CHALMERS

Diesel Hybrid Powertrain Concept Study for Long Truck Combinations

Master's Thesis in the Master's programme Automotive Engineering

ASHWINKUMAR UMASANKAR

DEVANSH MEHTA

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Applied Mechanics
Division of Vehicle Engineering and Autonomous Systems
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

The commercial vehicle industry faces strong challenges in the forthcoming years; such as reducing the dependency on fossil fuels, lowering energy consumption, fulfilling stricter legislation regarding emissions and also increased congestion on the roads. Thus, there is a high demand for more economically and environmentally viable transport solutions.

Long haul applications are interesting for fuel consumption reduction studies, due to the fact that even 1-2% reduction in fuel consumption can result in significant savings, since the distances and the mileage in context are large. The current hybridization and downsizing of existing combustion engines for long-haul applications can lead to decreased fuel consumption, but not enough to motivate the higher cost of the hybrid powertrain. Also, it is not favoured by the market as it affects the vehicle's longitudinal propulsion performance. Hence, longer vehicle combinations are being evaluated, as they lead to less energy consumption per unit of mass transported, because of increased cargo carrying capacity. The market will also have the advantage of saving in labor costs such as driver wages because fewer drivers are needed to transport the cargo capacity in question.

The thesis aims to electrify an intermediate unit in a typical long combination, called a dolly, and simulate the resulting powertrain. Feasibility studies are conducted for packaging the resulting components from powertrain sizing. 5 different concepts are constructed for the Dolly powertrain from the selected components. Rule-based control strategies are formulated for the concepts, which have a layout comparable to that of a Parallel Hybrid. The powertrain models are combined with the vehicle dynamics model of the long combination to create a simulation platform, and typical vehicle maneuvers are studied.

Results in terms of fuel consumption and performance related parameters are recorded and compared for the different concepts. Conclusions are derived from the results and the most interesting concepts for different parameters are evaluated and presented.

Key words: Hybrid Powertrain, Control Strategy, Long combinations

Konceptstudie av Dieselhybrid Drivlina för Långa Fordonskombinationer
Examensarbete inom *Master's programme Automotive Engineering*
ASHWINKUMAR UMASANKAR
DEVANSH MEHTA
Institutionen för tillämpad mekanik
Division of Vehicle Engineering and Autonomous Systems
Vehicle Dynamics group
Chalmers Tekniska Högskola

SAMMANFATTNING

Den kommersiella fordonsindustrin står inför stora utmaningar under de kommande åren: Att minska beroendet av fossila bränslen, sänka energiförbrukningen, uppfylla strängare lagstiftning för avgasemissioner och hantera ökad trängsel på vägarna. Således finns en stor efterfrågan på mer ekonomiska och miljömässigt hållbara transportlösningar.

Långdistanstransporter är högintressanta för studier i bränsleförbrukningsreduktion. Även en minskning av bränsleförbrukningen med 1-2% leder till betydande besparingar eftersom avstånd och körsträcka i sammanhanget är stora. Dagens hybriddrivlina med elektrisk motor, energiåtervinning till ett batteri och nedskalning av den befintliga förbränningsmotorn leder till minskad bränsleförbrukning även på långdistansapplikationer men inte tillräckligt för att motivera den högre kostnaden för hybriddrivlinan. Konceptet efterfrågas inte heller av marknaden eftersom det i vissa situationer påverkar fordonens framdrivningsprestanda.

Längre fordonskombinationer studeras av flera fordonstillverkare då de ger lägre energiförbrukning per massenhet transporterat gods på grund av ökad lastkapacitet. Ytterligare fördelar är minskade arbetskostnader, för t.ex. förarlöner eftersom färre förare behövs för att transportera en given godsmängd samt ger även mindre trängsel på vägarna. Längre fordonskombinationer innebär dock större krav på stabilitet och körbarhet. En del av fordonet man studerar är en s.k. ”dolly”, en liten släpvagn som används som styraxel till en semitrailer och då förvandlar semitrailern till en släpvagn. En reglerbar dolly skulle kunna bidra med ökad stabilitet, startbarhet och vändbarhet för den långa kombinationen.

Detta examensarbete syftar till att elektrifiera en dolly och simulera den resulterande drivlinan.

En packningsstudie har genomförts, med komponenter som idag finns tillgängliga inom Volvo. Fyra olika hårdvarukoncept har konstruerats med de valda komponenterna.

Styrstrategier har formulerats för den kompletta fordonskombinationen vars layout blir jämförbar med en parallellhybrid. Drivlinemodeller har sedan kombineras med en fordonsdynamisk modell av fordonskombinationen för att skapa en simuleringsplattform där typiska fordonsmanövrer studeras map stabilitet och körbarhet. Bränsleförbrukning och prestandarelaterade parametrar har simulerats och utvärderats för de olika hårdvarukoncepten och styrstrategierna. Simuleringsresultaten och konceptens olika egenskaper utvärderas och presenteras och slutsatser dras.

Nyckelord: Hybriddrivlina, kontrollstrategi, Långa kombinationer

Contents

Acknowledgements

This report is the result of the master thesis work carried out in the Electrical Propulsion Controls department of Volvo Group Trucks Technology, towards the partial requirement for the Master's degree in Automotive Engineering at the Department of Applied Mechanics at Chalmers University of Technology. The thesis was performed from February 2014 till August 2014, at the Volvo Group Trucks Technology headquarters in Lundby, Gothenburg.

We would like to thank Andreas Roupé, Group Manager, Electric Propulsion Controls, for giving us this opportunity and all the necessary resources for carrying out this thesis work in his group. We would like to thank Kristoffer Rydquist and Mattias Åsbogård of the same group for volunteering to be our supervisors for this thesis work, for without their support and insight, this level of progress with the thesis work would not have been possible. We would also like to thank our examiner Bengt Jacobson and supervisor Sixten Berglund for supporting us as and when required.

Last but not the least, we would like to express our gratitude to the various personnel at Volvo who offered advice and invaluable feedback on the thesis work, such as Andreas Jansson, Mattias Hansson, Rasmus Andersson, Sachin Janardhanan, and Leo Laine.

This thesis work has been a great learning experience for us, and has provided us a very good foundation for our professional career. The time we spent interacting with the various employees and infrastructure has helped us cultivate a sound analytical and technical frame of mind.

Göteborg September 2014

Ashwinkumar Umasankar

Devansh Mehta

Preface

About Volvo Group Trucks Technology

Volvo Group Trucks Technology (GTT) is a worldwide entity supporting the Group Trucks and Business Area's within the Volvo Group. It provides state-of-the-art research, engineering, product planning and purchasing excellence to final delivery of complete products and also supports the products in the aftermarket [12].

The GTT organization is spread across the world. Its 10 000 employees are multi-brand, multi-cultural and work in global teams on international projects.

About Powertrain Engineering

Powertrain Engineering is a global organization within Volvo GTT with 2000 colleagues in six countries; Brazil, France, Japan, USA, India and Sweden. The scope of work includes the engineering and design of engines, gearboxes and axles for Volvo Group customers.

About Powertrain Control Systems

Powertrain Control Systems, within Powertrain Engineering is globally responsible for the design of all powertrain embedded electronic systems. It includes HW and SW developments.
Engine, after treatment and transmission management systems are the most well-known electronic platforms developed and delivered to all group products and installations. Control Systems contributes to the innovation assets of the Volvo Group by providing competences and technical solutions in the area of controls theory, advanced driveline control systems and support for new technology such as E-mobility and alternative fuels.

About Drivelines & Hybrids

The Driveline and Hybrid technology area is responsible for systems and components within transmission and electro-mobility development. This includes; transmissions, clutches, propeller shafts driven axles, Energy Storage System and Motor Drive System. This Technology Area is also responsible for the platform development of these products. Transmissions are in-house developed. There are two platform sites directly linked to the technology area that perform the core component development and three applications sites linked to the sites that install the systems into the vehicles.

About Chassis & Vehicle Dynamics Engineering

Chassis & Vehicle Dynamics Engineering is a global organization with highly skilled teams located in six countries. They propose and develop profitable and competitive technical solutions for each truck company in the Volvo Group.

About Chassis Strategy & Vehicle Dynamics

This department of Chassis strategy & Vehicle Dynamics is responsible for performing the following functions:

- Support development of mid and long term content in Technology Strategies, Technology Roadmaps and required activities in the CVDE AE Portfolio.
- Develop, secure and verify complete vehicle features (i.e. active safety, durability, transport efficiency) by use of analysis.
- Establish and support a structured approach to differentiated targets on modules/systems for different brand requirements and operating conditions.

This Master thesis project involved interaction with both Drivelines & Hybrids and Powertrain Control Systems, due to the nature and scope of the thesis work. The Drivelines & Hybrids department provided support for the powertrain packaging feasibility study and also provided data for the various components. The Electric Propulsion Control team within Powertrain Control systems provided support on simulation models and control strategies. Also, the Complete Vehicle Control team under the Chassis Strategy & Vehicle Analysis department offered support for the vehicle dynamics simulation models and provided information about the important vehicle performance criteria used in the thesis work.

Notations

Abbreviations

AE	Advanced Engineering
AER	All Electric Range
AMT	Automated Manual Transmission
AMT PS	Automated Manual Transmission Power Shift
BLB	Boras Landvetter Boras
CAD	Computer Aided Design
CDCS	Charge Depleting Charge Sustaining
DoD	Depth of Discharge
EB	Energy Buffer
ECU	Engine Control Unit
EM	Electric Motor
EMS	Energy Management System
ESS	Energy Storage System
EV	Electric Vehicle
GPS	Global Positioning System
GSP	Global Simulation Platform
GTA	Global Transport Application
HCU	Hybrid Control Unit
HEV	Hybrid Electric Vehicle
HW	Hardware
IC	Internal Combustion
ICE	Internal Combustion Engine
IMF	International Monetary Fund
ISAM	Integrated Starter Alternator Motor
ISG	Integrated Starter Generator
KE	Kinetic Energy
MDS	Motor Drive System
MHD	Medium Heavy Duty
MHEV	Mild Hybrid Electric Vehicle
PBS	Performance Based Standards
PE	Potential Energy
PHEV	Plug-in Hybrid Electric Vehicle
SoC	State of Charge
SW	Software
TCU	Transmission Control Unit
VTM	Vehicle Transportation Models

1 Introduction

1.1 Background

The fuel prices in the world today are about 4 times of that in 2000 [16]. For example, the cost of gasoline in Sweden has doubled in the past 20 years [17]. Regarding future price of fuel, a study by IMF [1] predicts an increase in fuel price of 80% over the next 10 years, whereas a similar study by Volvo [Volvo Internal] estimates a more conservative figure of 30.Thus, there is a need to develop vehicles that consume less fuel per kilometer of distance travelled, in order to have cost-efficient transport [1].

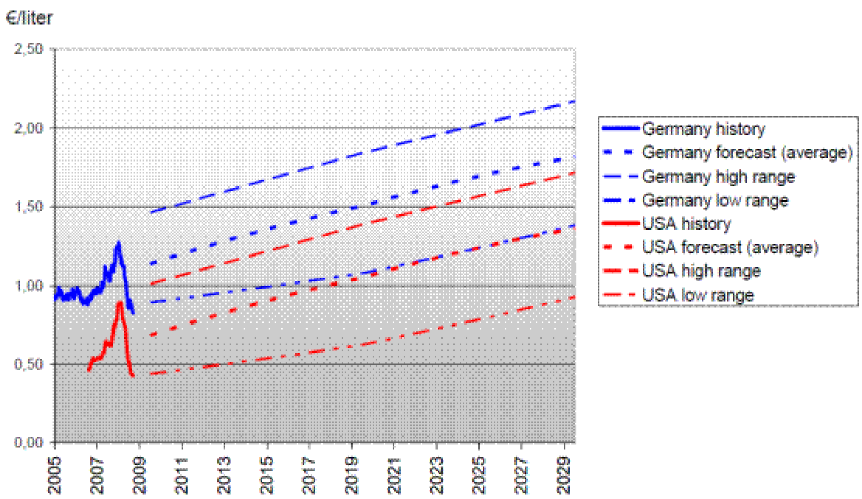


Figure 1: Volvo estimated fuel price increase [Volvo Internal]

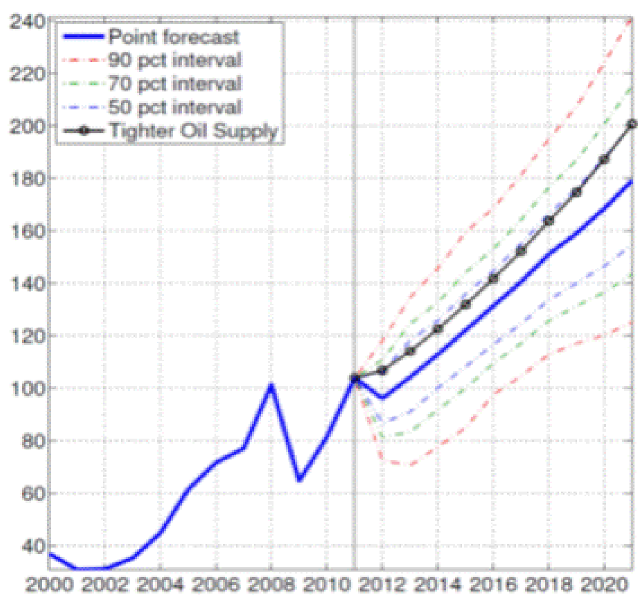


Figure 2: IMF estimated fuel price increase in USD per barrel [1]

Moreover, heavy-duty trucks are the largest consumers of fuel per year, as seen in the statistics below. This is because they provide the highest fuel consumption per kilometer of distance travelled (although they have the highest fuel economy per ton per km and highest thermal efficiency) and also have the highest mileage per year. Hence, a reduction in fuel consumption of even as little as 5% in long-haul heavy duty truck applications can have a great effect on the overall fuel consumption, running costs, and emissions at a macroscopic level.

