional electrical power for cabin heating, as the heat loss from the motor is too small to cover such a demand.

All these characteristics influence the total vehicle efficiency (see Table 12). The difference between powertrain and vehicle efficiency is small, however a small improvement is noted in vehicles with an electric powertrain, compared to internal combustion powertrain.

Table 12 Vehicle powertrain efficiency and vehicle efficiency calculations

Vehicle	% of Energy used at wheels (WA)	% of Energy recovered from regenerative braking	% of Energy output from powertrain	% of Energy supplied to powertrain (WB)	% of Idling energy losses	% of Total energy supplied to vehicle (WC)	% of Engine losses	% of Parasitic losses	% of Drivetrain losses	% of Powertrain efficiency	% of Vehicle efficiency
BEV	100	5.00	95.00	146.15	0.00	146.15	15.00	15.00	5.00	65.00	68.42
Combined HEV	100	5.00	95.00	365.38	0.00	365.38	66.00	5.00	3.00	26.00	27.37
FCEV	100	5.00	95.00	316.67	0.00	316.67	63.00	4.00	3.00	30.00	31.58
ICEV	100	0.00	100.00	500.00	6.00	506.00	71.00	5.00	4.00	20.00	19.76

Total energy supplied to vehicle (WC) = Energy output from powertrain ÷ powertrain efficiency

Powertrain efficiency η = WA /WB where WA is the useful energy at the wheels .WB is the energy supplied to the powertrain

Vehicle efficiency η = WA/WC where WA is the energy used at the wheels and WC is the energy supplied to the vehicle

Primary energy efficiency η = WA/WD where WA is the energy used at the wheels and WD is the primary energy

4.2 ENERGY REQUIREMENTS

The vehicle's gradient continuously varies as it travels along the road. The gradient is determined by calculating the difference of the height of the front wheels relative to the rear wheels of the vehicle.

In turn the gradient calculations are used to determine the forces acting on the vehicle. The forces acting on the vehicle are then used to determine the power required by the vehicle, and ultimately the energy required by the vehicle is calculated. The calculations are carried out at 1 metre intervals.

The simulated vehicle was "run" on all six routes which consist of uphill, flat and downhill sections. (see Fig 16-21)

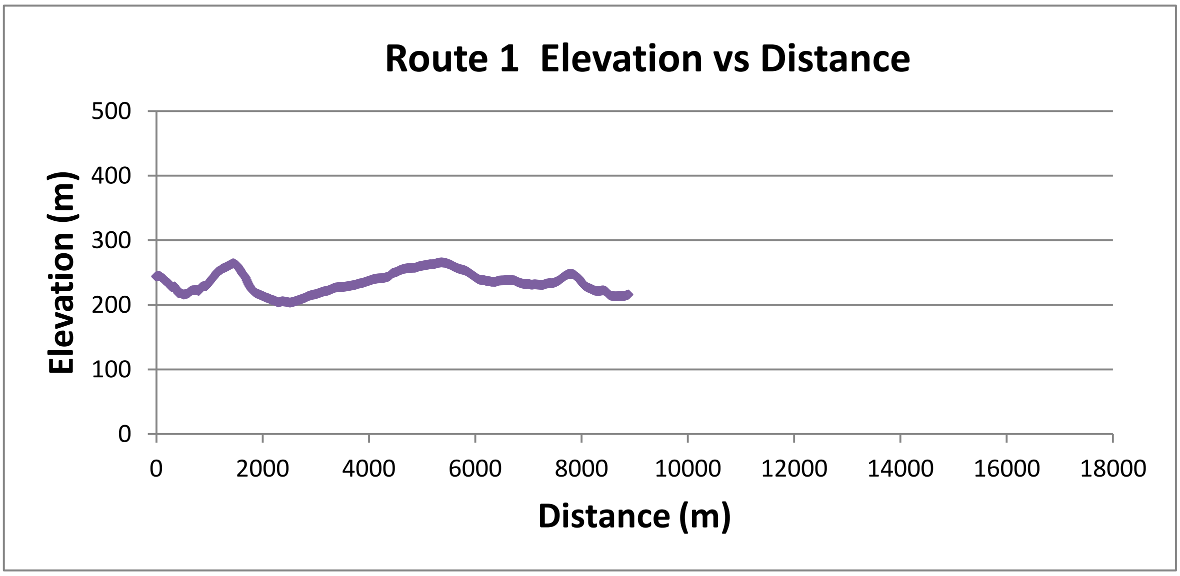

Figure 16 The graph is a representation of the elevation profile of Route 1 displaying the height in metres vs the distance that the vehicle travelled in metres

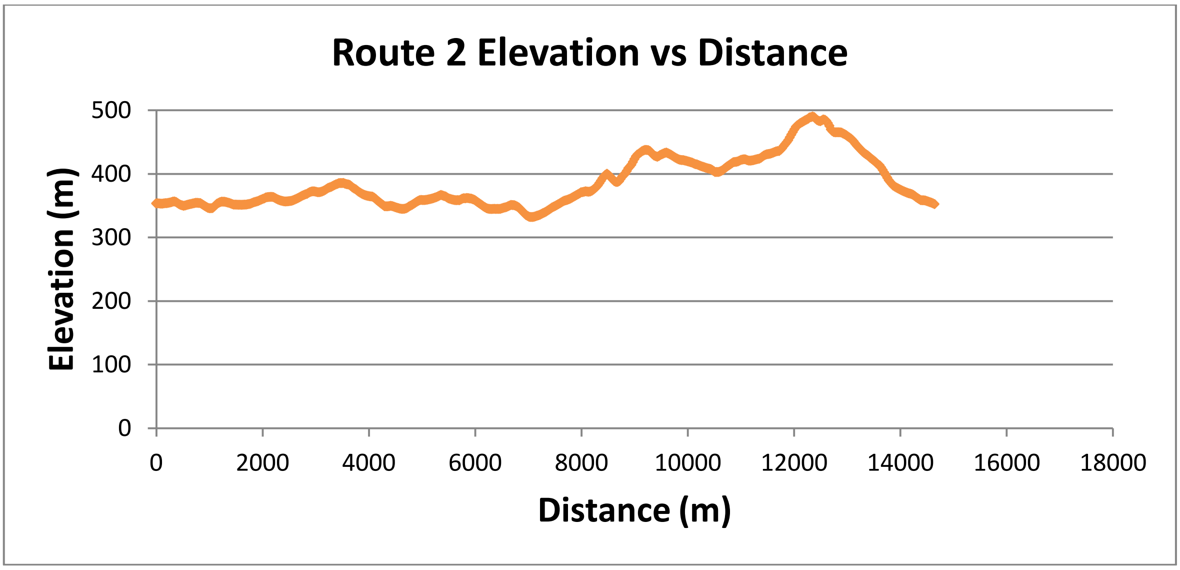

Figure 17 **The graph is a representation of the elevation profile of Route 2 displaying the height in metres vs the distance that the vehicle travelled in metres**

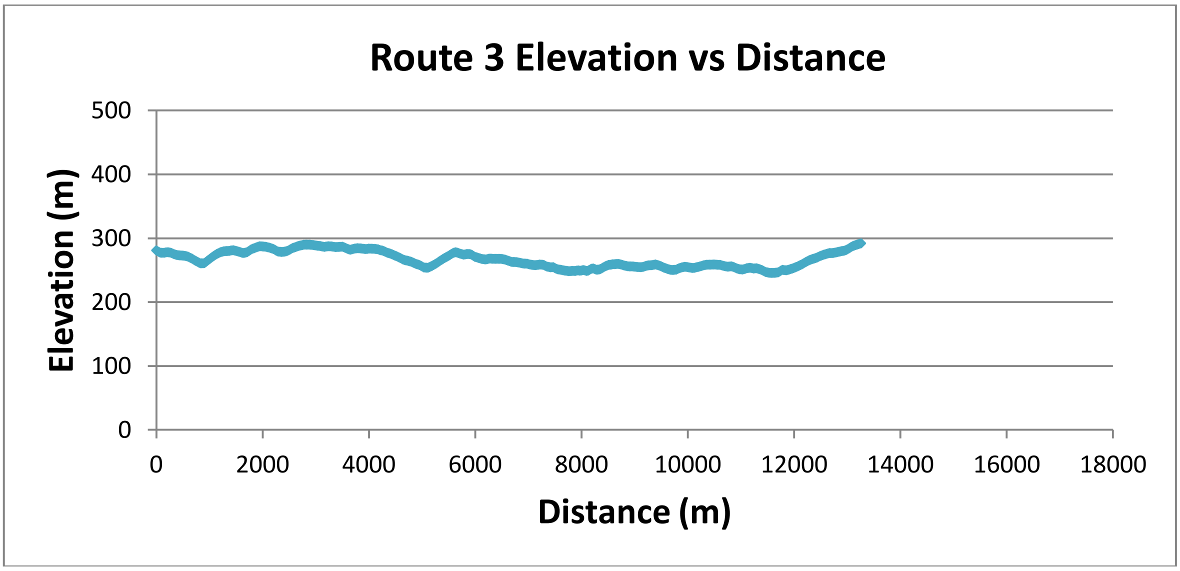

Figure 18 **The graph is a representation of the elevation profile of Route 3 displaying the height in metres vs the distance that the vehicle travelled in metres**

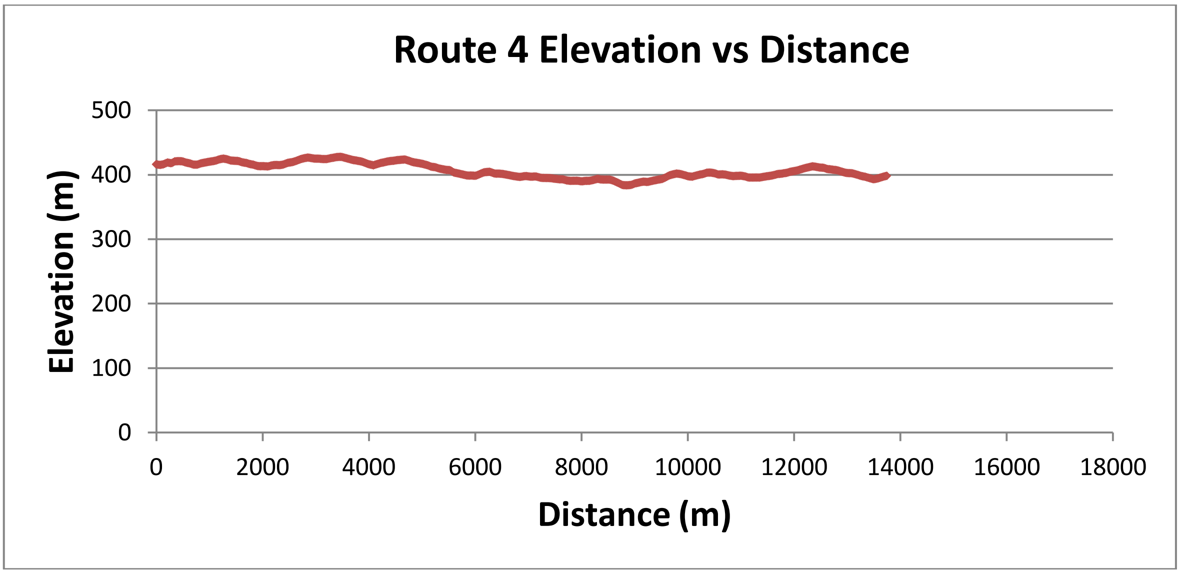

Figure 19 The graph is a representation of the elevation profile of Route 4 displaying the height in metres and the distance that the vehicle travelled in metres