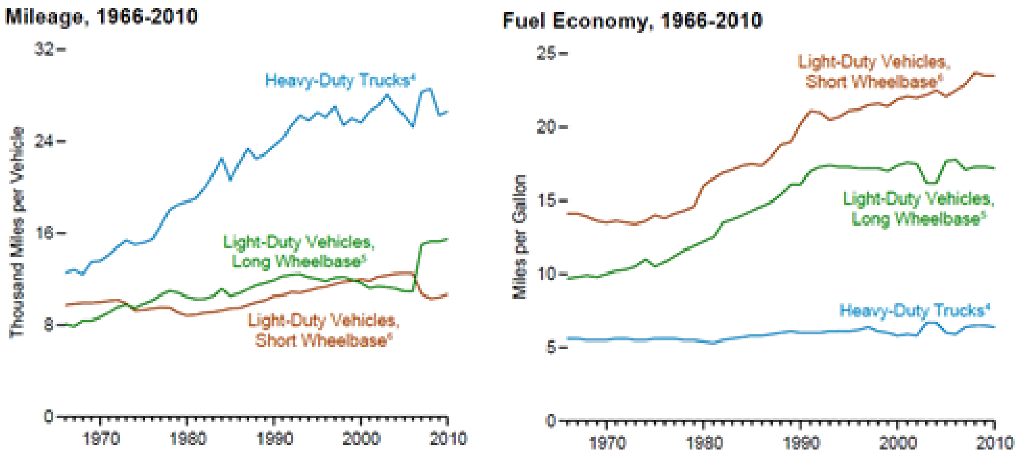


Figure 3: Mileage and Fuel economy of Vehicles in the US Market

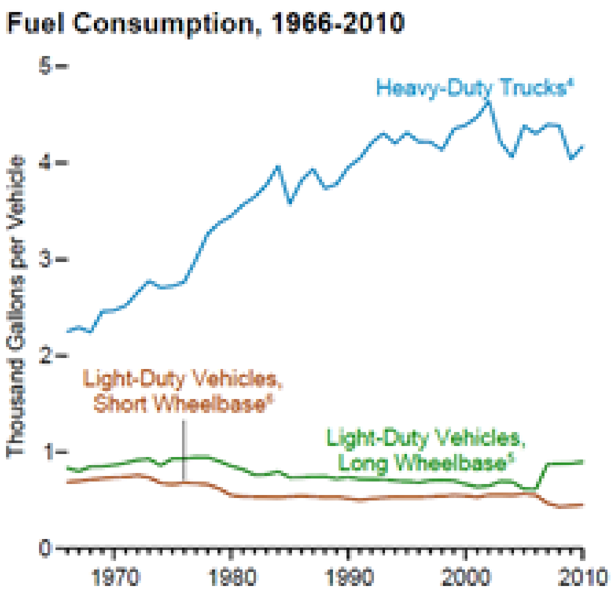


Figure 4: Fuel Consumption of Vehicles in the US Market

1.2 Vehicle configuration

This thesis deals with long truck combinations, which can transport a much larger cargo than conventional single trailer trucks. In order to have long truck combinations, a device called as a Dolly must be used to connect two or several trailers. There are various types of vehicle combinations present in the market or in the concept phase, but this thesis will be limited to the A-double configuration.

1.2.1 Dolly

Figure 5: Picture of a typical truck dolly

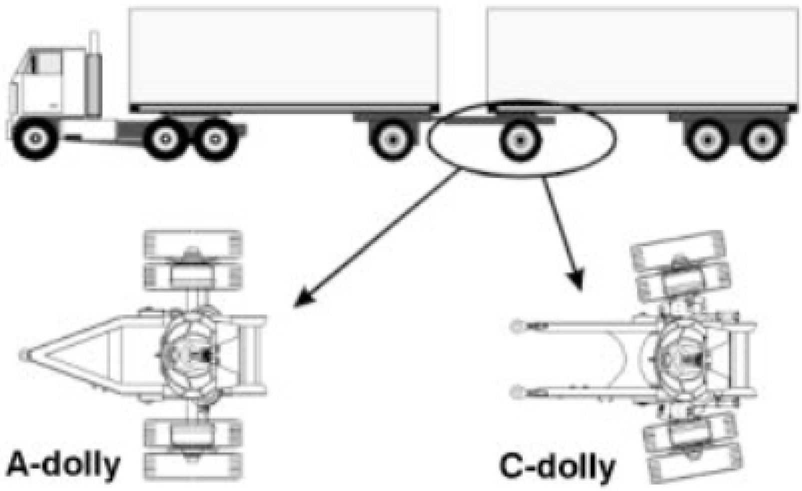


Figure 6: Diagram of an A-type and C-type Dolly

A dolly is a small trailer that can be coupled to a truck or trailer so as to support a semi-trailer. A semi-trailer is a trailer without a front axle. A large proportion of its weight is supported by a road tractor, a dolly, or the tail of another trailer. [11]

The dolly consists of a bogie equipped with a kingpin and a fifth wheel, to which the semi-trailer is coupled [12].

Depending on design style, dollies may have a single- or double-tow-drawbar arrangement for coupling to the towing trailer. In either case, the tow bars terminate in a simple, rugged towing eye. The towing trailer is equipped with one or two pintle hitches consisting of a hook and locking mechanism, which engages and secures the eye(s), thereby supporting and towing the dolly. There are two types of converter dollies, which are distinguished by the number of tow bars, are illustrated in the above figure.

1. A-dolly: The defining quality of the A-dolly is its single-point tow bar. The A-dolly is the most common type of converter dolly; over 99 percent of the dollies in use in the U.S. are of this type. The single hitching point allows the dolly to articulate in yaw (steering), pitch (fore/aft rotation), and roll (side-to-side rotation) with respect to the towing trailer. The advantage of an A-dolly is its excellent low-speed maneuverability and turning capability. However, its ability to provide yaw and roll articulation leads to considerable rear-ward amplification and dynamic roll instability. Hence, this type of dolly is more suited to low speed applications, such as city driving [2].

2. C-dolly: The defining quality of the C-dolly is its double-tow-bar configuration. The C-dolly originated in Canada. Its attractive quality is its ability to improve the stability of multiple-trailer combination vehicles. This is accomplished because the double-tow-bar hitching arrangement eliminates yaw and roll articulation with respect to the lead trailer. Eliminating yaw, in particular, can degrade low-speed maneuverability and produce excessive hitch forces and tire scrubbing during tight turns at low speeds. To mitigate these low-speed problems, the wheels of the C dolly are allowed to steer by a caster mechanism. However, a centering mechanism provides mechanical resistance to this self-steering action as required for dynamic stability at highway speeds. Hence, this dolly type is more suited to high-speed applications, especially those involving multiple trailer combinations.[18]

1.2.2 A-double combination

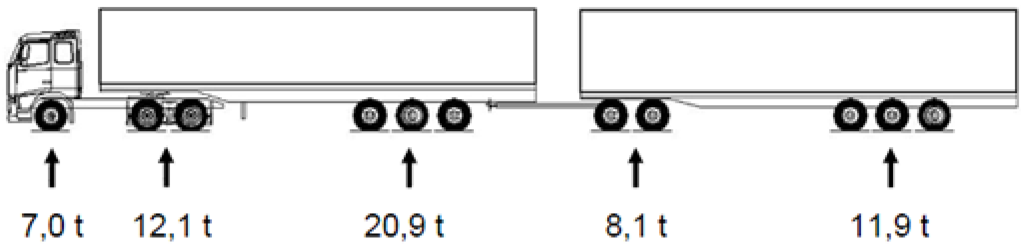


Figure 7: Diagram of an A-Double vehicle combination

Table 1: Mass & Payload Distribution in an A-Double Combination

Vehicle Unit	1	2	3	4
Mass (kg)	900	31000	3000	17000
Payload (kg)	-	24000	-	10000

The A-double combination will be used for vehicle simulations in this thesis. This combination consists of a tractor, two identical standard semitrailers and a converter dolly. It has a total length of 31.5 m. The distance from the pintle hitch coupling to the end of the semitrailer is 1.5 m. The first semitrailer is fully laden and the rest of the payload is on the second semitrailer. Hence, the total payload for this 60ton vehicle is 34tons. It is not possible to achieve 25 % of the total weight on driving axles with even load distribution [3].

1.3 Problem Definition

The motivation behind performing this thesis work is the potential benefits that can be achieved by hybridization of truck powertrains for long haul applications. Due to the indispensable nature and the sheer distances covered during long haul applications, a reduction of fuel consumption by even 1% can result in considerable economic and environmental savings.

Increasing the total capacity of such long haul applications by increasing the length of vehicle combinations remain an interesting option for study due to increased productivity, decreased road footprint of the vehicle fleet for the same amount of cargo, and a reduction in amount of fuel required per mass of cargo transported for a mission, as well as the number of drivers required to move the same amount of cargo.

An additional way of reducing the fuel consumption per mass of cargo transported per unit distance is to use an electrified dolly. An electrified dolly is basically a dolly with one or two axles driven by an electric motor(s). There is a battery pack attached to the bottom of the dolly that supplies energy to the electric motor(s). More about the electric dolly concept will be described later in Chapter 7 of the report.

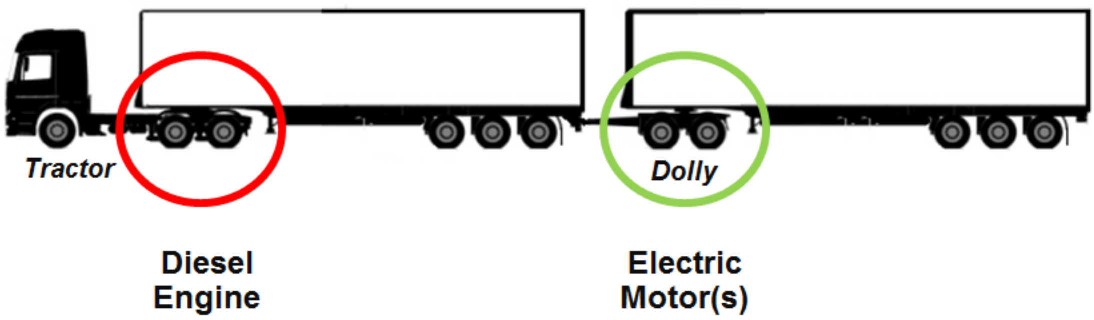


Figure 8: A-Double combination with an Electric Dolly

Previous studies have been done on electrification of the trailer unit, and although the fuel consumption reduction results were promising, they haven't proved feasible. This is because the trailer is often not owned by the company which owns the truck and is interchanged between transporters. Electrifying the dolly, however, seems to be a commercially viable option if the dolly can be owned by the customer and can be attached to various semitrailers. An electric dolly is a modular solution, as it can be sold as an add-on product along with the truck which can be disconnected at a loading bay for in-city applications or any sort of transport that involves lower cargo capacities. Hence it is also a more flexible and adaptable solution than hybridization of either the tractor powertrain or a complete trailer. Also, it could improve startability of the combination as it would have more driven wheels.

1.4 Objective

The objectives of the thesis work are encapsulated in the following points:

- Construction of a complete powertrain simulation model of the vehicle combination, in order to study the vehicle's fuel consumption and performance.
- Sizing of the components of the Electrified Dolly (refer Chapter 7.2) with respect to performance requirements and driving cycle, taking basic geometrical limitations into account by means of a feasibility study.
- Rule-based Control Strategies for the Hybrid Powertrain, taking into consideration the performance requirements and limitations imposed by vehicle dynamics.
- Simulation results with regard to performance, fuel consumption and vehicle dynamics.

1.5 Limitations

The limitations of the thesis are defined in such a way so as to make the scope of the thesis work clearer, and work towards reaching the goals while keeping in mind various factors such as geometrical constraints, feasibility, practicality and cost. They are listed out as follows:

- The Packaging study to be done to determine the feasibility of packaging the propulsion components in the dolly, hence it is approximate.
- Off-the-shelf propulsion and energy storage components have been used.
- The energy storage system to be used is of battery type.
- The long combination layout is considered as the so called A-Double configuration (refer chapter 1.2.2).
- The powertrain layout is simplified to be a Parallel Hybrid layout for formulating the control strategies, with one conventional diesel engine in the truck and electric motor(s) on the dolly.
- Engine-based charging mode is not possible, due to the lack of physical connection between the dolly powertrain components and the IC engine.
- The power consumption required for heating/cooling the electric powertrain is considered to be negligible.
- Charging from grid during cycle has not been considered.
- Startability and Gradeability have not been investigated.

2 Literature Review

2.1 Hybrid Powertrain Classification

A hybrid powertrain is one which utilizes two different sources of energy for propulsion of the vehicle. The most common type of hybrid uses an internal combustion engine which derives energy from a fuel, and an electric motor which derives energy from a battery. Such a fuel-electric hybrid can be classified in different ways, based on:

2.1.1 Hybrid System functions

Hybridization of a powertrain allows new functionalities that determine the class of HEV, such as:

Start/stop: A start-stop system automatically shuts down and restarts the internal combustion engine to reduce the amount of time the engine spends idling, thereby improving fuel economy.

Regenerative braking: This feature allows converting the kinetic energy of the vehicle into electrical energy by using the electric motor as a generator. This 'free energy' is often stored into a battery and reused later to propel the vehicle. In an HEV, this feature is fundamental and generates a major part of the fuel savings.

Torque assist: The electric energy contained in the battery can be used to propel the vehicle through the electric motor. In case of torque assist, the power delivered by the ICE is reduced by an amount equal to the power supplied by the electric machine. Thereby the vehicle achieves the same performance as a conventional would.

Boost: This feature differs from the torque assist in a sense that the sum of the ICE torque and EM torque exceeds the maximum torque capacity of a conventional ICE powered vehicle. Thus the vehicle can achieve better accelerations than a non-hybridized drivetrain.

Electric only: In electric only mode, the hybrid vehicle is driven by the electric machine only. Meanwhile the engine can be turned off. This feature is particularly useful at low speeds when ICE has low efficiency. Also, the power needed at these low speeds is low enough to be within the EM's maximum power limit. In consequence, no fuel is consumed and the vehicle achieves a zero-pollution level. Note also that shutting down the engine considerably reduces the noise generated by the vehicle (which makes it suitable for city driving, amongst other things).

Plug to grid: Such a feature offers the possibility to plug a hybrid vehicle directly onto the electrical power grid. The batteries can thereby be charged when they are nearly depleted. This allows the vehicle to run longer in Electric mode, Boost mode and Torque assist mode as compared to a non-plugin hybrid. [15]

2.1.2 Rate of hybridization

The contribution of the electric machine to the propulsion of the vehicle can be quantified through the rate of hybridization. Rate of hybridization (Hr) is a measure used to describe how strongly a parallel powertrain is hybridized. It is defined in the equation below as the ratio of maximal electric power to the maximal power deliverable by the powertrain and is often expressed as a percentage [Volvo Internal].

$$Hr = \frac{P_{EM}^{max}}{P_{ICE}^{max} + P_{EM}^{max}} * 100$$

Table 2: Common Rates of Hybridization

Type	**Rate of hybridization (%)**
EV	Hr = 100
PHEV	Hr > 50
HEV	25 < Hr < 50
MHEV	10 < Hr < 25
μHEV	Hr < 10
Conventional	Hr = 0

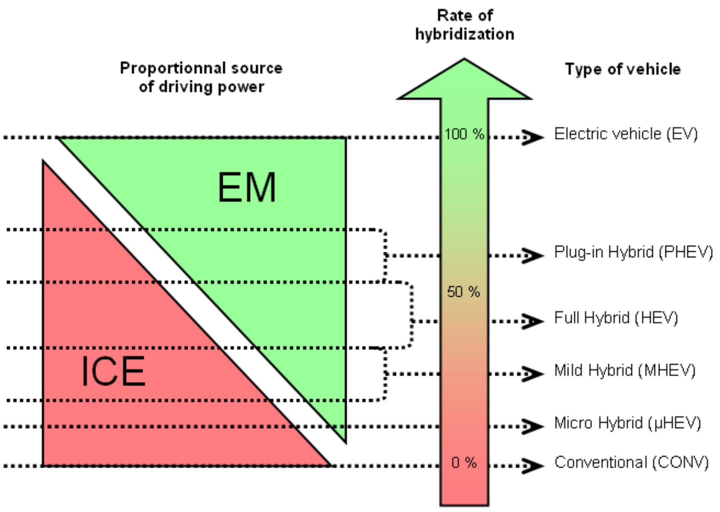


Figure 9: Examples of typical Rates of Hybridization for different types of vehicles

Table 3: Examples of hybrid vehicles in the market with their rate of hybridization [Volvo Internal]

Vehicle		P_{EM}^{max}(kW)	P_{ICE}^{max}(kW)	P_{ICE}^{max}(hp)	Hr (%)	Type
Toyota Prius II		50	58	78	46	HEV
Toyota Prius III		60	73	99	45	HEV
Volvo Hybrids	City Bus SD-DD	120	160	215	42	HEV
	Refuse Truck EU	120	246	330	32	HEV
	Distribution Truck EU	120	223	300	34	HEV
	Mack Truck US	120	242	325	33	HEV
	Long Haul 120	120	343	460	25	MHEV
	Long Haul 60	60	343	460	14	MHEV

2.1.3 Power/Energy flow through a hybrid driveline:

There are three main types depending on the layout [4]:

1. Series Hybrid

A series hybrid is one in which only one energy converter can provide propulsion power. The IC Engine acts as a prime mover in this configuration to drive an electric generator that delivers the power to the battery or another form of energy storage, and the propulsion motor.

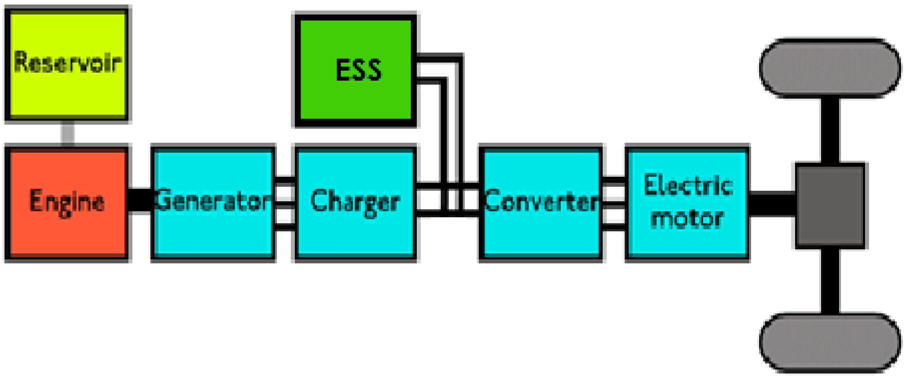


Figure 10: Layout of a Series Hybrid Powertrain

2. Parallel Hybrid

A parallel hybrid is one in which more than one energy conversion device can deliver propulsion to the wheels. The IC Engine and the electric motor are configured in parallel with a mechanical coupling that blends the torque coming from the two sources. Hence, the IC Engine and electric motor can be used either simultaneously or separately to meet the power demand.

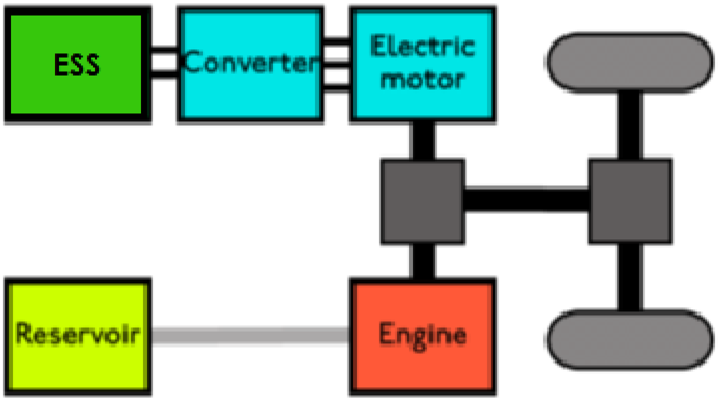


Figure 11: Layout of a Parallel Hybrid Powertrain

3. Power-split Hybrid

In a Power-split hybrid, the power flow from the engine to the wheels can either be mechanical or electrical. Hence, the IC Engine can be also used to charge battery through the electric motor, and then send power to the wheels through the electric motor. Thus, it has the functionalities of both a series and parallel hybrid.

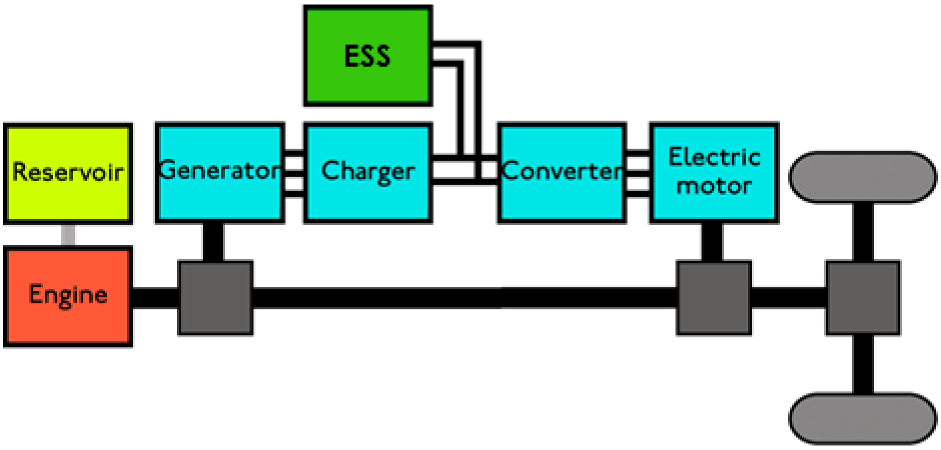


Figure 12: Layout of a Power-split Hybrid Powertrain

2.2 Driveline Topology

2.2.1 AMT

AMT stands for Automated Manual Transmission. It is a standard gearbox with a dry clutch, but the clutch pedal and the gear lever is removed. The control of the clutch and the selection of the proper gears are done by software and actuators. The gearbox consists of an unsynchronized mainbox with three forward and one reverse gear, a synchronized range gearbox which splits every gear into two fairly similar gears, and a synchronized range gearbox which gives every gear a high speed and a low speed range. So, combining these three gearboxes result in a gearbox with a total of 12 forward gears and 4 reverse gears.

2.2.2 ISAM Configuration

In the ISAM (Integrated Starter Alternator Motor) layout, the electric motor is placed between the clutch of the ICE and the transmission input shaft. A special electric motor is used, which has a large diameter but short in length. This provides a shorter but wider powertrain layout. The electric motor has to be placed between the gearbox and the extra-clutch, and is always connected to the driveline. It is possible to connect the ISAM directly on the ICE (without a clutch) but this solution (sometimes referred to as ISG) has limited functionalities since it is impossible to physically disconnect the electric motor from the engine.

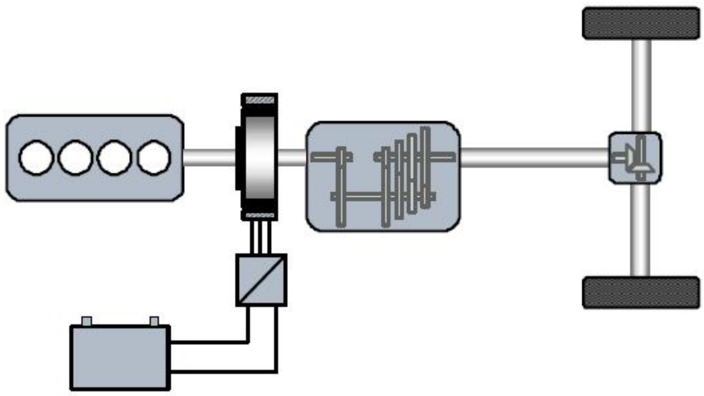


Figure 13: Layout of an ISAM configuration

2.3 Energy Storage System

An energy storage system is one which is used to store, charge and discharge energy as and when required. They are usually either batteries or supercapacitors in automotive applications. The energy storage type has been limited to batteries in this thesis. Batteries are devices that transform chemical energy to electrical energy and vice versa [5].