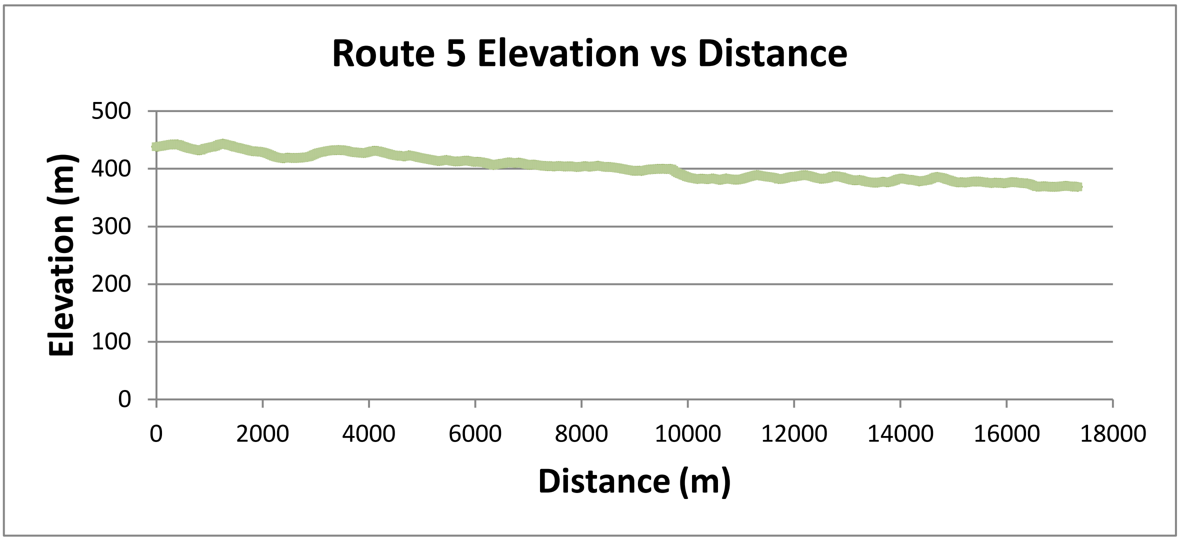

Figure 20 The graph is a representation of the elevation profile of Route 5 displaying the height in metres vs the distance that the vehicle travelled in metres

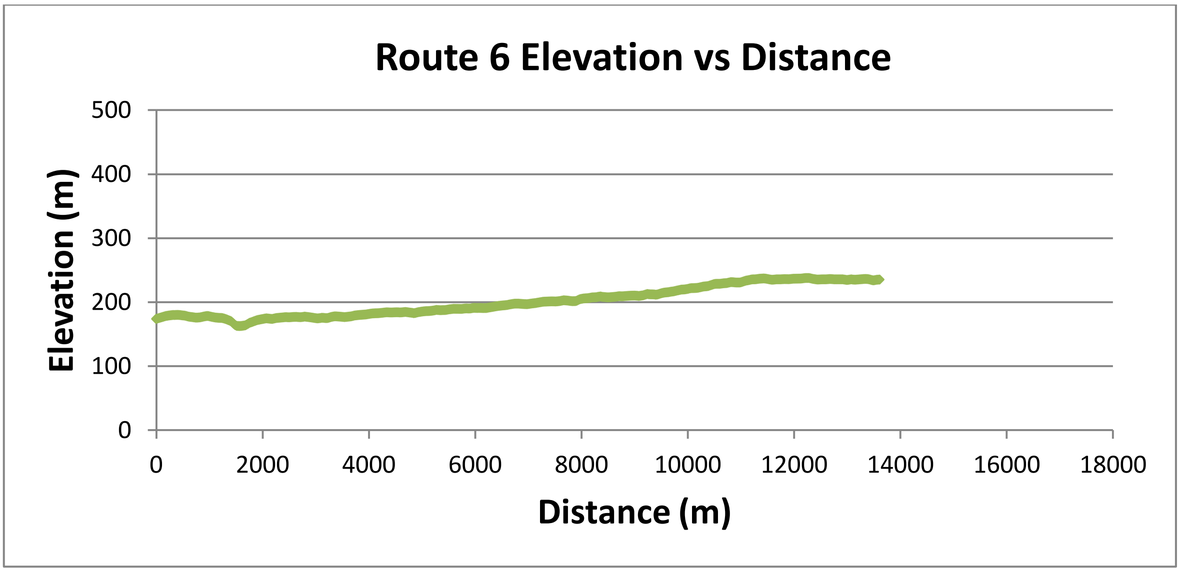

Figure 21 The graph is a representation of the elevation profile of Route 6 displaying the height in metres vs the distance that the vehicle travelled in metres

The energy usage for the particular route varies amongst the different types of vehicle due to their powertrain efficiencies. Powertrain efficiencies were calculated for all the different types of vehicles and are given in Table 12.

Taking into consideration the powertrain efficiencies of each vehicle type, the total input energy and amount of fuel for each vehicle type is then calculated for all the routes. This is shown in Table 13 below.

Table 13 Calculated values of the input energy and fuel requirements of the (BEV-Electricity, HEV–Petrol, FCEV-H_2(g) and ICEV-Petrol) vehicles for Routes 1 to 6

Travelled Routes	Battery Electric Vehicle(BEV)		Combined Hybrid Electric Vehicle(HEV)		Fuel Cell Electric Vehicle (FCEV)		Internal Combustion Engine Vehicle (ICEV)	
	Input Energy kJ	Electricity kWh	Input Energy kJ	Litres Petrol	Input Energy kJ	Kilograms Hydrogen	Input Energy kJ	Litres Petrol
Route 1	9956.54	2.77	24891.35	0.73	21572.51	0.18	32358.76	0.95
Route 2	17395.01	4.83	43487.52	1.28	37689.18	0.31	56533.78	1.66
Route 3	3720.95	1.03	9302.37	0.27	8062.06	0.07	12093.09	0.36
Route 4	3204.82	0.89	8012.05	0.24	6943.78	0.06	10415.67	0.31
Route 5	19102.53	5.31	47756.32	1.4	41388.81	0.34	62083.22	1.83
Route 6	4932.07	1.37	12330.17	0.36	10686.15	0.09	16029.22	0.47

The total energy losses experienced by the different vehicle technologies for each route are also calculated.

In Routes 1 to 6, as shown in Fig 22-27, the calculated values reveal that the energy losses of the ICEV is almost 8 times greater, followed by the HEV at over 5 times, and lastly by the FCEV at over 4 times greater compared to the BEV.

The BEV energy losses represent approximately 12.5% of the ICEV energy loss, approximately 19% of the HEV energy losses, and approximately 23% of the FCEV energy losses.

All the different vehicle technologies experience the most energy losses on Route 2 and Route 5. Route 2 displays small up hills and down hills, while Route 5 displays mainly down hills.

We would have expected a smaller loss in energy when the vehicles move down hill as in Route 5, due to the effect of gravity on the vehicle, however more energy was used. This high energy loss can be attributed to the surface of the route being sand and the longer length of these routes,as well as the use of the vehicle's brakes to slow it down when going downhill.

From the calculations we can see that the consumption of energy is almost 4 times as much when the different vehicle technologies are simulated on sandy roads surfaces. This is due to greater forces exerted on the vehicles, such as rolling resistance, traction forces losses, which resist the forward movement of the vehicle and increase fuel consumption.

The best performance and energy usage is achieved on Routes 3,4,6, where the surface is tar.