Desirable attributes of traction batteries for EV and HEV applications are high specific power, high specific energy, long calendar and cycle life, low initial and replacement costs, high reliability, and high robustness. Among other current technical challenges, a key point is developing accurate techniques to determine the capacity or the state of charge (SoC) of batteries during their operation [5].

The capacity of a battery, usually expressed in Ah, is the integral of the current that can be delivered under certain conditions. A dimensionless parameter is the state of charge, which describes the amount of charge remaining in the battery, expressed as a percentage of its nominal capacity. Another key design parameter is the specific energy, i.e., the energy that can be stored in the battery per unit mass, typically expressed in Wh/kg [5].

Lithium-ion batteries have been used as the ESS in this thesis. Their high specific energy and specific power make them suitable for HEVs. They have a carbon based anode, usually made up of graphite, in which lithium ions are intercalated in the interstitial spaces of the crystal. Hence, the cathode is a lithium oxide, and the electrolyte is a lithium salt solution. The cell voltage is usually 3.6 V [5].

2.3.1 Battery Selection and Sizing

Battery selection can be done based on: power discharge capacity, energy capacity, allowed volume, allowed mass, load profile, price, nominal voltage, resistance, current charge and discharge. A cost function is minimized in order to select the most adequate battery.

For a plug-in hybrid, the battery can be sized such that it has enough capacity to be able to complete a certain number of transport tasks per day.

$$tripsperday * working\_daysperyear * trip\_length \ = \ annual\_mileage$$

Figure 14: SoC versus Time for a battery in a typical hybrid vehicle application [Volvo Internal]

2.3.2 Influence of Depth of Discharge on Battery Degradation

Battery degradation increases with the amount of energy flowing through the battery, i.e. the total and maximum energy throughput during the battery lifetime. The energy throughput strongly depends on the depth of discharge. The DoD is the difference between the minimum and maximum value of SoC in a battery during the driving cycle of an electrified vehicle. The lifetime of a battery N_{cmax} (DoD) is defined as the maximum number of charge cycles after which the battery capacity reduces to less than 80% of the original capacity, when run at a certain depth of discharge.

The battery life greatly depends on the DoD, as show below:

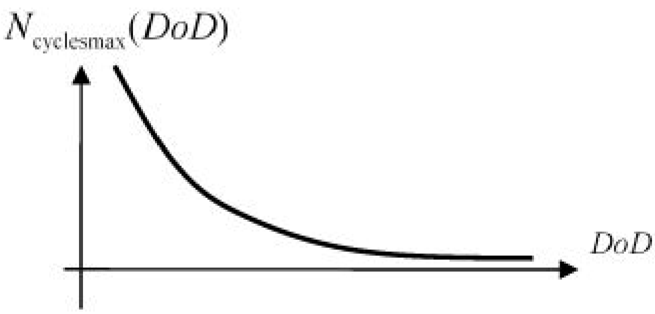


Figure 15: Battery Life versus Depth of Discharge [Volvo Internal]

2.3.3 Energy Throughput

The total energy throughput of a battery is the total amount of energy in watt-hours that is put into and taken out of the battery over all the cycles in its lifetime. It can also be measured for each operation of the vehicle, i.e. for each driving cycle. The average energy throughput (kWh/h) of a battery is the amount of energy that in average is stored and released during a driving cycle [Volvo Internal]. It can be calculated as below:

$$Average\ Energy\ Thoroughput\ (AET) = \frac{\int_0^t |V * I|}{1000 * t}\ \ \text{kWh/h}$$

Where,
V= Battery Voltage (Volts)
I= Battery Current (Amperes)
t= Time taken to complete driving route (hours)

The maximum energy throughput of the battery changes as the battery life decreases due to wear as shown below:

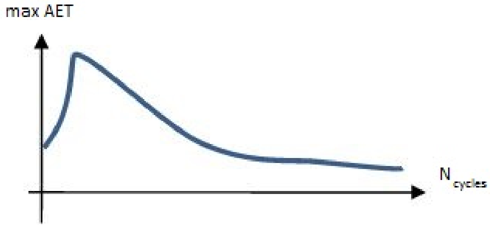


Figure 16: Maximum Energy Throughput versus Battery Life [Volvo Internal]

The total energy throughput of a battery can be calculated by the formula:

$$E_{life} = N_{cycles\,max}(DoD) * E_{batt} * DoD$$

The maximum energy throughput of a battery can be calculated by the formula:

$$E_{tpmax}(DoD) = 2 * V * Q * N_{cycles\,max}(DoD) * DoD$$

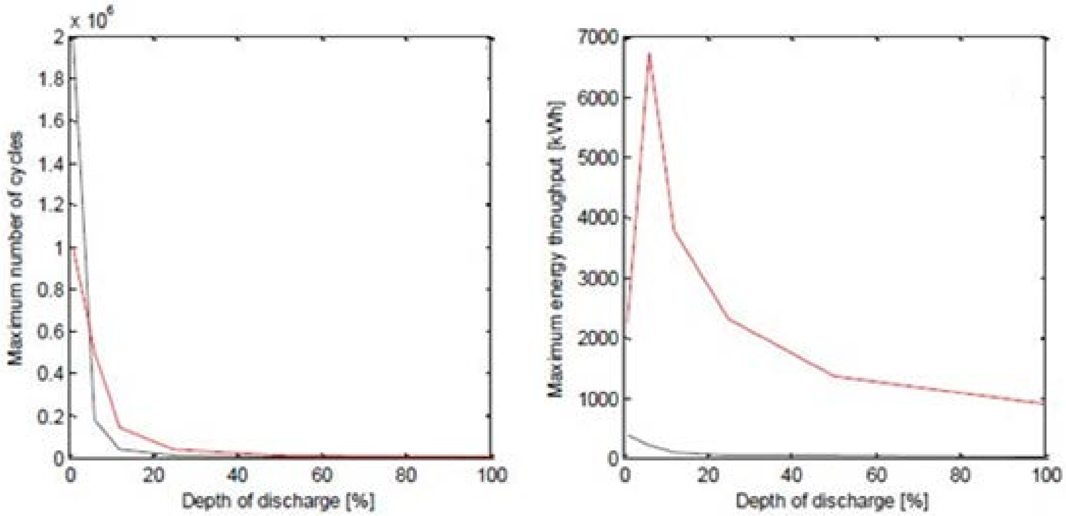


Figure 17: Plots of Maximum number of cycles and Maximum Energy Throughput versus Depth of Discharge [Volvo Internal]

2.4 Energy Management & Control Strategies

An energy management strategy (EMS) is required in a hybrid powertrain as it has more degrees of freedom than a conventional one, and should utilize the IC Engine, electric motor, and battery in the most energy efficient manner. The basic idea behind most control strategies is to be able to run the IC Engine at its most efficient point with the help of the electric motor, to efficiently regenerate energy, and to be able to supply sufficient power to the wheels in order to maintain the required performance. Also, the ICE can be shut off completely if enough energy and power can be provided by the EM. The various types of energy management strategies can be classified as follows:

Table 4: Control Strategies and their description [Volvo Internal]

Aspect	Description
Rule or model based	Examples of rule-based methods are neural networks and fuzzy logic. Model based methods uses a mathematically (state space formulization) described plant model to derive control signals.
Predictive or non-predictive	Predictive strategies need future information, for example the predicted vehicle power need. The future information can be guessed or derived from an 'intelligence gathering system', for example a camera. Non-predictive strategies just use the present information.
Length of prediction horizon	Full or partial. Seconds, minutes or hours.

Minimization function	Fuel, wasted energy, battery wear, or combinations of these are examples of possible objective functions.
Hybrid or plug-in hybrid	If grid power is fed into a hybrid vehicle, it is a plugin hybrid. In such a case a charge depleting control strategy is needed. It means that the battery energy level in the end of transport task shall be lower than in the beginning.
Adaptive or non-adaptive	An adaptive control automatically adapts its behaviour during vehicle operation. One can for example think of a strategy that uses less battery power if the battery health is bad. This aspect is a bit vague and much coupled to if a control is model based or not. Updating a parameter, for example battery capacity, in the plant model of a model-based strategy will make it adaptive.

The EMS can split the demand for traction power between the ICE and Energy Buffer (EB), based on three signals: SoC, desired vehicle velocity (v), and demand for traction power (P_{dem}). The difference between the demanded tractive power and power supplied by the ICE can be used to charge/discharge the battery [6].

2.4.1 Heuristic Control Strategies

The strategies described below are relatively simple and thus easy to implement as they are rule-based, and can lead to a significant reduction in fuel consumption.

2.4.1.1 Heuristic Energy Management

In the heuristic methods, the energy management controller is often put together directly using engineering intuition as a set of rules. Even if these kinds of controllers lack a guaranteed level of optimality; the intuitive approach remains as a common way to design energy management controllers.

The heuristic control strategy described below has been implemented in the Mild Hybrid Long Haul project in 2009. In this strategy, the power split between the ICE and the EM is calculated by comparing the current SoC to a reference SoC value. The reference SoC calculation is based on the vehicle speed as shown in the figure below. The basic principle of this curve is to:

a) Keep the SoC low when the vehicle speed is high since a braking phase is likely to happen later (and therefore be prepared to charge the battery). The goal here is to recover as much energy as possible when the vehicle decelerates.

b) Maintain the SoC at high value when the vehicle speed is low to provide EM torque assist to the ICE with the electric machine and therefore deplete the battery during acceleration to a higher speed.

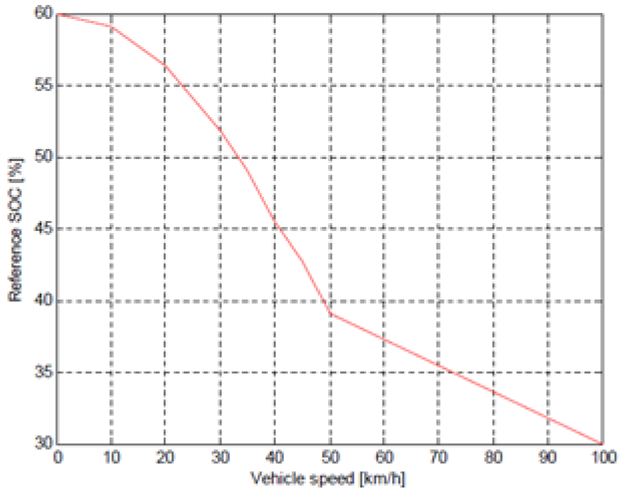


Figure 18: Look-up plot of Reference SoC versus Vehicle Speed [Volvo Internal]

However this control strategy can be overridden in some occasions. For example during braking phases, the energy recuperation is prioritized. Therefore the controller will aim at filling up the battery with as much free regenerated energy as possible. The recuperated energy is then used to propel the vehicle and feed the electrical auxiliaries. Note that this strategy does not aim at improving the performance of the vehicle: the hybrid vehicle is supposed to achieve the same performance as the equivalent conventional vehicle [Volvo Internal].

The reference SoC is used in the rule based controller to split the energy contained in the fuel tank and in the battery. This description is based on an example presented on figure 25 below and divided into 4 cases:

Case 1: braking demand

Case 2: propelling demand and SoC > SoC_{ref}

Case 3: propelling demand and SoC_{ref} > SoC > SoC_{win_min}

Case 4: propelling demand and SoC = SoC_{win_min}

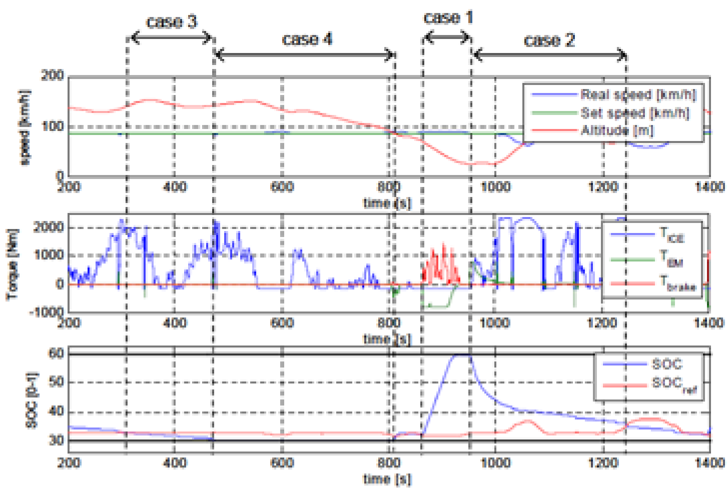


Figure 19: Plots of Vehicle Speed, Torque and SoC versus Time [Volvo Internal]

Case 1

When braking power is required, regeneration is prioritized. Therefore the reference SoC is totally disregarded in this case. The goal is to maximize the energy regeneration and to charge the battery. Note that, if the SoC comes to the maximum SoC window (60% for example), the braking power is not supplied by the electric machine anymore but by the service brake. This phenomenon is referred as ESS saturation.

Case 2

In this case, the vehicle power demand requires propelling the vehicle. Since the energy level in the battery is higher than the reference value, the EM will be partly used to propel the vehicle. The EM power demand is given by the following formula:

$$P_{EMdemand} = K \times \left(\frac{SOC - SOC_{ref}}{SOC_{win\_max} - SOC_{ref}} \right)^n$$

An example of this control strategy is given on the figure 27 below with $SoC_{ref} = 35\%$. The higher the SoC, the more power will be used by the EM. This way the battery will be depleted faster at high SoC and slower at low SoC.

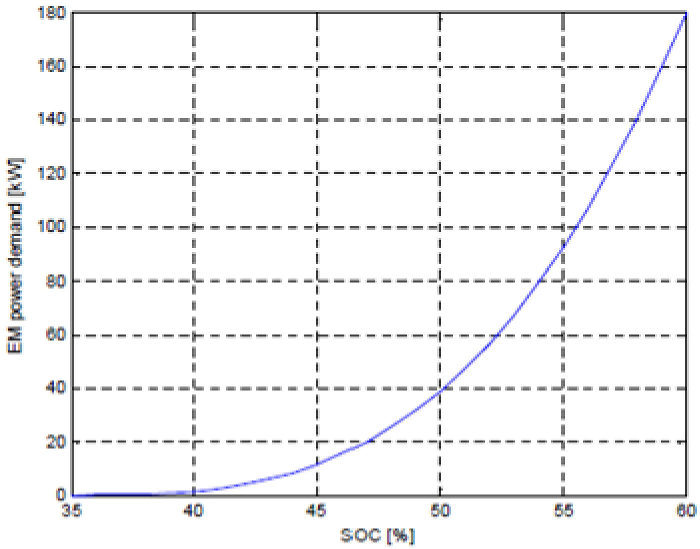


Figure 20: [Volvo Internal] EM power demand as a function of SoC for SoC_{ref} = 35% when SoC > SoC_{ref}

The ICE torque is the result of the difference between the torque supplied by the electric machine and the total torque demanded. This ensures that the mild hybrid vehicle achieves the same acceleration performance of a conventional vehicle. As a result, the battery is depleted and a significant amount of fuel is saved. This kind of phase is referred to as *Torque assist.* The energy contained in the battery is also used to feed the electrical auxiliaries.

Case 3

The goal here is to keep depleting the battery but slower than in case 2. The electric machine is not used anymore to deplete the battery but the electrical auxiliaries are still fed by the battery. This will make the energy level decrease in the battery. Since the electric machine is not used at all to propel the vehicle, the powertrain demand is only fulfilled by the ICE.

Case 4

When the SoC has reached the lower limit of the SoC window (typically 30%), it has to be maintained at this level for several reasons:

a) The first reason to avoid falling below the lower limit of the SoC window (below SoC_{win_min}) is that exceeding the SoC window will hasten the ageing process of the battery and reduce therefore its life length.

b) The other reason is to be able to recover as much energy as possible if a braking phase would occur.

To make this SoC control possible, the electric machine is driven by the ICE to supply the electric power consumed by the electric auxiliaries and the idle losses of the electric machine. In this way, the SoC in the battery remains constant. These phases should be avoided since the electrical energy is provided by the ICE through the electric machine. The global efficiency of the powertrain is known to be low since the EM works at low-efficiency operating points and thus energy conversion losses will occur [Volvo Internal].

The control strategy described above had been partly adopted in the controller developed later in the thesis, in the sense that it has been also designed around trying to follow a reference SoC and using the ICE to provide the torque difference between the EM and the total demand. The feature which allows the ICE to charge the batteries via the EM will not be used in the thesis as the ICE and EM are not connected to each other in the selected vehicle configuration.

2.4.1.2 Pure Electric Propulsion at Low Torque

The EM is used to propel the vehicle when torque demand is below a certain threshold. The purpose of this is to avoid using the ICE at low loads, where the efficiency is low. However, the system is usually underused as the torque demand in heavy vehicles is seldom below ~400Nm and thus there are no considerable fuel savings. Hence, this strategy might be of more use in passenger vehicles.

2.4.1.3 Sailing

Electric energy is used to propel a vehicle after a downhill regeneration phase. The ICE engine is also kept disconnected by disengaging the clutch or selecting the neutral gear in order to avoid engine friction losses (a function called Ecoroll in the conventional application), until the vehicle goes below a certain velocity threshold. The EM keeps propelling the vehicle even above the target speed in order to extend the Ecoroll phase. This strategy leads to a considerable decrease in fuel consumption of about 5% as compared to a conventional vehicle without Ecoroll. This is expected since engine internal friction leads to almost 20kW of power loss at cruising speed, and 9kW at idle speed [1].

2.4.1.4 Shift strategy to increase regeneration power in downhill driving

The basic strategy is to downshift during a slope in order to increase the EM speed, and thus increase the amount of power regenerated. The transmission can be upshifted again when the acceleration pedal is pressed or the brake is released. The downshift should be avoided if the ESS is saturated, if the brake demand is less than the maximum EM torque, or if the braking phase is too short (in order to avoid frequent gear changes) [Volvo Internal]

2.4.2 Optimal Control Theory

Optimal control theory deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. A control problem includes a cost function J that is a function of state variables x(t) and control variables u(t). The optimal control policy can be derived using Pontryagin's minimum principle (necessary condition), or by solving the Hamilton-Jacobi-Bellman equation (sufficient condition) [Volvo Internal].

2.4.2.1 Optimal controller

This controller assumes that the driving cycle is exactly known. It solves an optimal control problem where the optimal control signal is used to minimize the fuel consumption over a given drive cycle. Numerical methods such as dynamic programming can be used to solve this problem. However, several significant drawbacks make this controller inapplicable to a real vehicle:

a) Computational time: Dynamic programming is well-known for needing huge computational resources especially when the time-horizon is large and when the number of state variable increases (also known as the *curse of dimensionality*). It turns out that the implementation of such controllers into current ECU's is almost impossible.

b) In real driving, most of the time there is no information available of the route ahead, or at least not an exact prediction of the full drive cycle which makes this controller inapplicable to a real vehicle. For instance, it is not possible to predict a drop in speed due to an accident on the road or varying traffic situations.

Despite these drawbacks, optimal control is very valuable. Since the drive cycle is fully known in a simulation environment and the time-horizon finite, this method can be used to assess the optimal fuel consumption. Even if this controller is not practically implementable, it has the strength to provide a reference lowest possible fuel consumption that can be used to benchmark other controllers [7].

2.4.2.2 Acausal optimal controller

An acausal system is defined in as "a system that is not a causal system, i.e. one which depends on some future input values and possibly on some input values from the past or present. This is in contrast to a causal system which depends only on current and/or past input values."

This kind of controller uses prediction of the future drive cycle to control the energy in the battery. This type of controller can, for instance, anticipate the desired depletion of the buffer before a downhill (since the forthcoming downhill will allow recuperation of energy). Methods such as stochastic dynamic programming can be used to design such controllers [7].

2.4.2.3 Causal optimal controller

A causal system (also known as non-anticipative system) is a system where the output depends on past/current inputs but not future inputs. A solution to design such controllers consists in simplifying the optimal control problem into two parts:

1. Solve the static optimization defined in (25) for every possible combination of ω_{req} and T_{req} (i.e. find the optimal torque split in all cases).

2. Define the equivalence factor W with a heuristic formula since no information is available ahead.

Equivalence factor calculation

Since no information is available ahead, the equivalence factor W has to be defined with a heuristic formula as a function of the state variables (SoC in this case). The tangent function suits to this kind of application, and thus W can be expressed as follows [7]:

$$W\,(SoC) = p_1 * tan\,(p_2 * SoC + p_3) + p_4$$

2.4.3 Battery Discharging Strategies

This section deals with various strategies that can be used to control the state of charge of the battery in such a way so as to utilize the SoC window of the battery in an efficient manner in parallel hybrid applications [7].

2.4.3.1 CDCS Strategy

Most effective PHEV's have a battery sized to give an AER of only 20-30km. The average number of trips taken by an average commuter usually exceeds this AER, which is why it is interesting to optimally discharge the battery along the trip such that it is almost fully depleted by the end of the trip. This can be implemented in a simple way by the CDCS (Charge Depleting charge sustaining) strategy. This strategy consists of a "charge-depleting" phase during which the battery is nearly depleted, followed by a "charge-sustaining" phase during which the engine is run in order to keep the SoC around the SoC_{ref} level [7].

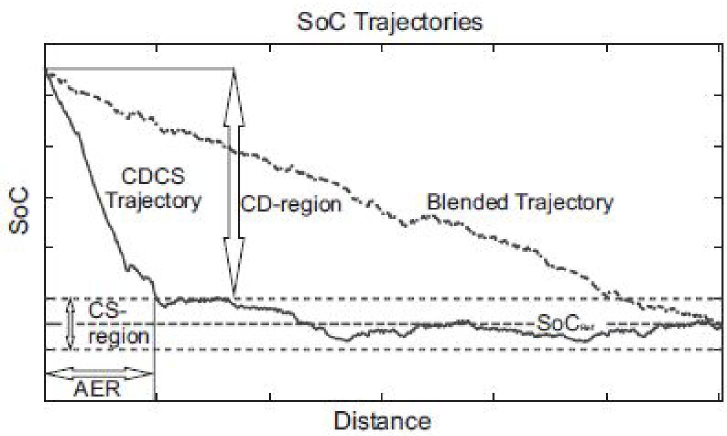


Figure 21: Plot of SoC versus Distance for both the CDCS and Blended Strategy

2.4.3.2 Blended Cost-Optimal Strategy

A cost-optimal discharge strategy can also be implemented, i.e. blended strategy can be used by applying optimal control theory. This blended strategy can achieve lower fuel costs than a CDCS strategy. However, a blended strategy is highly dependent on the trip length, as it is not cost-optimal to end the trip with a high SoC. The predicted length of the trip can be modeled as a stochastic variable and dynamic programming can be used to calculate the blended strategy which minimizes the expected total fuel cost. The main disadvantage with this strategy is that prior information about a future trip is required. Thus, the EMS can be operated in two modes based on whether or not a trip has been recognized. When no trip has been recognized, CDCS can be used, where $SoC_{ref}= SoC_{low}$. When a trip is recognized, the blended mode can be used, and the reference SoC is calculated as [7]:

$$SoC_{ref}(t) = SoC(t^*) - min\left[1, \frac{z_c(t) - z_c(t^*)}{\hat{z} - z_c(t^*)}\right] * \left(SoC_{min} - SoC(t^*)\right)$$

Where, t^*: $time\ when\ trip\ is\ recognized$

$z_c(t) = z(t) + \Delta z^*(t)$: corrected vehicle distance position along route

To prevent overestimation of trip length, the trip length reference is set to $\hat{z} = \bar{z} - 2\sigma_z$

The overall advantages of using such a blended strategy are:

- It reduces average battery current (thus leading to higher battery life).
- It avoids ICE-based charging (thus leading to lower fuel consumption).
- Its benefit will increase with battery aging, as the resistance losses increase with age.

2.4.4 GPS-based Transmission Control

ZF Friedrichshafen AG has developed the Prevision GPS transmission shift program for the Traxon transmission system. This program aims to enable gear selection on any route in the same anticipatory way as an experienced truck driver with excellent route knowledge. The system also contributes to reducing driver fatigue and improving driving safety. The program requires a constant feed of GPS data, which includes not only street maps, but also information such as speed limits, traffic signs, traffic signals, curves, roundabouts, and topography [14].