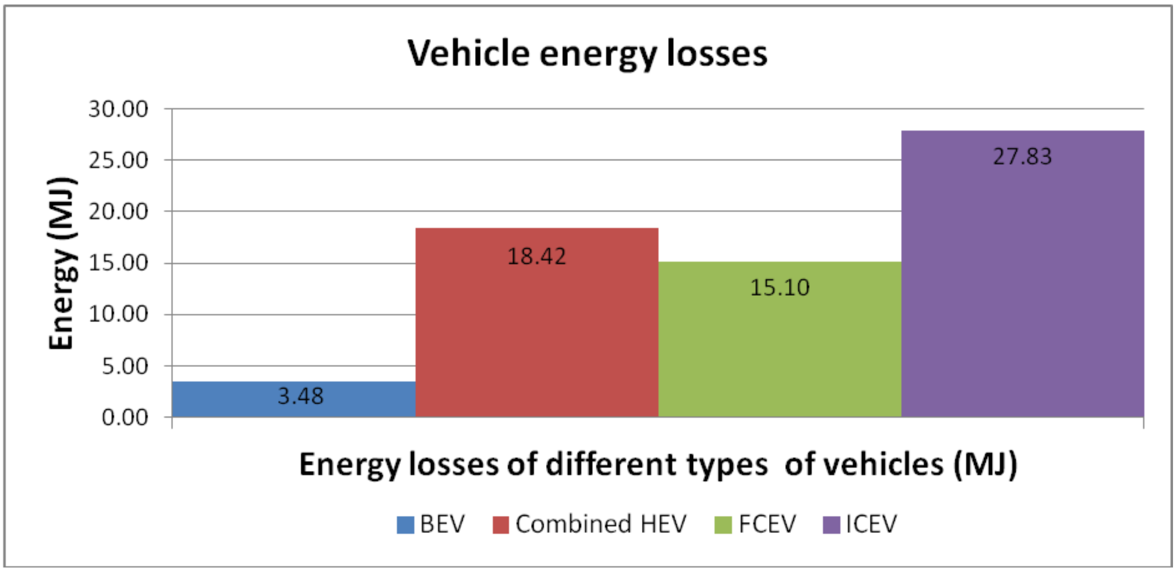

Figure 22 Total energy losses for the different vehicles on Route 1

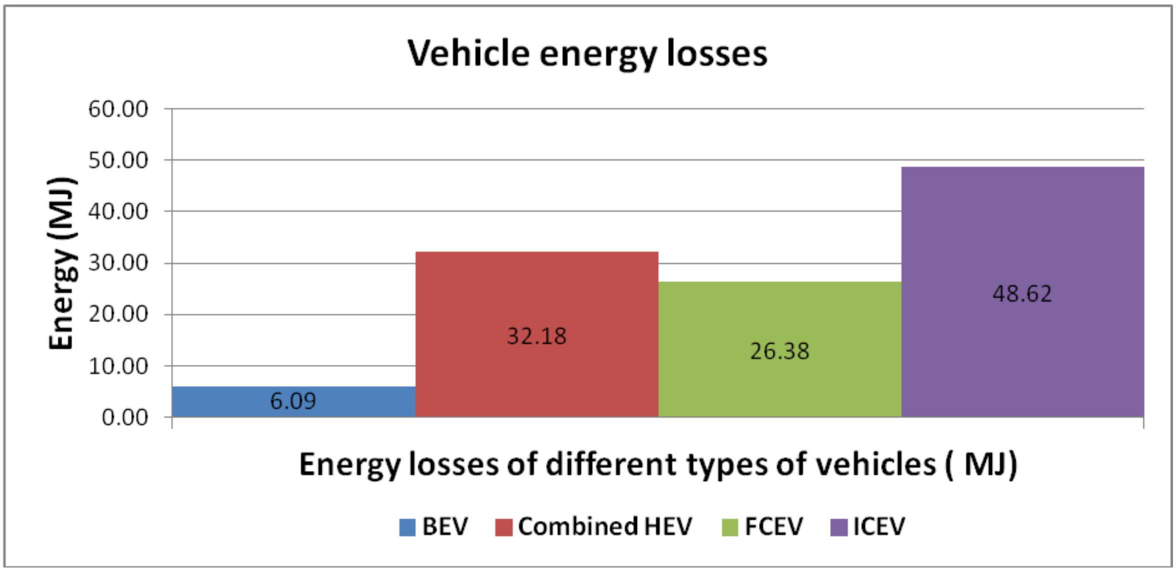

Figure 23 Total energy losses for the different vehicles on Route 2

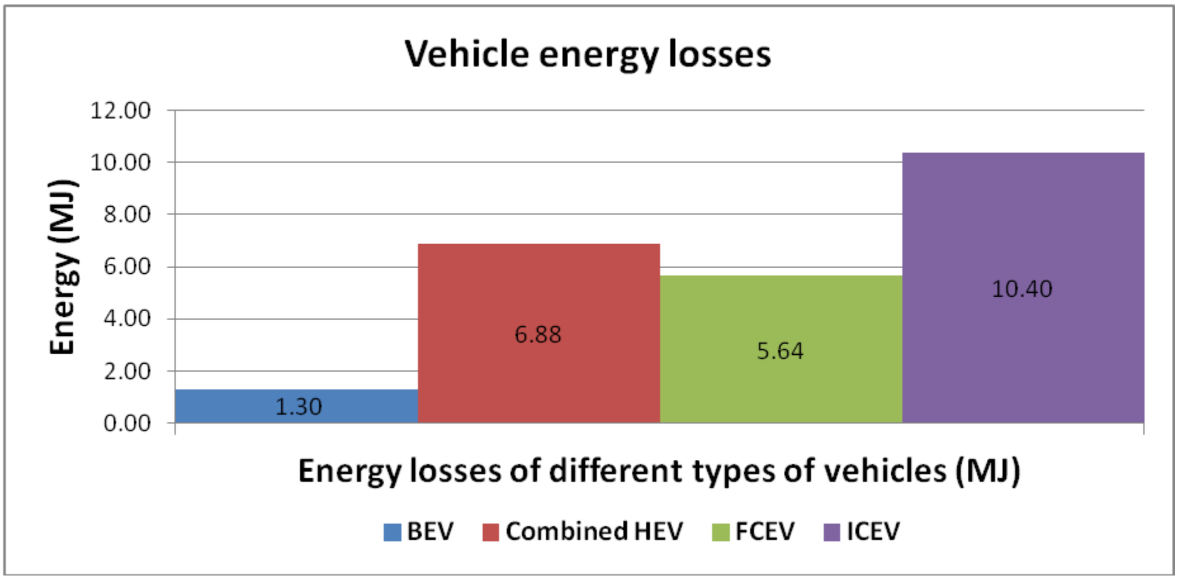

Figure 24 Total energy losses for the different vehicles on Route 3

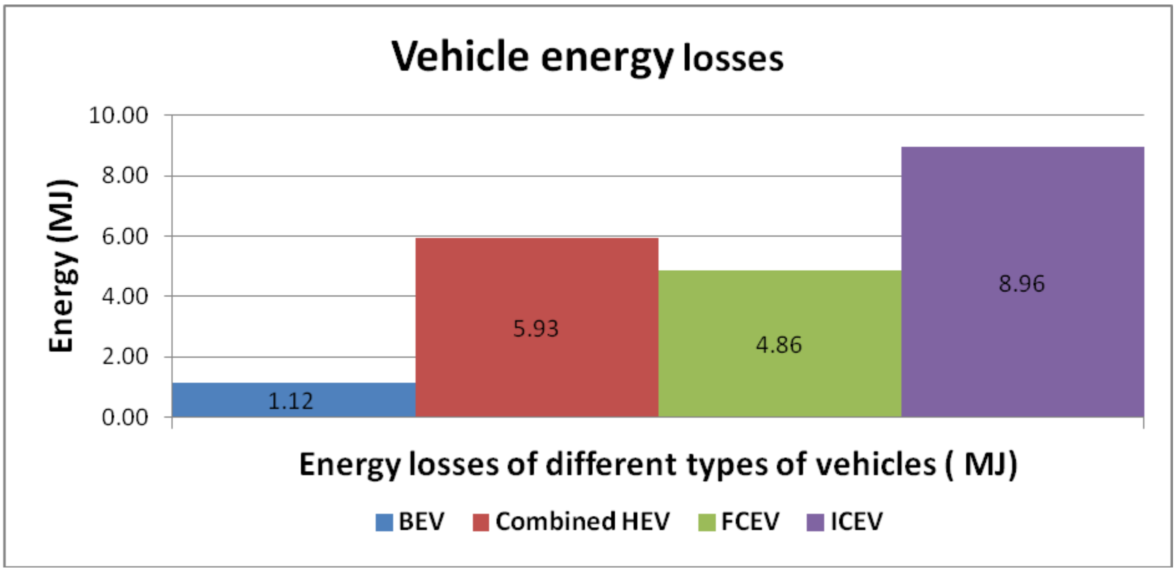

Figure 25 Total energy losses for the different vehicles on Route 4

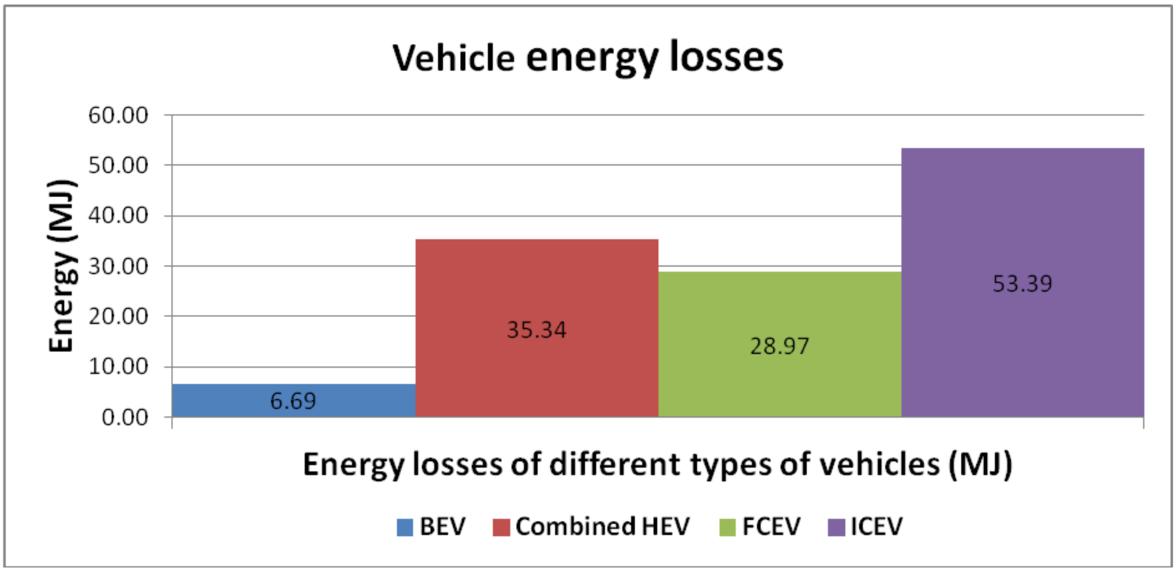

Figure 26 Total energy losses for the different vehicles on Route 5

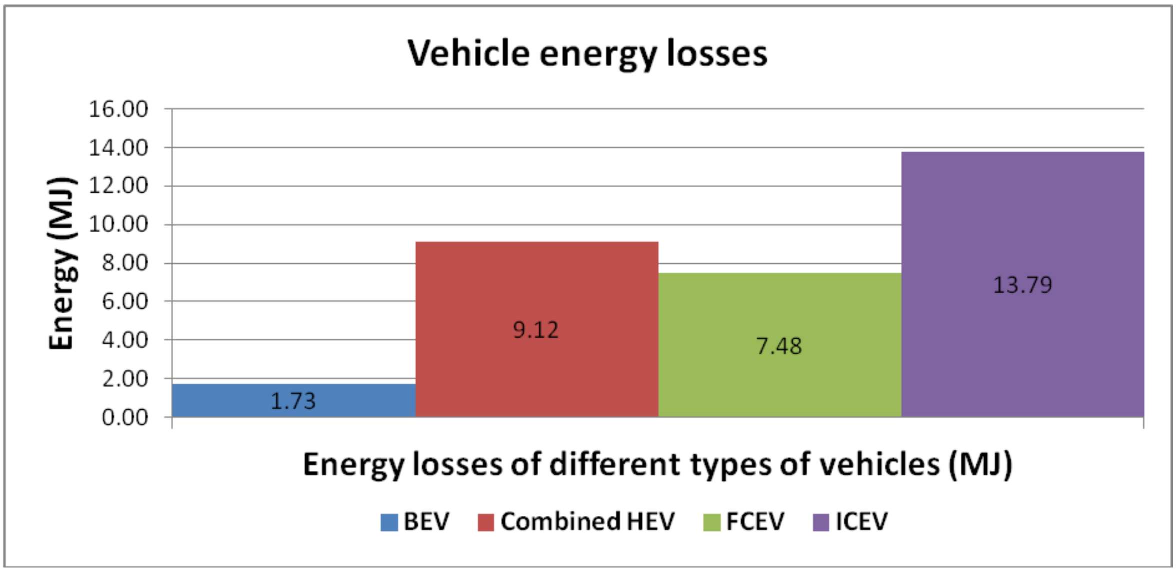

Figure 27 Total energy losses for the different vehicles on Route 6

Furthermore for each of the routes, the total energy losses experienced by the different vehicles have been broken down to individual components consisting of engine losses, idle losses, parasitic losses, and powertrain losses. These are shown in Fig 28-33.

Parasitic loads refer to mechanical and electrical loads such as air conditioning, alternator, water pump etc.

On all the routes it can be clearly seen that the internal combustion engine vehicle (ICEV) experiences the most engine losses as well as idle losses, and thus performs the worst.

The combined hybrid electric vehicle (HEV) shows an improvement in energy usage as it has no idle losses coming second worst, followed by the fuel cell electric vehicle (FCEV) with no idle energy losses but with total energy losses of over 4 times that of the battery electric vehicle (BEV).

The battery electric vehicle (BEV) experiences the least energy losses per component, except for parasitic losses which are on par with the other vehicle technologies.

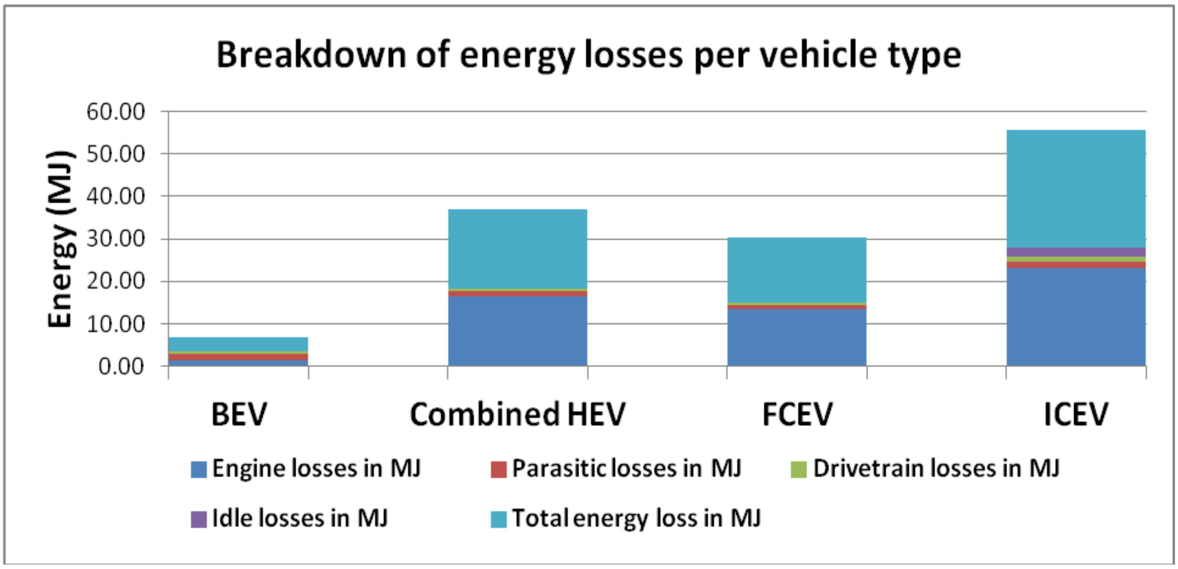

Figure 28 Graph showing a breakdown of the different types of losses for each vehicle type on Route 1