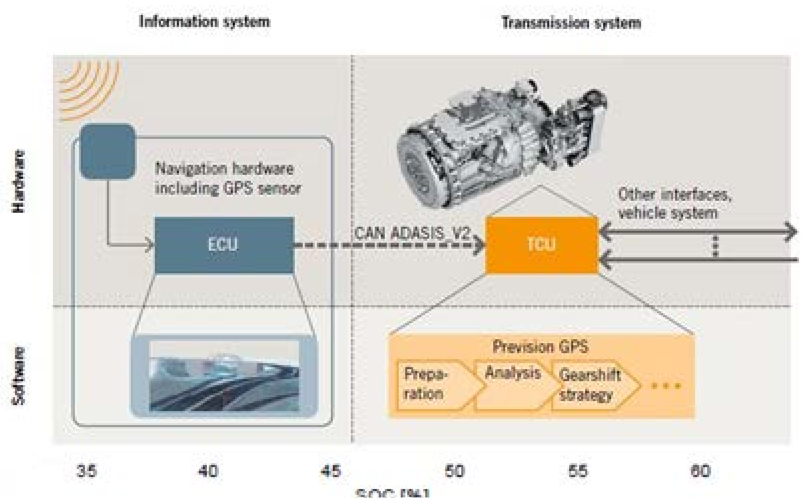


Figure 22: Schematic of a GPS-based Transmission system [14]

The ECU prepares topographic information for the oncoming road section, and transmits messages to the TCU. Various evaluation criteria are then used by the Prevision GPS program in order to derive the optimal shift strategy. The implementation of this system can lead to two major advantages:

1. Avoiding of unnecessary and frequent gear shifts.

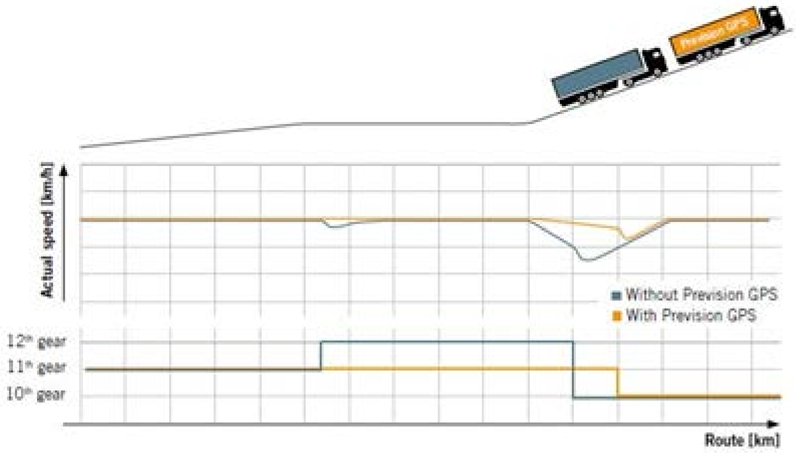


Figure 23: Plot of Gear position versus Actual speed with and without Prevision GPS [14]

The Prevision program prevents an upshift when an uphill gradient is directly ahead, or if the vehicle is passing through a short section of flat road during long uphill tours. Thus, this system prevents loss of tractive force and speed which normally occurs due to frequent gear changes and hence leads to additional fuel savings. Fewer gear changes also leads to reducing wear of the transmission and clutch system. Additionally, the program accepts a short-term lower vehicle performance (such as by selecting a higher gear before the end of an uphill gradient, if a flat/downhill section is to follow) in order to keep the engine running at more efficient operating points [14].

2. Truck rolling function

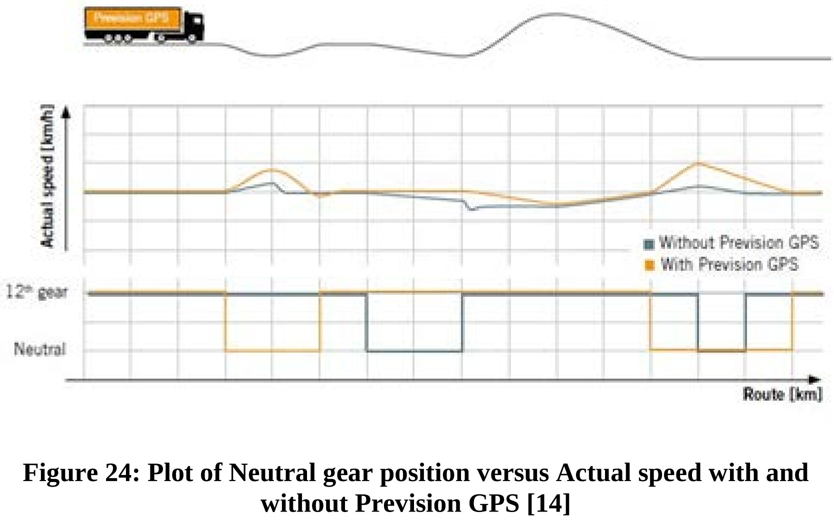


Figure 24: Plot of Neutral gear position versus Actual speed with and without Prevision GPS [14]

This function allows the kinetic and potential energy of the vehicle to be exploited under certain conditions in order to reduce fuel consumptions and CO_2 emissions. For example, this function enables the truck to drive from a downhill to flat gradient with an open driveline, which prevents loss of the vehicle's kinetic energy by engine friction. However, this would not be beneficial if an uphill gradient was to follow.

Thus, this system uses the available topography information in order to calculate when and for how long this rolling function should be activated. Moreover, the combination of Prevision GPS with intelligent cruise control can be used to provide for speed reductions and rolling before driving through roundabouts or road-signs. The above described functions can cause an average fuel saving of 2-3% and consequently a reduction in CO_2 emissions [14].

2.5 Performance standards for Long Heavy Vehicle Combinations

The increasing interest towards long heavy vehicle combinations due to possibilities of fuel consumption reduction and lesser road footprint, lead to a necessity to improve road safety and protect road infrastructure. Thus there exists a set of vehicle performance-based regulations which put restrictions on the vehicle design. Performance Based Standards (PBS) is an initiative introduced by the National Road Transport Commission in Australia to achieve this goal [8].

The following are definitions of important performance based characteristics that must be met by such long heavy vehicle combinations in order to enable them to participate in road transportation [9]. It is important to note that the following characteristics are the ones which are decided to be studied for the vehicle dynamics behavior within the scope of this thesis work.

2.5.1 Rearward Amplification

Rearward amplification is defined as the ratio of the maximum value of the motion variable of interest (e.g. yaw rate or lateral acceleration of the center of gravity) of the worst excited following vehicle unit to that of the first vehicle unit during a specified maneuver at a certain friction level and constant speed [9].

When a sudden lateral movement is made, as in a turn, *each unit in the combination experiences different lateral acceleration, and this is amplified* towards the end of the vehicle. Lower values of rearward amplification imply better performing combination.

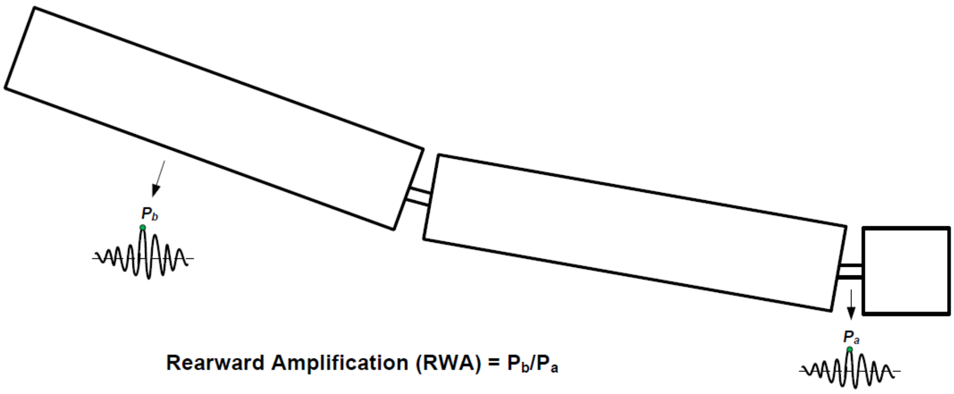


Figure 25: Rearward Amplification of a vehicle combination [9]

2.5.2 Low Speed Swept Path

Low speed swept path is defined as the maximum width of the swept path between the outermost and innermost points of the body of the vehicle combination in a low speed turn with a certain outer radius at a certain friction level and a certain angle between entry and exit [9].

It is important to minimize the road space occupied by the long combination vehicles at intersections so that the safety risk is managed in such conditions. A high value implies that the vehicle needs more space that is available space. The vehicle is likely to collide with objects or other vehicles in the road or run off the road during turning maneuvers.

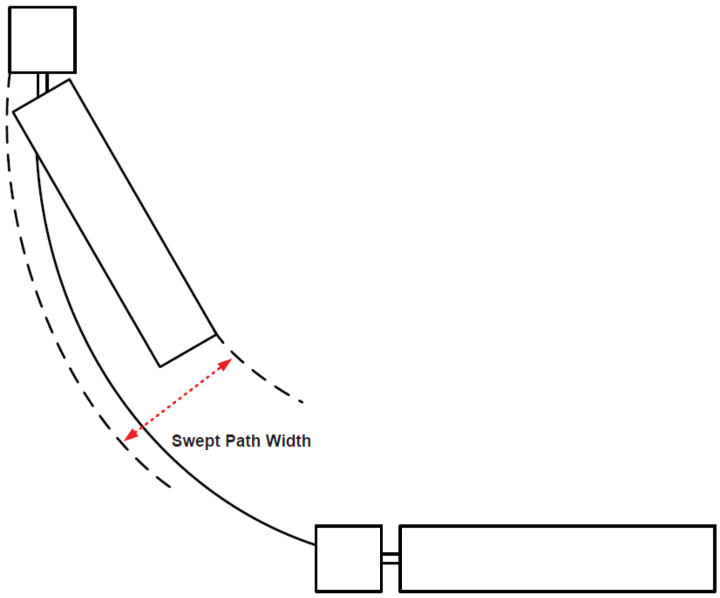


Figure 26: Swept Path Width of a truck [9]

2.5.3 High Speed Transient Offtracking

High speed Transient Offtracking is defined as an overshoot in the lateral distance between the paths of the center of the front axle and the center of the most severely offtracking axle of any unit in a specified maneuver at a certain friction level and a certain constant longitudinal speed [9].

When a long heavy vehicle is turning at a high speed, there is a tendency for the rear axles to sway outside the front axle's path. This tendency is referred to as high speed transient offtracking. A high value of this might lead to collision with the road objects or other vehicles.

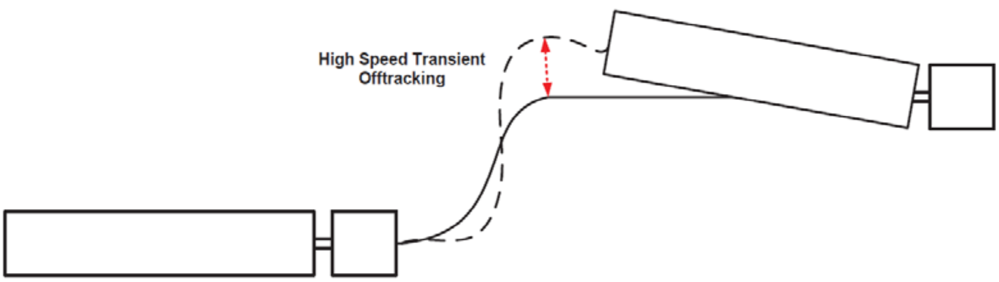


Figure 27: High Speed Offtracking of a truck [9]

2.5.4 High Speed Steady-state Offtracking

High speed steady-state offtracking is define as the lateral offset between the paths of the center of the front axle and the center of the most several offtracking axle of an unit in a steady turn at a certain friction level and a certain constant longitudinal speed [9].

Just like high speed transient offtracking, high speed steady-state offtracking is the lateral displacement of the rear end of the last trailer of a long vehicle combination from the final path of the front axle of the hauling unit can lead to collision with the road objects or other vehicles especially when the road lane width is narrow and traffic flow is high on the road.

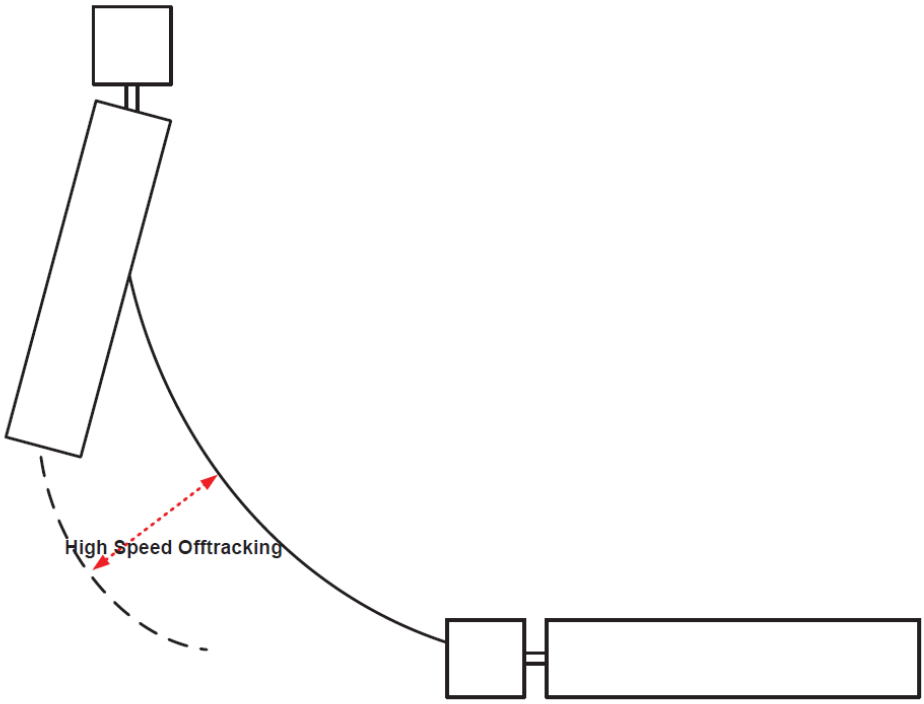


Figure 28: High Speed Steady-state Offtracking of a truck [9]

3 Methodology

The first phase of the thesis work was marked by literature review of the engineering reports from previous projects involving long haul hybridization, and learning of the simulation tools used at Volvo Group Trucks Technology, namely Global Simulation Platform (GSP) and Volvo Transportation Models (VTM) (refer Chapter 5).