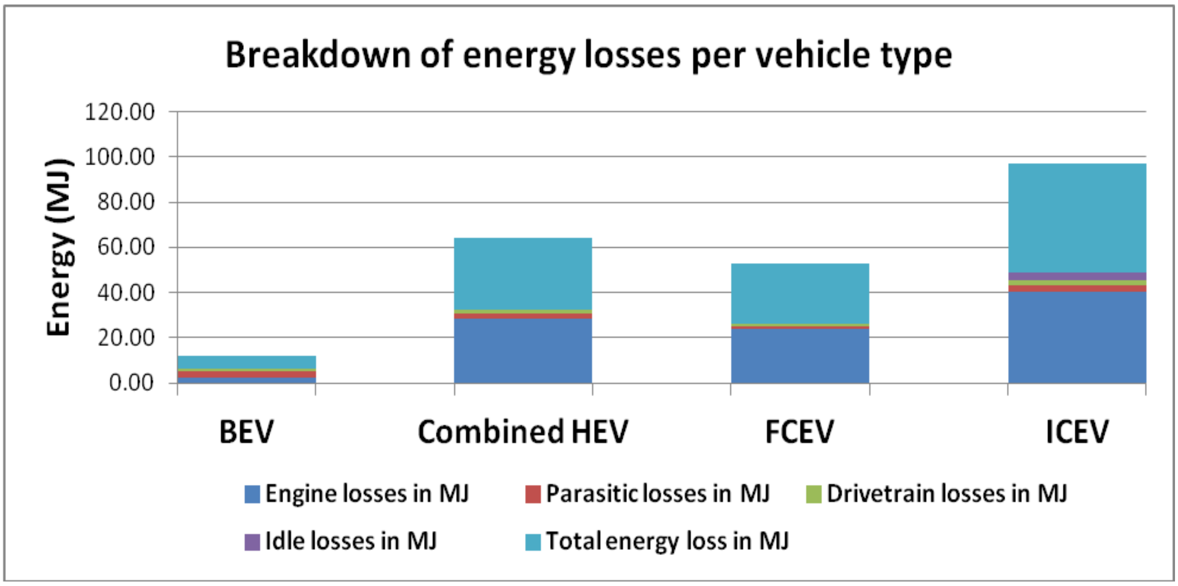

Figure 29 Graph showing a breakdown of the different types of losses for each vehicle type on Route 2

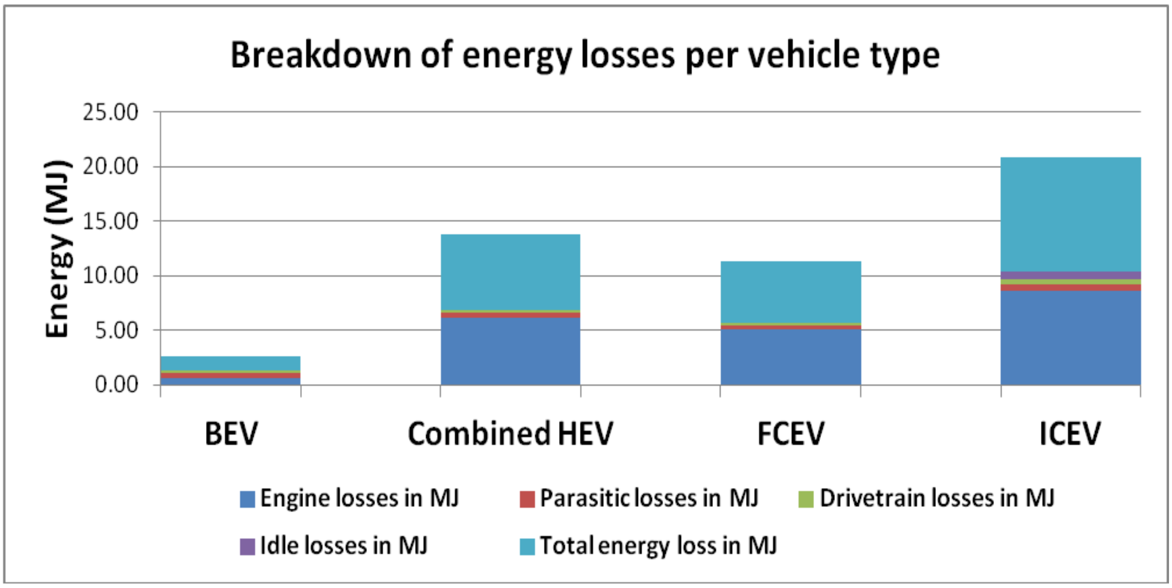

Figure 30 Graph showing a breakdown of the different types of losses for each vehicle type on Route 3

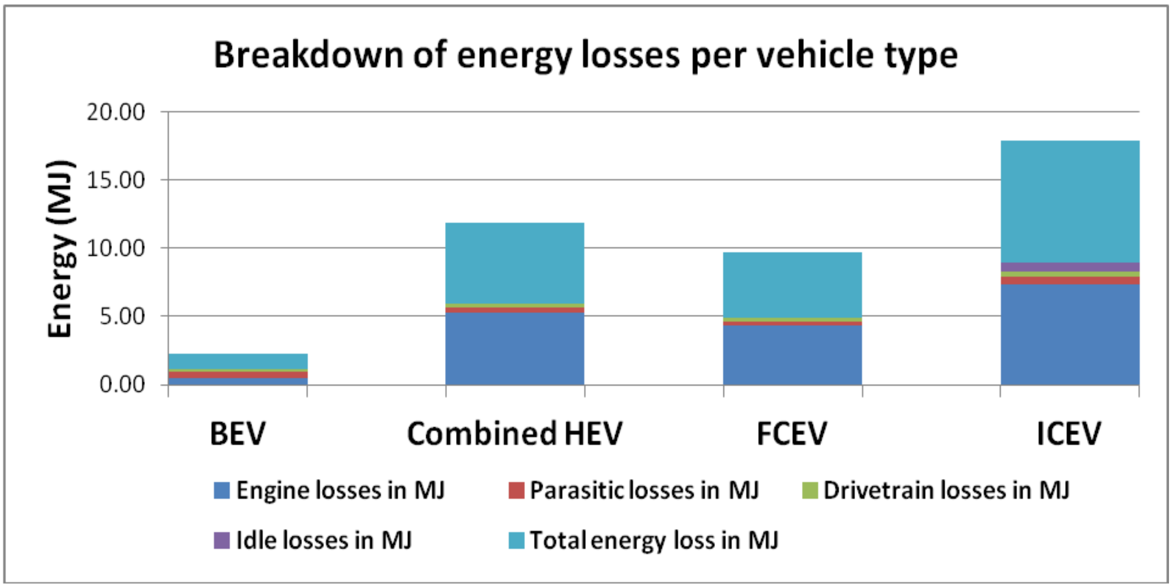

Figure 31 Graph showing a breakdown of the different types of losses for each vehicle type on Route 4

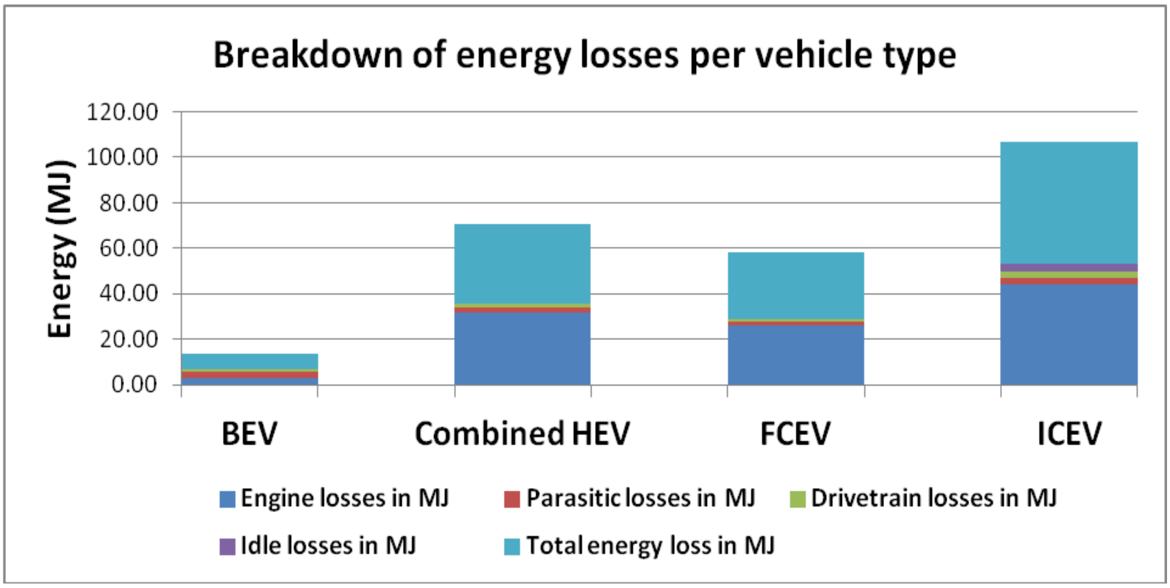

Figure 32 Graph showing a breakdown of the different types of losses for each vehicle type on Route 5

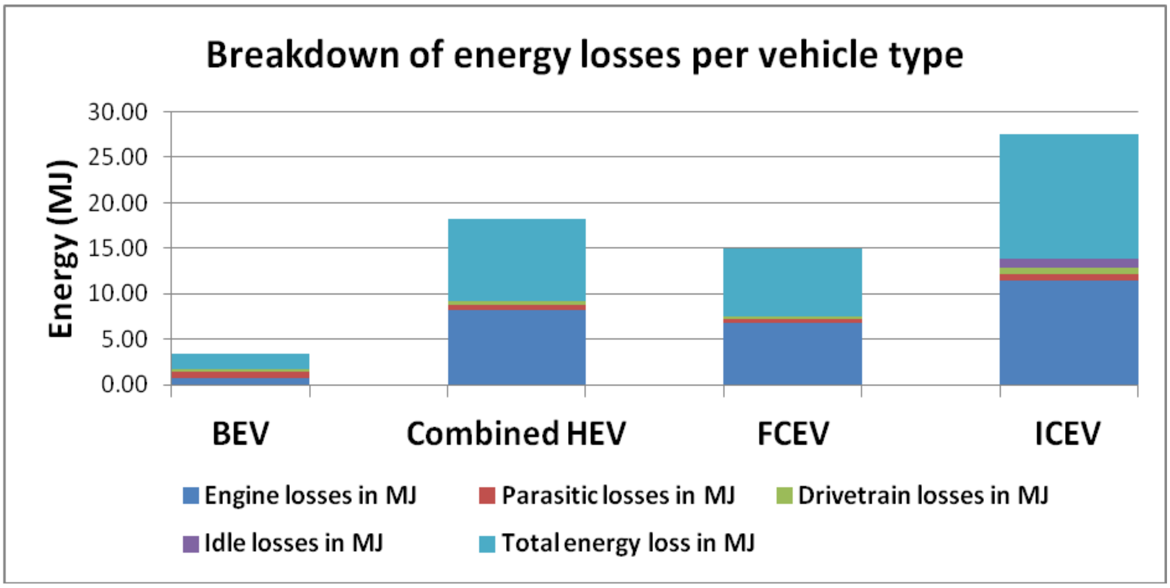

Figure 33 Graph showing a breakdown of the different types of losses for each vehicle type on Route 6

Present energy and fuel costs

The price of electricity in South Africa continues to increase year-on-year from 2013 onwards. The National Electricity Regulator of South Africa (NERSA) announced that the price will increase 8% at least each year for the next five years. The prices for the next four years based on the 8% annual increase would be as follows, illustrated in Fig.34:

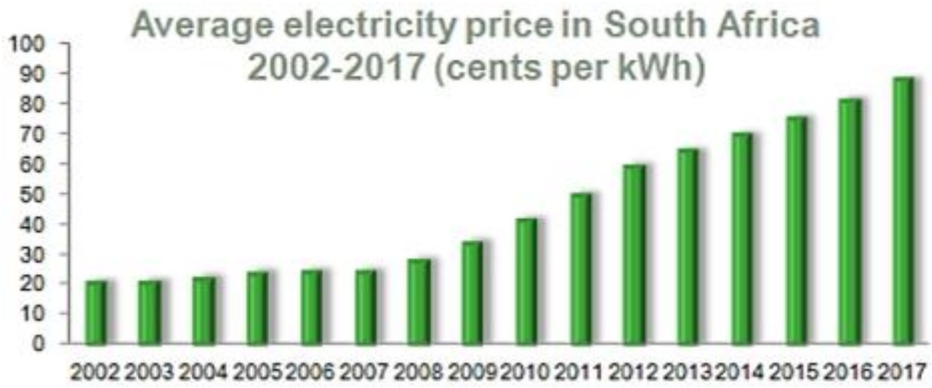

Figure 34 Graph of electricity price (NERSA)

Table 14 Average Eskom charges for electricity.

Years	Cost
2014/15	70.75c/kWh
2015/16	76.41c/kWh
2016/17	82.53c/kWh
2017/18	89.13c/kWh

Many residents and businesses pay a higher rate for electricity as they purchase electricity from local municipalities who in turn purchase from Eskom. The municipality rates are shown on Table 15

Table 15 Average municipal charges for electricity

Years	Cost
2014/15	135.00c/kWh
2015/16	145.80c/kWh
2016/17	157.46c/kWh
2017/18	170.06c/kWh

The energy and fuel costs are calculated for the different types of vehicles.BEV costs are calculated at R1.35/kWh (source Rates Ekurhuleni municipality 2014).The cost of a litre of unleaded at R 14.04 is used in the ICEV and HEV fuel calculations (source Shell South Africa).The cost of Hydrogen gas at $2 per kg is used in the cost of the FCEV (source NREL).

The present energy and fuel costs of the different vehicle technologies for Routes 1-6 are calculated and are shown in South African Rands as well as US Dollars in Table 16.The data for US$ is presented for ease of reference for foreign readers who are not familiar with the South African currency (ZAR) exchange rate. The exchange rate used was 1$ =R10.67(February 2014)

Table 16 Present energy and fuel costs of the different vehicle technologies

Travelled Routes	Battery Electric Vehicle(BEV)		Combined Hybrid Electric Vehicle(HEV)		Fuel Cell Electric Vehicle (FCEV)		Internal Combustion Engine Vehicle (ICEV)	
	Costs in Rands (ZAR)	Costs in (US$)	Costs in Rands (ZAR)	Costs in (US$)	Costs in Rands (ZAR)	Costs in (US$)	Costs in Rands (ZAR)	Costs in (US$)
Route 1	3.73	0.35	10.10	0.95	3.81	0.36	13.12	1.23
Route 2	6.52	0.61	17.64	1.66	6.65	0.63	22.93	2.16
Route 3	1.40	0.13	3.77	0.35	1.42	0.13	5.01	0.47
Route 4	1.20	0.11	3.25	0.31	1.23	0.12	4.31	0.41
Route 5	7.16	0.67	19.37	1.82	7.31	0.69	25.18	2.37
Route 6	1.85	0.17	5.00	0.47	1.89	0.18	6.50	0.61

Future energy and fuel costs

The price of a barrel of crude oil is projected to fall from $103.50 per barrel in 2014 to $96.70 in 2025 and this represents a fall of 6.57% [71]. By using this data, a projection of the costs of BEV energy costs together with the equivalent costs in fuel of the ICEV up to 2025 can be estimated and is shown in Fig 35 – 40. Although the price of oil is projected to fall indicating a reduction in the price advantage of the BEV however the price at the pumps of a litre of petrol or diesel did not decrease much as expected because the price also includes levies and taxes. This analysis should have been done using the price of fuel at the pumps. Even with the reduction BEV's are at least 50% cheaper to operate.

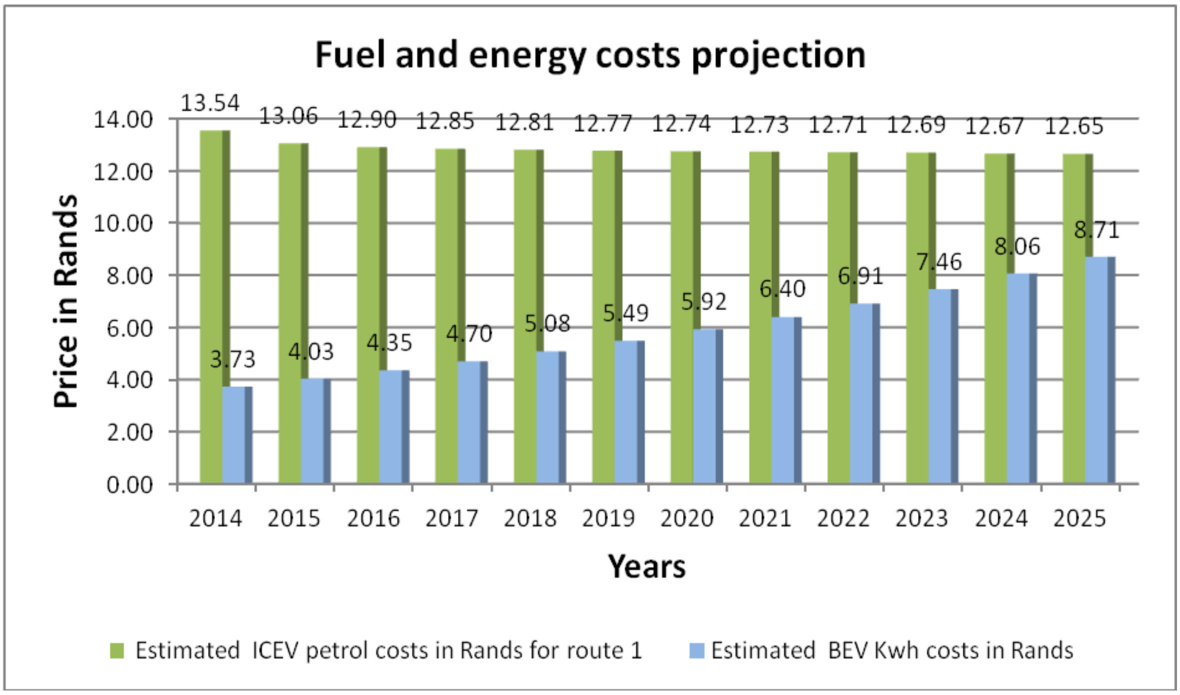

Figure 35 Future projected fuel and energy costs (Route 1)

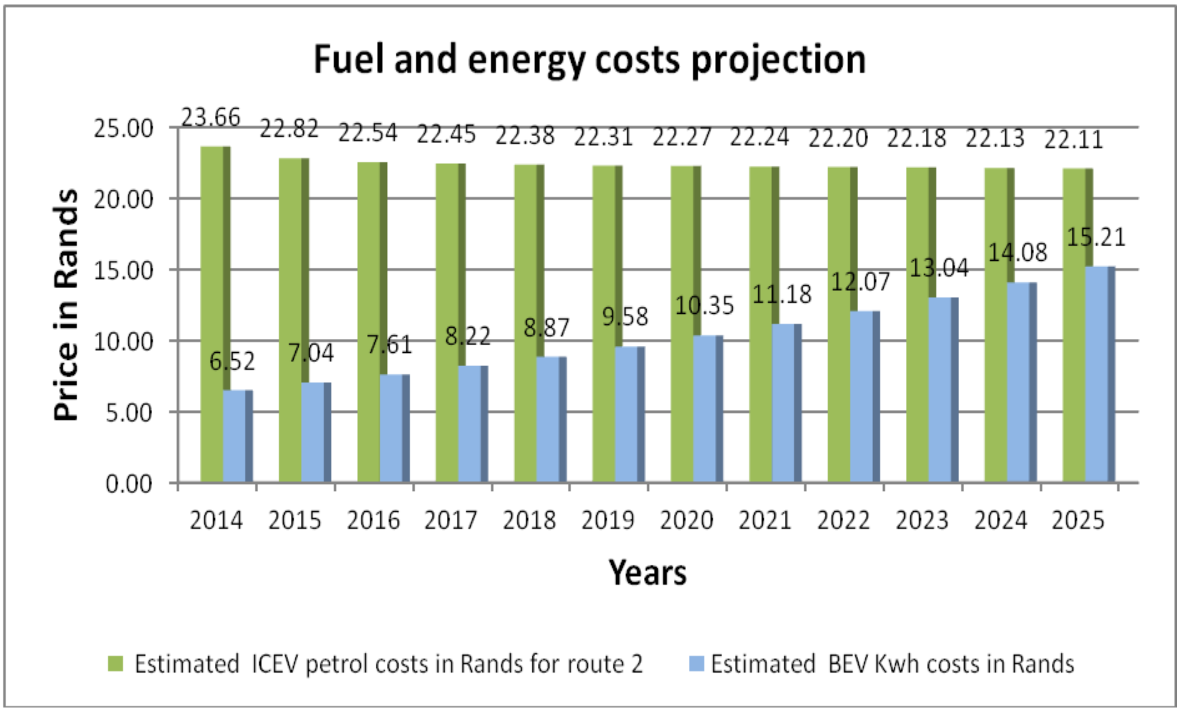

Figure 36 Future projected fuel and energy cost (Route 2)

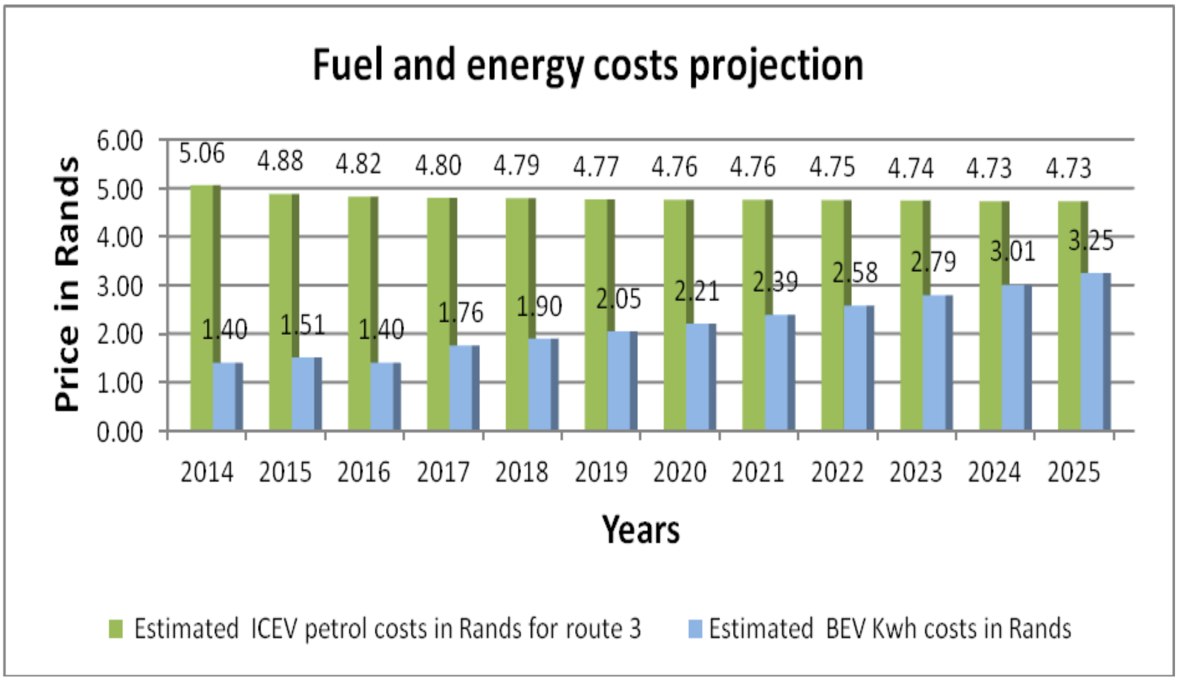

Figure 37 Future projected fuel and energy costs (Route 3)