The simulation model of a baseline truck was chosen and modifications were performed on the model to develop the combined model of the truck and the electrified dolly, in GSP. The next step from there was to integrate the VTM model of the A-Double configuration with the previous GSP model.

After the previous step, Packaging study and Powertrain sizing was performed in parallel with the building of detailed Powertrain control strategies, and simulation of the new control strategies with the developed GSP model. The packaging study was performed by collecting geometric data of the components and a typical dolly, and construction of mock-ups using CAD software CATIA.

The next phase of the thesis work was the evaluation of the simulation results with the combined GSP + VTM model platform, and performing simulations on it. The final phase was analysis and conclusions, which involved documenting results, analysis of those results and drawing conclusions from it. A flowchart illustrating the above mentioned methodology is as follows.

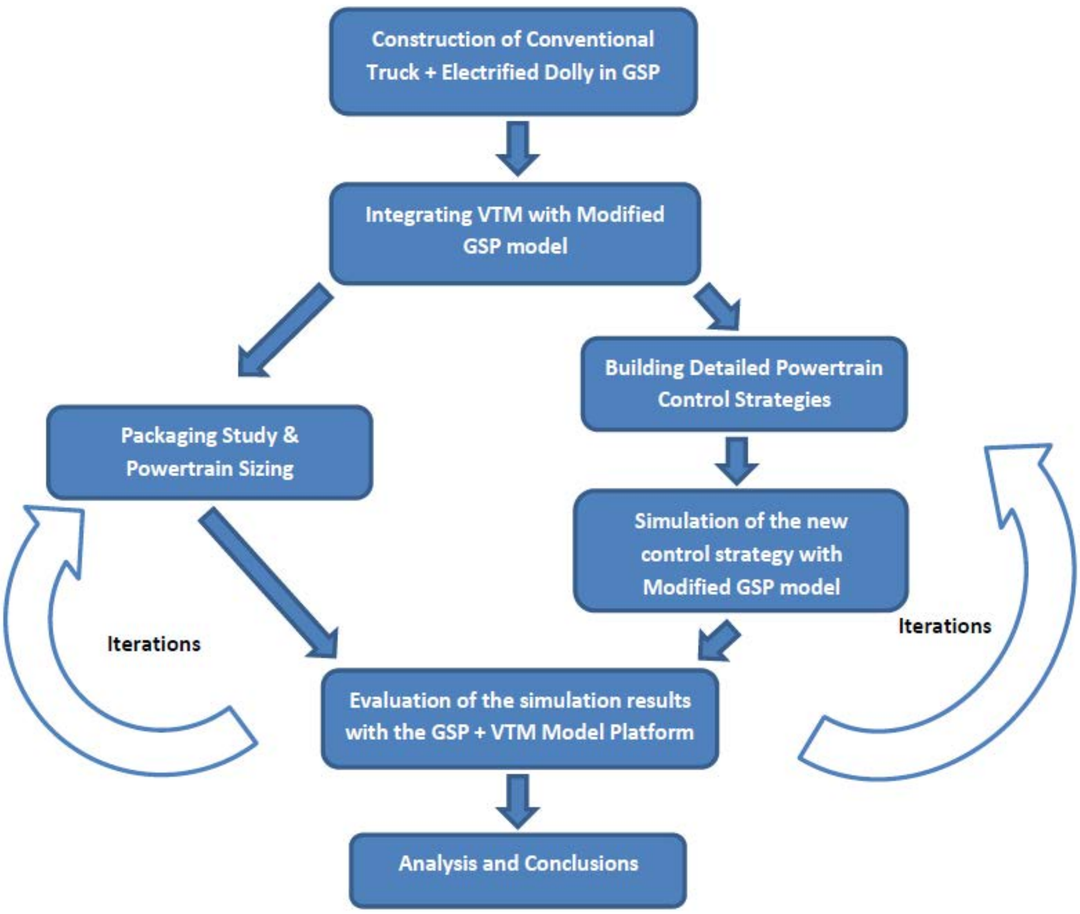


Figure 29: Flowchart of the thesis project methodology

4 Vehicle Specifications

The chosen vehicle configuration for the simulations were a result of discussion with the Volvo personnel on what the typical use case scenario of such a long combination would need, based on previous projects and experiences. Also considered in this discussion were the typical consumers of this application and their demands on the capability and the performance on the product. Relevance to the current market scenario and the technologies, as well as a thought on financial relevance, was highlighted. The resulting vehicle component specifications for the hybrid and conventional reference vehicle have been tabulated as follows.

Table 5: Specifications of the Hybrid and Conventional Vehicle

<table>
<tr><th>Component</th><th>Hybrid Vehicle</th><th colspan="2">Conventional Reference Vehicles</th></tr>
<tr><td>Engine</td><td>13 litre 500hp Euro5 Volvo Diesel Engine</td><td colspan="2">13 litre 500hp Euro5 Volvo Diesel Engine</td></tr>
<tr><td>Transmission</td><td>12 speed Direct-drive Automated Manual Transmission
2 speed Gearbox</td><td colspan="2">12 speed Direct-drive Automated Manual Transmission
-</td></tr>
<tr><td>ESS</td><td>Battery A 19.2kWh</td><td colspan="2">-</td></tr>
<tr><td>MDS</td><td>Motor A 120kW 800Nm
Motor B 179kW 430Nm
Motor C 110kW 800Nm</td><td colspan="2">-
-
-</td></tr>
<tr><td>Total Length of Combination</td><td>35.5m</td><td>35.5m</td><td>18m</td></tr>
<tr><td>Total weight of the Combination</td><td>60,000kg</td><td>60,000kg</td><td>32,000kg</td></tr>
</table>

5 Vehicle Simulation Models

The simulation models were designed with the help of proprietary tools that Volvo has developed. They are namely the Global Simulation Platform (GSP) and Volvo Transportation Models (VTM), which are used by the Powertrain and Vehicle Engineering departments respectively. The tools are present as add-ons to the library of Matlab Simulink.

There are two types of vehicle simulations used in industry depending on how the tractive power demand is determined:

A. Driver throttle and brake pedal behavior (Forward simulation): The demanded traction power can be calculated with the accelerator pedal position level (0 to 1), and the maximum power available that the current vehicle speed. The negative demanded braking power can be calculated as a multiplication of maximum regeneration force, which is scaled by the brake pedal position (0 to 1) and the current vehicle speed. This type of forward simulation is similar to how a vehicle is operated in real life.

B. Power Demand Equation (Backward simulation): A more accurate method would be to calculate it by the equation:
$P_{tract} = (m*a + m*g*\sin\Theta + m*g*C_r*\cos\Theta + 0.5*C_d*A*\rho*v^2)*v$; which accounts for the acceleration/retardation, climbing resistance, rolling resistance, and aerodynamic drag. Hence, no driver model is required in this type of simulation. One disadvantage of using this estimated value of power demand is that the pedal position no longer controls the power flow. Although the pedal position is sent to many subsystems as a control signal, the powertrain torque demand will be incorrect if there is no feedback possibility.

(Optimizing energy management and component sizing of hybrid powertrain)

Method A, i.e. forward simulation is used in both the GSP and VTM simulation tools as it has the same causality as the real world and hence it can be readily implemented in a prototype. These tools were developed based on the needs of the respective departments, and hence the level of detail used in modeling the different components vary based on the need. The GSP models contain greater level of detail towards the powertrain components as the need is to study the longitudinal dynamics characteristics of the vehicle such as acceleration, gradeability, fuel consumption and the suspension and tyres are not modeled in detail. Whereas, in the VTM models, the lateral and vertical dynamics characteristics are of more concern, and hence represented in detail. The reasons behind this prioritization could be mostly attributed to the availability of computing power, as it is the limiting factor to how detailed the models can be.

The major part of the thesis is to analyze the fuel consumption and performance of the resulting hybrid powertrain. Additionally, this thesis also aims to study the lateral dynamics behaviour of the vehicle combination after the electrification of the dolly, and if the resulting control strategy has any questionable impact on it. Hence, it is important to prioritize and employ the right simulation model towards the right application due to lack of computational power.

The complete powertrain model of the A-double combination is developed in GSP and it is used to compute the fuel consumption and the related longitudinal performance parameters. This model is then united with the VTM model of the A-double combination and the vehicle dynamics behaviour is analyzed.

5.1 Powertrain Model (GSP)

GSP is the Volvo Group's common interface for evaluation of fuel consumption and vehicle performance. It is a database repository for vehicle and machine simulation models .This database is of high standard that guarantees traceability and quality assurance. It provides common guidelines and a unified model structure that facilitates sharing of data and reuse of model components. The open platform architecture of GSP ensures transparency and enables the system to integrate efficiently with other systems and processes [10].

The base GSP model was studied to understand, familiarize with and use as a starting point to develop the hybrid powertrain of the A-double long combination. It was a simulation model of a conventional truck with the same engine and transmission that is to be used in the target vehicle. . The longitudinal simulations have been done on GSP models with different control strategies and powertrain concepts. Energy-related parameters such as fuel consumption, energy throughput of the ESS, regenerated energy have been calculated for two different driving routes, which will be explained in detail in the results section of this report.

5.2 Vehicle Transportation Models (VTM)

The lateral simulations have been carried out in order to study the effect of electrification of the dolly axle(s) on the stability and performance of the vehicle during certain common maneuvers, such as lane-changing, taking a U-turn, and driving around a roundabout. The tool used in order to simulate these phenomena is by the name Vehicle Transportation Models, which is used by various departments at the Chassis & Vehicle engineering department at Volvo GTT. It consists of an extensive Simulink library consisting of SimMechanics and other components used in order to create an accurate mathematical description of the physical components used.

The VTM model for the A-Double long combination was combined with the GSP model of the powertrain and this unified platform was used to evaluate the maneuvers for the lateral simulations which were set up.

6 Driving Cycles & Vehicle Maneuvers

The thesis work deals with long haul truck application, and hence the driving cycles chosen towards the simulation were typical long haul driving cycles taken from the GSP repository. The driving cycles considered were Borås-Landvetter-Borås, and German Highway.

Driving cycles are a collection of data that describe the speed of a vehicle versus time. The driving cycles are used as an input for models of vehicles to perform simulations to analyze the parameters of the model. They are aimed to be a representation of the road. There exist different types of driving cycles, designed specifically to test a certain aspect of the performance of the vehicle, such as emissions or fuel consumption. Driving cycles can be broadly defined based on the speed profile as city driving cycles and long distance cycles. They can also be classified based on the type of vehicle to be tested, as passenger car driving cycles and commercial vehicle driving cycles.

It is to be mentioned that altitude is also included in the dataset of the driving cycles, as it is interesting to study the effect of altitude on the control strategies for hybrids. Some important parameters of the driving cycles chosen are tabulated below. The plots showing the vehicle speed and altitude versus time follow the table.

Table 6: Data on the Borås-Landvetter-Borås and German Highway cycles

Driving Cycle Name	Total Distance (km)	Average Speed (km/h)	Number of stops	Max gradient (%)
Borås-Landvetter-Borås	87	84.6	0	Uphill 5.3 Downhill -5.3
German Highway	546	85.8	4	Uphill 6.5 Downhill -7.1

As is evident from the table above, the Borås-Landvetter-Borås cycle is a constant speed cycle with no stops during the route. The gradient is also considerably significant, with a maximum value of 5.3%. This cycle was selected because it is very well known within Volvo Powertrain and is used as an internal reference. It is also quite easy to practically test a vehicle in this driving cycle.

The German Highway cycle is a long distance route in Germany, with a constant cruising speed of ~86km. The major difference between the nature of this cycle and the BLB one is that this route involves 4 complete stops to a standstill. Also, this route has more frequent gradient variations as well as a wider range in gradients (maximum 6.5% and minimum -7.1%). This route was selected as it represents a typical European long-haul application, and has both stops as well as considerable gradient variations.