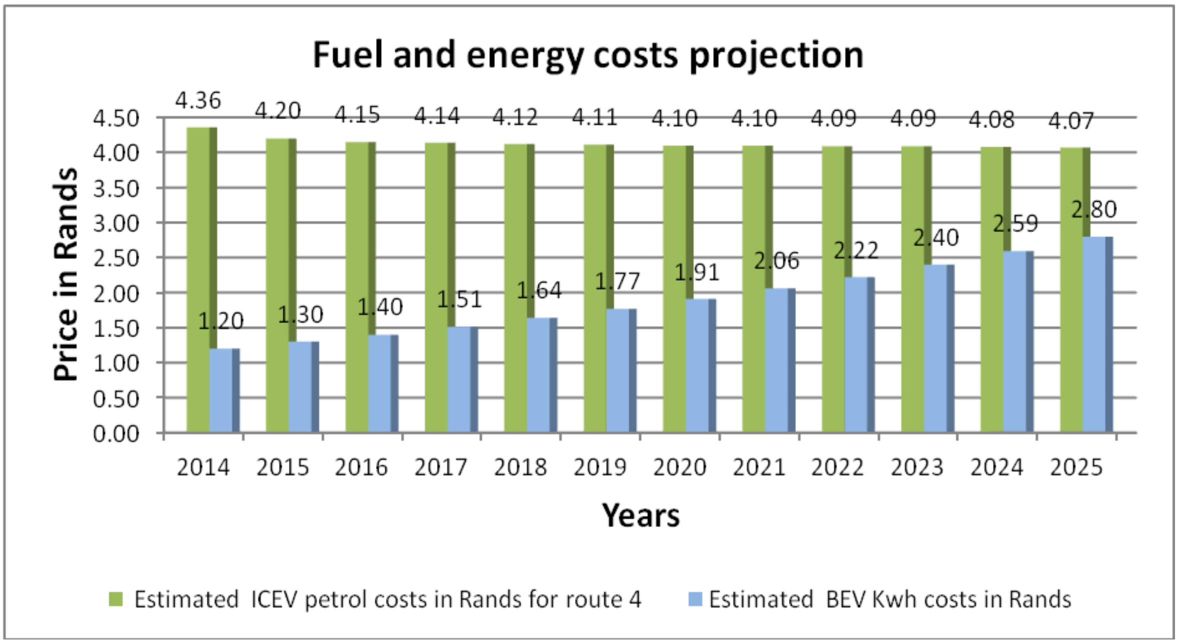

Figure 38 Future projected fuel and energy costs (Route 4)

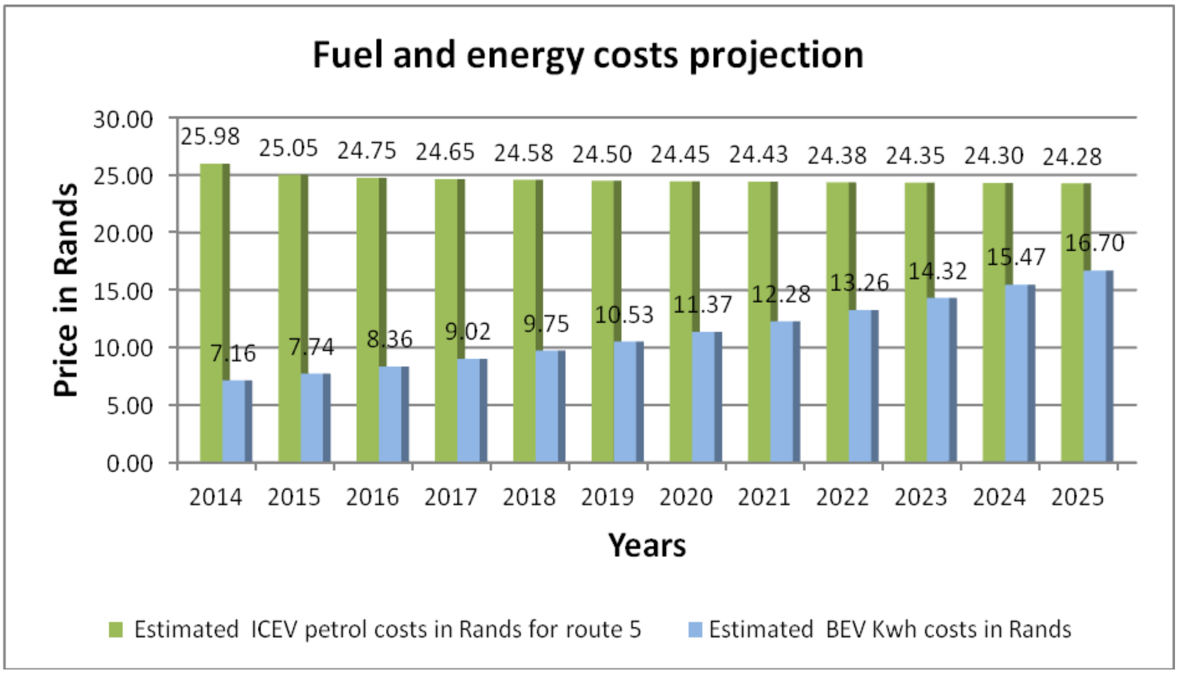

Figure 39 Future projected fuel and energy costs (Route 5)

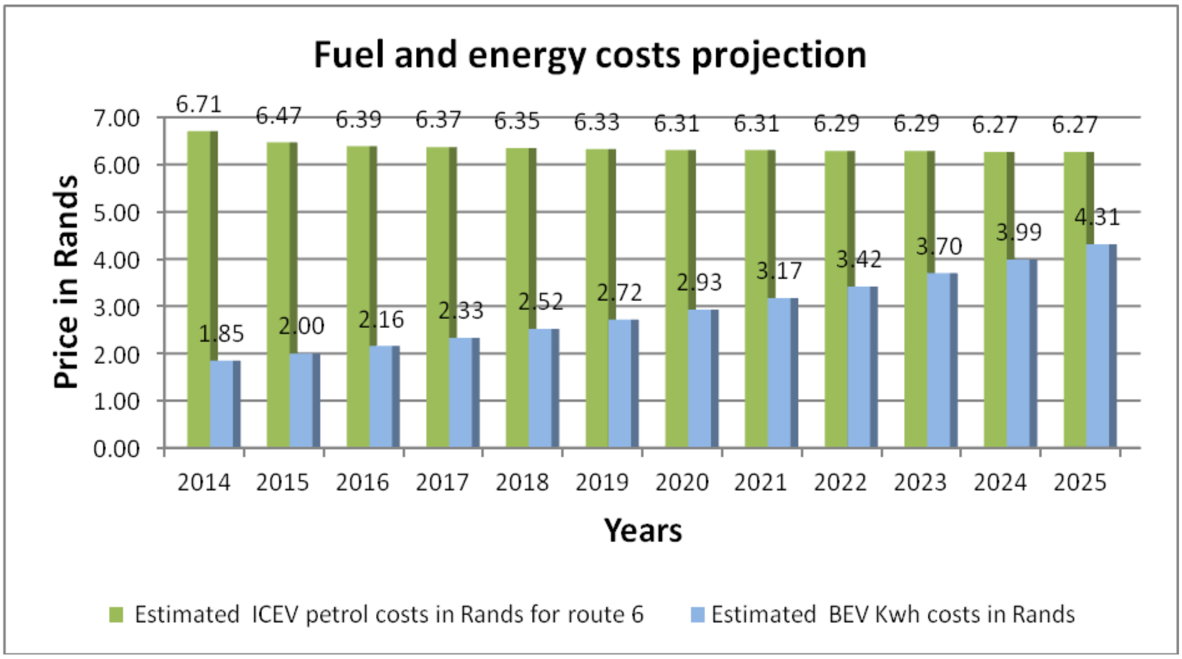

Figure 40 Future projected fuel and energy costs (Route 6)

4.3 SUMMARY OF THE ENERGY LOSSES PER VEHICLE TYPE ON ALL ROUTES

The energy losses of each vehicle type as experienced in each route are combined and are shown below as a total energy loss.

The battery electric vehicle (BEV) total energy losses on all routes are shown in Fig 41.

The combined hybrid electric (HEV) total energy losses on all routes are shown in Fig 42.

The fuel cell electric vehicle (FCEV) total energy losses on all routes are shown on Fig 43.

The internal combustion engine vehicle (ICEV) total energy losses on all routes are shown on Fig 44.

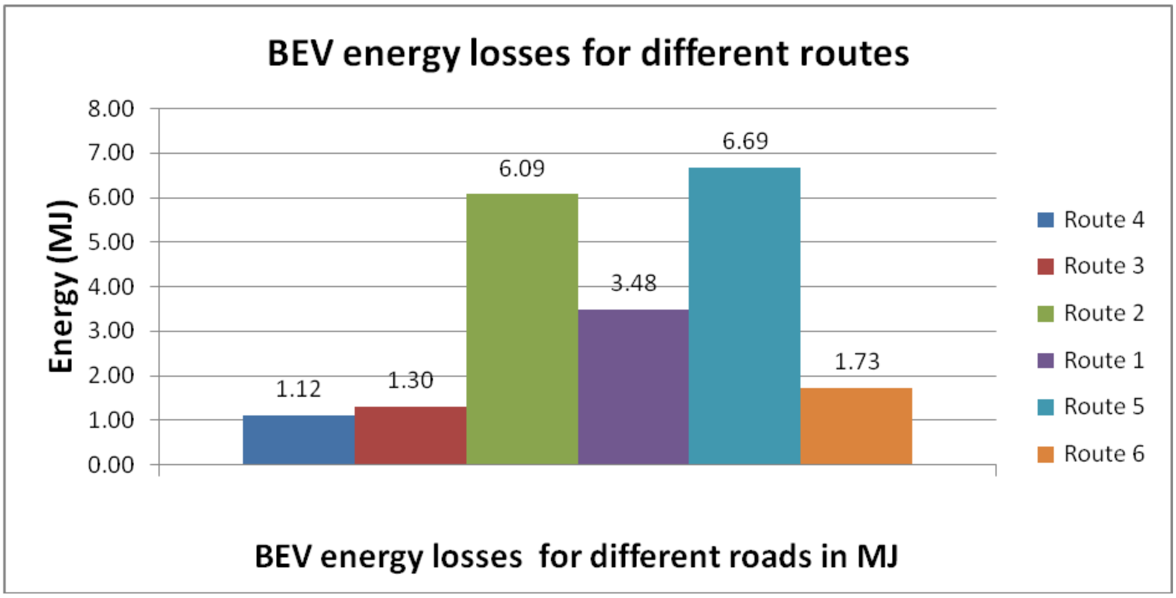

Figure 41 Battery electric vehicle (BEV) energy losses on all the routes

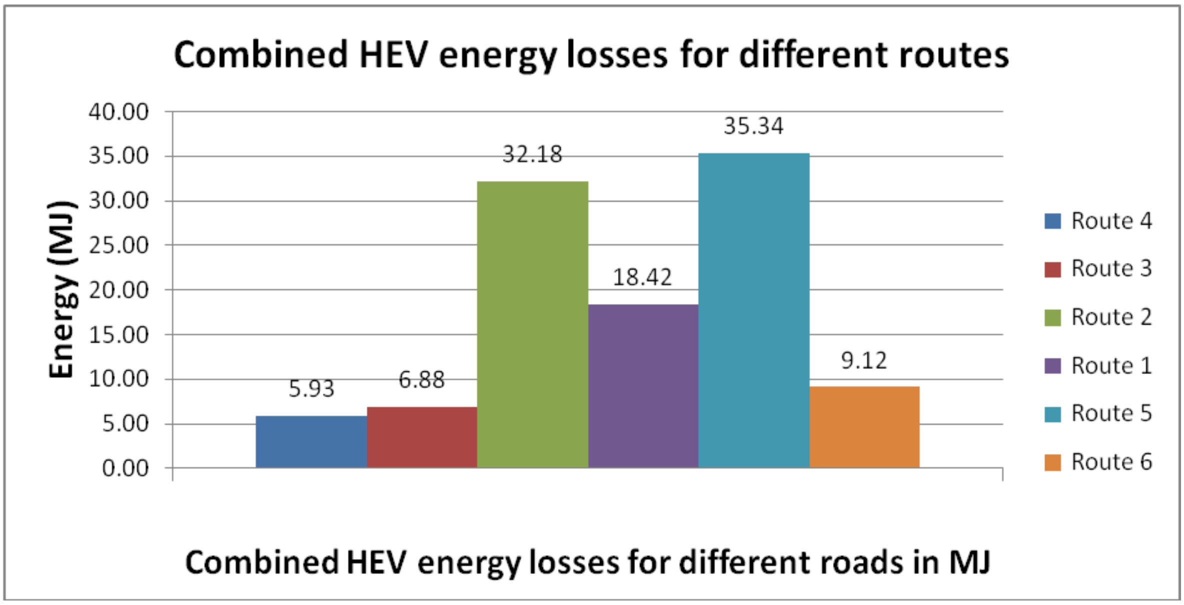

Figure 42 Combined hybrid electric vehicle (HEV) energy losses on all the routes

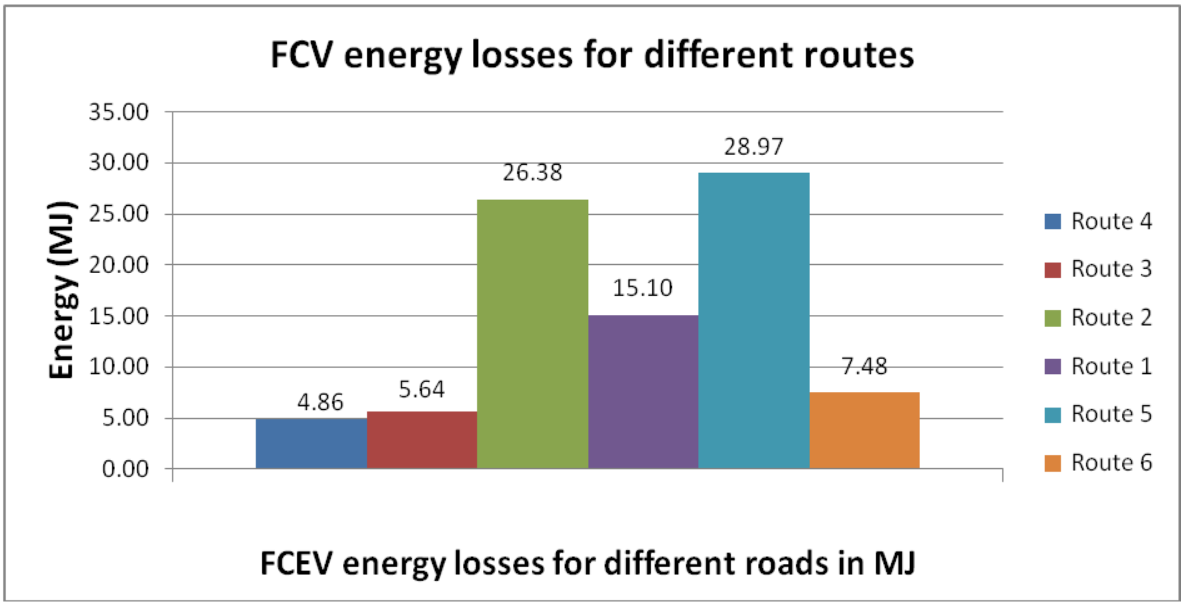

Figure 43 Fuel cell electric vehicle (FCEV) energy losses on all the routes

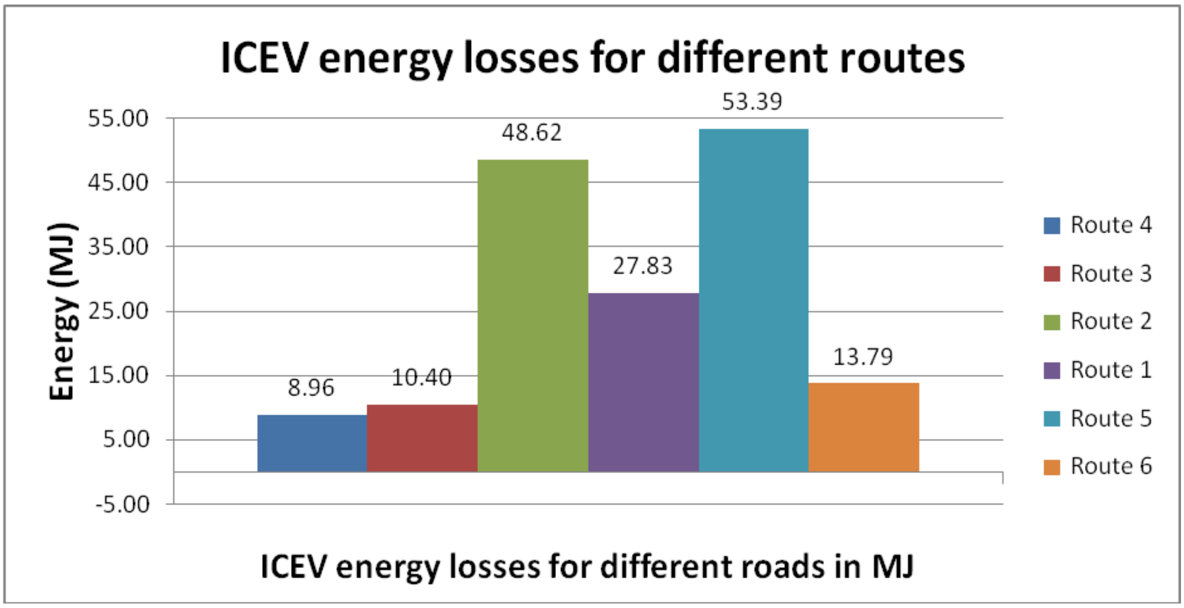

Figure 44 Internal combustion engine vehicle (ICEV) energy losses on all the routes

CHAPTER 5 DISCUSSION

Battery electric vehicles (BEV) are seen as the cars of the future. They are energy efficient, cause almost no pollution and do not contribute directly to global warming. They are designed mainly for city or urban use as their range is limited to their electrical energy holding capacity of their onboard batteries.

There are a number of battery electric vehicles presently available to consumers worldwide. In South Africa the Nissan Leaf is presently available to South African consumers.

While the use of battery electric vehicles (BEVs) has been predominantly within an urban environment, the idea of using such vehicles in an extra urban environment, but within a confined area such as a game reserve provided a platform to investigate the feasibility of a battery electric vehicle (BEV) as an alternative recreational or off-road vehicle.

The performance of a battery electric vehicle (BEV) had to be tested on actual routes as found in an actual game reserve. The Kruger National Park was chosen as a suitable terrain for calculation testing of the battery electric vehicle (BEV). The Kruger National park was chosen due to its rich geology that provides a number of different road surfaces and varying gradients. A number of routes were chosen for the calculation purposes and analyzed.

The aim of the different route analysis was to find the energy consumption of other vehicle technologies and compare it with the energy consumption of the battery electric vehicle (BEV). The analysis went further to investigate the battery electric vehicle’s feasibility to be used as a recreational vehicle for game parks, considering the present and future savings that can be achieved by the use of a battery electric vehicle (BEV).

5.1 ENERGY CONSUMPTION

Calculation testing of the other vehicle technologies inclusive of the battery electric vehicle (BEV), was conducted at a speed of 30km/h.

The calculations also involved taking into consideration the drivetrain, parasitic, and engine losses for each vehicle technology. The data collected was then used to calculate the energy consumption of each vehicle as it travelled on each route.

The energy consumption of each vehicle was noted and ranked.

After investigating the energy consumption of the different vehicles on the different routes, it was found that the energy consumption of each vehicle technology reveals similar trends and ranking, no matter on which route it travelled on. The highest energy efficiency is still achieved by the battery electric vehicle (BEV), followed by the fuel cell electric vehicle (FCEV) and then by the combined hybrid electric vehicle (HEV) and lastly by the internal combustion engine (ICE) vehicle.

5.2 TOTAL ENERGY LOSSES

The findings reveal that irrespective of the terrain, gradient or road surface a vehicle travels on, its energy consumption will always be proportional to the energy losses it experiences.

These losses are in the form of engine, drivetrain and parasitic loads which increase energy consumption.

The higher the efficiency of the power train the higher the energy efficiency of the vehicle and the lower the energy costs.

The battery electric vehicle (BEV) experiences the least vehicle energy losses as it travels on the different routes and thus it requires the least input energy for any of the routes. This is achieved as a result of the high efficiency of the electric vehicle powertrain.

The electric powertrain has no losses due to idling and it has the potential to recover energy by means of regenerative breaking.

5.3 ENERGY COSTS

The calculations confirm that the battery electric vehicle (BEV) can compete with other vehicle technologies and is not limited to its uses.

It can provide an energy efficient and environmentally friendly alternative mode of transport for game reserves. It can do so by providing the same performance as other vehicles using much less input energy.

Lower input energy requirements equate to lower energy costs and this is what is achieved by the battery electric vehicle (BEV).

Although the price of crude oil is projected to fall,, the electric vehicle is still cheaper to operate than a fossil fuel powered vehicle.

The cost of electricity charging can be offset if renewable energy sources such as solar photovoltaic panels are used to charge such vehicles.It is recognized that this use of renewable energy sources could potentially increase the CAPEX of the BEV due to the need for infrastructural improvements within the Kruger Park, this analysis is beyond the scope of this study. The cost of infrastructural improvements could be partially offset by utilizing them for other purposes such as providing electricity to the visitors camps,and for powering electric fences.

CHAPTER 6 CONCLUSION

The project involved simulating driving of vehicles of different type of technologies on six different routes within the Kruger National Park.

The objective was to measure and investigate the energy consumptions and efficiency of the different types of vehicle.

In addition the project investigated the operating costs of all the vehicles.

This was achieved by measuring, calculating energy consumptions of the vehicles and the cost of the fuel source required for the particular technology. It was found that:

- The fuel efficiency of each vehicle technology was proportional to the route it was tested, and the difference in energy efficiency between the different technologies remained constant.
- Irrespective of the route profile, the route surface or its total distance, the highest energy efficiency is achieved by the battery electric vehicle (BEV), followed by the fuel cell electric vehicle (FCEV) and then by the combined hybrid electric vehicle (HEV) and lastly by the internal combustion engine (ICEV) vehicle.
- The battery electric vehicle (BEV) experiences the least vehicle energy losses as it travels on different routes, and thus requires the least input energy for any route. This is achieved as a result of the high efficiency of the electric vehicle powertrain. The electric powertrain has no losses due to idling and it has the potential to recover energy by means of regenerative breaking.
- Lower input energy requirements equate to lower energy costs, and this is what is achieved by the battery electric vehicle (BEV). Although the price of crude oil is projected to fall, and taking into account the increasing costs of electricity, the electric vehicle is still cheaper to operate than a fossil fuel powered vehicle.

- Although calculations provide a stable test environment it does not represent real world driving conditions. Different geographical areas provide different topographical properties and road surface conditions. An actual road test drive under real every day conditions might help to answer the question of how energy efficient are the different vehicle technologies.

- Measuring energy consumption on just a single drive cycle, might overestimate the energy consumption of the vehicles due to higher friction on a cold drivetrain.

- Further investigations might include how varying the vehicle's aerodynamics, speed and mass,combined with different driving styles could affect the energy consumption and fuel costs of the vehicle.But this is beyond the scope of this study.

The overall significance of the study was to investigate the suitability of battery electric vehicles (BEVs) as recreational vehicles, and in particular their use in game reserves in South Africa.

The energy efficiency of battery electric vehicles (BEVs) and low operational costs are well documented in many studies done before. A number of battery electric vehicles (BEV) are presently available to consumers on the market, including South Africa. They are suitable mostly for urban driving due to their limited range as dictated by their energy storing capacity and cannot compete with the driving range of the internal combustion engine vehicles (ICEVs). Its driving range limitation is compensated by allowing operation within the boundaries of a game park.

However the battery electric vehicle (BEV) has proved through this study that it has a great potential in a recreational or off-road role in terms of energy usage and operating costs.

Providing charging points within the game parks camps will ensure adequate charging of the battery electric vehicle (BEV) by also making use of alternative energy sources such as photovoltaic solar panels. Its technology is environmentally friendly, silent, and highly energy efficient. It provides a worthy alternative to the internal combustion engine (ICE).

REFERENCES

[1] http://www.southafrica.info.Last accessed November 2014

[2] http://www.environment.gov.za/mediastatement/climatechange-extinctionthreat,Last accessed November 2014

[3] European Commission, EU Energy and Transport in Figures, 2010 http://ec.europa.eu/transport/publications/statistics/statistics_en.htm

[4] Automotive Innovation. http://www.wfjholdings.com,Last accessed September 2014

[5] http://www.sanparks.co.za,Last accessed November 2014

[6] A portfolio of power-trains for Europe: a fact based analysis.

[7] http://ec.europa.eu/transport/.../2011-01-25-future-transport-fuels-report.pdf,Last accessed November 2014

[8] http://www.goelectricdrive.org,Last accessed February 2015

[9] US DOE:http;//www.uscar.org/guest/article,Last accessed August 2014

[10] A study on the costs and benefits of hybrid electric and battery electric vehicles in Ireland 2007 Edition, Version 1

[11] European Commission, EU Energy and Transport in Figures, 2010 http://ec.europa.eu/energy/publications/doc/statistics/part_2_energy_pocket_book2010.pdf

[12] McKinsey study 2010 Future transport fuels-tank to wheels articles

[13] G. Maggetto, P. Van den Bossche and J. Van Mierlo, CITELEC report "Force electrique en Wallonie: les vehicules electriques et hybrides en Wallonie, une solution ecologique durable pour la circulation urbaine"

[14] US department of energy http:// www.transportation.anl.gov,Last accessed December 2014

[15] Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. Stefano Campanari, Giampaolo Manzolini, Fernando Garcia de la Iglesia; Folder Articles electric vehicles) Politecnico di Milano, Department of Energy, Piazza Leonardo da Vinci 32, 20133 Milano, Italy 1 August 2008

[16]US Department of Energy,Energy Efficiency & Renewable Energy. http://www.fueleconomy.gov

[17] Ecotraffic. The life of fuels. Stockholm, 1992.

[18] Metz N, Sporckmann B. Comparison of the energy consumption and emissions of future drive trains for passenger cars at the year 2000. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[19] Wang Q, Deluchi MA. Impacts of electric vehicles on primary energy consumption and petroleum displacement. Energy 1992;17(4):351–66.

[20] OECD/IEA. Electric vehicles: technology, performance and potential. Paris:OECD, 1993.

[21] Wabro R, Wagner U. Energieverbrauchsanalyse von elektro-Pkw-stand der technik und ausblick. ATZ Automobiltechnische Zeitshcrift 1998;100(2).

[22] Amann CH. The stretch for better passenger car fuel economy: a critical look Part 1 and 2. Automotive Engineering International 1998:305–13, 71–6.

[23] Cuddy MR, Wipke KB. Analysis of the fuel economy benefit of drivetrain hybridization. Society of Automotive Engineers 1997;101–9.

[24] Wang M et al. Total energy-cycle energy and emissions impacts of hybrid electric vehicles. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[25] Lipman TE, DeLucchi MA. Hydrogen fueled vehicles. International Journal of Vehicle Design 1996;17:562–89.

[26] Weiss MA, Heywood JB, Drake EM, Schafer A, AuYeung FF. On the road in 2020—a life-cycle analysis of new automobile technology. Energy Laboratory Report #MIT EL 00-003. Cambridge (MA): MIT, 2000

[27] Reuyl JS, Schuurmans PJ. Policy implications of hybrid-electric vehicles. Final report to NREL, NEVCOR Inc., Stanford (CA), 1996.

[28] DeCicco J, Ross M. An updated assessment of the near-term potential for improving automotive fuel economy.Washington (DC): American Council for an Energy Efficient Economy (ACEEE), 1993.

[29] NRC. Effectiveness of the United States advanced battery consortium as a government–industry partnership. Washington (DC): National Research Council, 1998.

[30] Rand DAJ, Woods R, Dell RM. Batteries for electric vehicles, vol. 1. Exeter: Research Studies Press, 1998.

[31] St-Pierre C et al. Lithium polymer battery for electric vehicle and hybrid vehicle applications. In: Electric Vehicle Symposium 16, Beijing (China), 1999.

[32] Lipman T. The cost of manufacturing electric vehicle batteries. Davis: ITS, University of California, 1999.

[33] Kopf C et al. Development of a multifunctional high power system: meeting the demands of both a generator and traction drive system. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[34] Lutz JF, Patel BR. Performance comparison of a 100 kW brush less PM and induction motor system. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[35] Sato Y et al. New control methods for high performance PM motor drive system. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[36]STOSEB. Framtidens bila—En energi-och miljo¨studie. STOSEB: Stockholm, 1994.

[37] BRUSA, 20/4 1999 http://www.rol.ch/BRUSA/fenglish/frame.htm

[38] Corrigan DA et al. Higher power ovonic nickel–metal hydride batteries for electric and hybrid vehicles. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[39] Georen P. Personal communication, Department of Applied Electrochemistry, KTH (Sweden), 1999.

[40] Kuller D. Personal communication, 3M/Hydro-Quebec (Canada), 1999.

[41] Sjo¨blom B, Rehn J, Volvo Aero Corporation Sweden. The Volvo high speed generation hybrid drive and associated combustion system. Energy Conversion & Management 1997;38(1013):1225–35.

[42] NRC. Review of the partnership for a new generation of vehicles, Fourth report. Washington (DC): National Research Council, 1998. p. 122.

[43] Peschka W. The status of handling and storage techniques for liquid hydrogen in motor vehicles. International Journal of Hydrogen Energy 1987;12(11):753–64.

[44] Shelef M, Kukkonen CA. Prospects of hydrogen-fueled vehicles. Progress Energy Combustion Sciences 1994;20:139–48.

[45] James BD et al. Onboard hydrogen storage in fuel cell vehicles. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[46] DeLuchi MA, Ogden JM. Solar-hydrogen fuel-cell vehicles. Transportation Research 1993;27A(3):255–75.

[47] Ogden JM et al. Hydrogen energy systems studies. Princeton, NJ: Center for Energy and Environmental Studies, Princeton University, 1995.

[48] Cleghorn SJC et al. PEM fuel cells for transportation and stationary power generation applications. International Journal of Hydrogen Energy 1997;22(12):1137–44.

[49] McNicol BD, Rand DAJ, Williams KR. Direct methanol–air fuel cells for road transportation. Journal of Power Sources 1999;83:15–31.

[50] Kordesh K, Simader G. Fuel cells and their applications. Weinheim: VCH, 1996.

[51] Borroni-Bird CE. Fuel cell commercialisation issues for light-duty vehicle applications. Journal of Power Sources 1996;61:33–48.

[52] IPCC. Climate change 1995—impacts, adaptations and mitigation of climate change: scientific-technical analyses. New York: Cambridge University Press, 1996.

[53] M.Ahman/Energy 26 (2001) 973-989

[54] Kalhammer FR et al. Status and prospects of fuel cells as automobile engines. Sacramento (CA): State of California Air Resources Board (CARB), 1998.

[55] Katofsky RE. The production of fluid fuels from biomass. Princeton (NJ): Center for Energy and Environmental Studies, 1993.

[56] Ogden JM, Nitsch J. Solar hydrogen. In: Johansson TB et al, editor. Renewable energy. Washington (DC): Island Press, 1994.

[57] Council Directive 70/220/EEC of 20 March 1970 on the approximation of the laws of the Member States relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles, 1970.

[58] M. Ehsani, Y. Gao, S.E. Gay, and A. Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, London: CRC Press LLC, 2005.

[59] Formula Hybrid Rules, SAE International, August 26, 2008. Available: http://www.formula-hybrid.org/pdf/Formula-Hybrid-2009-Rules.pdf

[60] W. Gao, E. Solodovnik, and R. Dougal, "Symbolically-aided model development for an induction machine in virtual test bed," IEEE Transactions on Energy Conversion, Vol. 19, No. 1, March, 2004, pp.125-135.

[61] T.D. Gillespie, Fundamentals of Vehicle Dynamics, Society of Automotive Engineers, Inc., Warrendale, PA, 1992.

[62] IEA-AFIS. Automotive fuels for the future—the search for alternatives. Paris:OECD/IEA, 1999.

[63] Blinge M et al. Livscykelanalys (LCA) av drivmedel Bilagor. Stockholm: KFB, 1997.

[64] Energikomissionen, Omstallning av energisystemet. Energikommisionen:Stockholm, 1995

[65] Olsson LO. Fordonskostnadens pa°verkan vid anva¨ndande av biodrivmedel. Stockholm: KFB, 1996.

[66] Gustavsson Let al.,ReducingCO2 emissions by substituting biomass for fossil fuels.Energy 1995;20:1097-113.

[67] Requirement Development for Electrical Vehicles Using Simulation Tools Wei Zhan, Member, IAENG, Make McDermott, Behbood Zoghi, and Muhammad Hasan

[68] http:// www.geocontext.org, Last accessed September 2014

[69] A Beginner's Guide to Energy and Power Article submitted by N Packer, Staffordshire University, UK, February 2011.

[70] US DOE Hydrogen Program 2000 Annual Review May 9-11, 2000 San Ramon, California

[71] http://www.fueleconomy.gov, Last accessed September 2014

[72] World Bank Commodities Price Forecast (released January 30, 2014)

APPENDIX

Interpolation was achieved by making use of Matlab programming.

The program structure is as follows:

```
x = [0];

y = [0];

xi = [0:1:x(end)];

y_ = interp1(x,y,xi,'spline');

xlswrite('testdata.xlsx', xi', 'Road8', 'P1');

xlswrite('testdata.xlsx', y_', 'Road8', 'Q1');
```

The distance values are placed in the brackets at x = [0]

The elevation values are placed in the brackets at y = [0]

After execution of the program, the output of the program is stored in the Excel file called "test data". The data stored in this file shows distances in 1 metre increments with a corresponding elevation