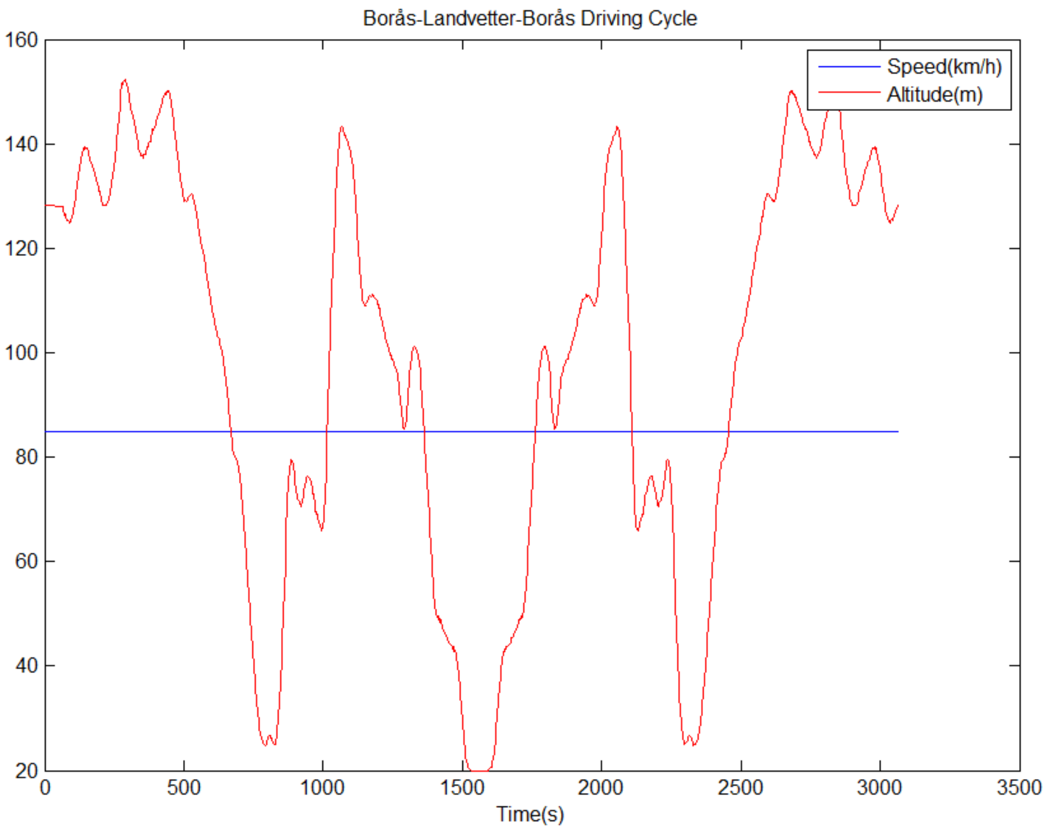


Figure 30: Speed and Altitude versus Time for the Borås-Landvetter-Borås cycle

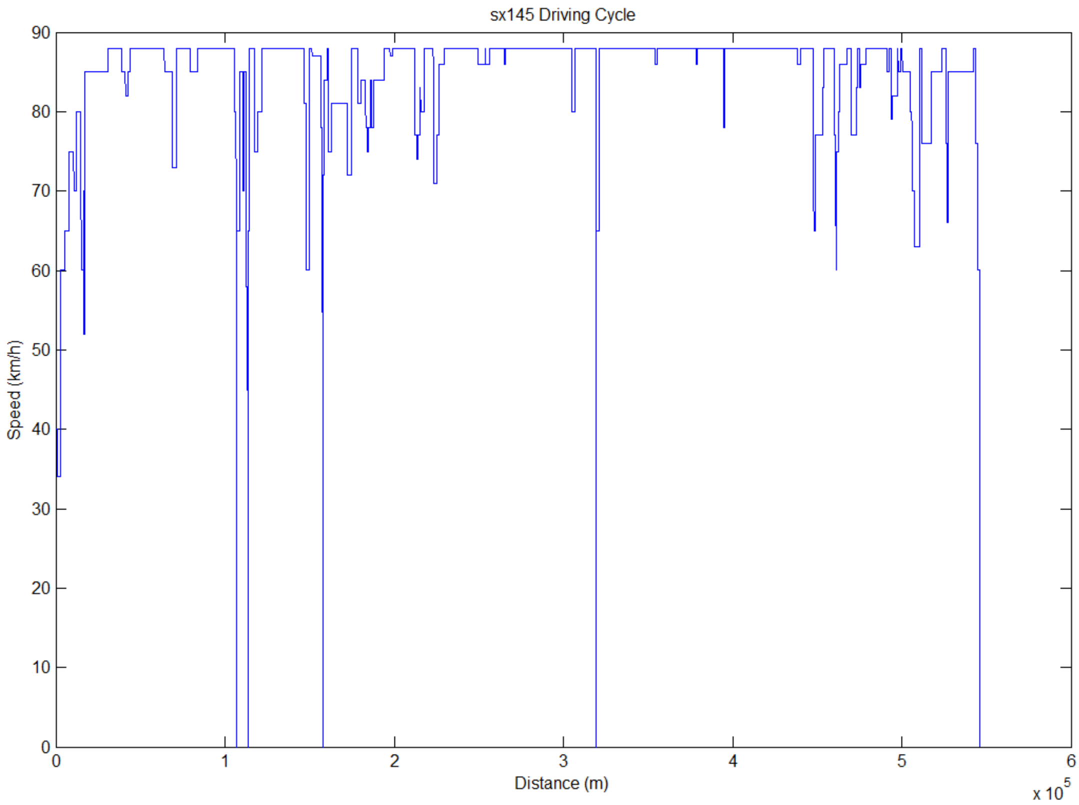


Figure 31: Speed versus Distance for the German Highway cycle

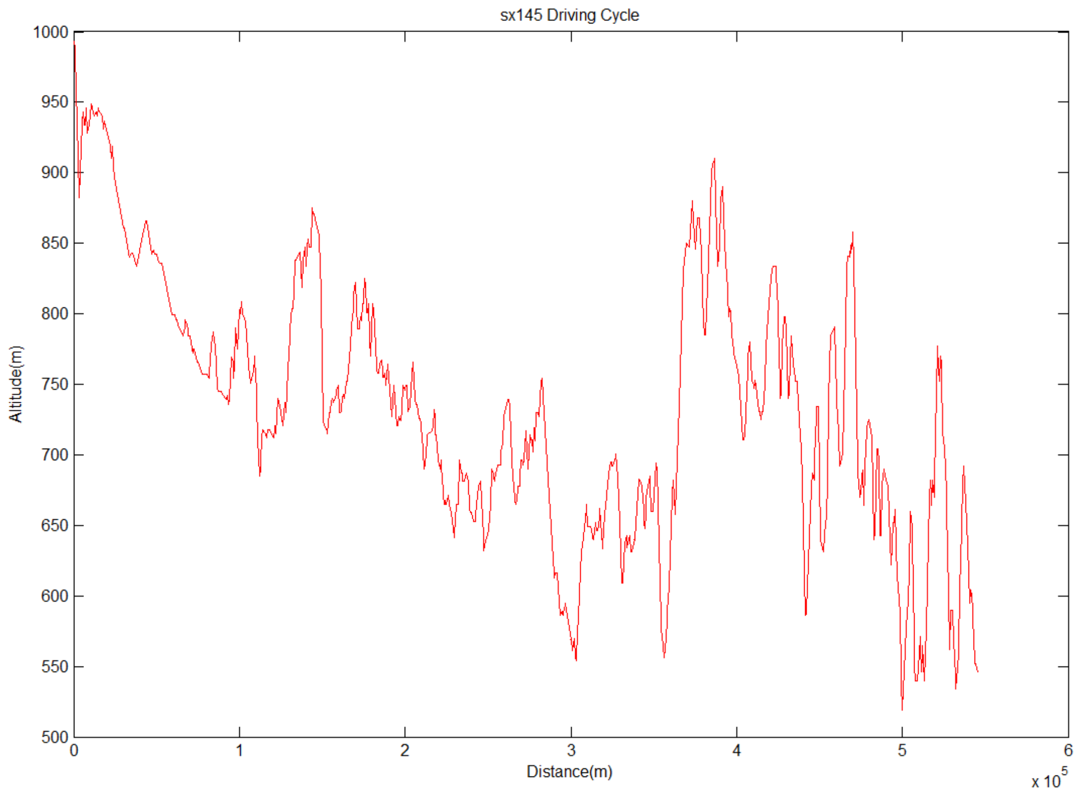


Figure 32: Altitude versus Distance for the German Highway cycle

7 Concept Study

7.1 Packaging Study

The packaging study is aimed at studying the feasibility of packaging the different powertrain components in the dolly. The 3D mock-up of the dolly and the powertrain components were built in CAD software by name CATIA, with the help of 2D component drawings and field measurements.

The dolly was built from the 2D drawing of a steerable dolly from a certain supplier with the suggestion from Vehicle Engineering department at Volvo GTT. The 2D drawings and the field measurements of the powertrain components were obtained from Drivelines & Hybrids department. The components were assembled in the dolly and the observations for different components are as follows.

Table 7: Observations regarding various components during the packaging study

Category	Component	Comment
ESS	Battery A	Extension of Wheelbase from 1.3m to 1.7m required to house the ESS.
	Battery B	Ground clearance less than 150mm.
MDS	Motor A	Ground clearance less than 150mm
	Motor B	Packaging is possible.
	Motor C	Ground clearance less than 150mm.
Gearbox	2 speed Gearbox	Packaging is possible.

It is important to mention that the dolly modeled towards the packaging study is a typical dolly used in an A-double configuration, and that the results of this study are more of a suggestive nature towards the motive of packaging the powertrain components in the dolly. The aim was towards solutions which involve the least modification to the established dolly designs which are prevailing in the market today.

The main parameter used to compare whether a component is desirable to study or not, was the ground clearance i.e., the distance of the ground from the lowest part of the component. This is a very important parameter as it is not wise to have an expensive and a vital component lying low, which makes it susceptible towards damage. Hence, on this parameter, Battery B, Motor A and Motor C were considered undesirable.

7.2 Powertrain Sizing

This thesis work was bound by the limitations that the usages of components were limited to the inventory, which made the calculation of the optimal powertrain sizing superfluous. Hence Powertrain sizing as per the scope of the thesis work is more related to the choice and the reasoning behind the selection of the components which were included in the concept study for the propulsion components of the Electric dolly.

With reference to the MDS components considered, motor B with a speed range of 0-11000 RPM was considered the most desirable of the selection, due to packaging ease. Motor C with a speed sweep of 0-6000 RPM was considered more suitable to the application than Motor A which had a speed sweep of 0-3000 RPM. The main reason behind this is that the Motor A was designed to work with the diesel engine in the Parallel hybrid layout by name ISAM (as explained in the Literature Review section), hence it has its speed range comparable to that of the diesel engine. Since the electric dolly is completely independent of any physical linkage with the diesel engine, it is possible to have a different range of speed for the electric motor.

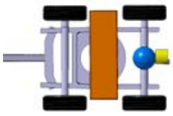
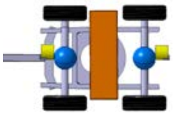
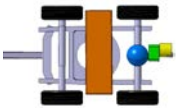
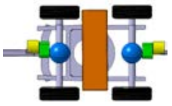
An additional reason why an electric motor with a small speed range was undesirable is the potential over-speeding of the electric motor in the regenerative mode, where the road is driving the electric motor. Due to the fixed gear steps involved, when the power flows from the road to the electric motor, often high speeds are achieved. This is more unlikely in the case of the other motors considered, which have higher speed ranges. A two speed gearbox was included to analyze the effect of having two gear ratios to operate with on the fuel consumption and performance. The two speed gearbox provides higher torque at low speeds and prevents overspeeding of the EM at higher vehicle speeds by shifting to a lower gear ratio.

With respect to the sizing of the final gear ratios, the inventory of GSP was used to list out all the available final gear ratio units. The values of the final gear ratios were again converged to 6 units, namely 0.89, 2.5, 5, 10, 15, 20 and then simulations were run with these units to further converge the number of units.

7.3 Concept Definition

Based on the inputs from the packaging feasibility study and the powertrain sizing, the combinations of the electric powertrain components for the dolly are arranged into different concepts for the final phase of the concept study. The concepts are defined as follows:

Table 8: Definitions of the hybrid concepts

Concept Number	Definition	Driven Axles	Thumbnail
Concept 1	• 1x Battery A • 1x Motor B • 1x Final gear unit	1	
Concept 2	• 1x Battery A • 2x Motor B • 2x Final gear units	2	
Concept 3	• 1x Battery A • 1x Motor B • 1x 2 speed gearbox • 1x Final gear unit	1	
Concept 4	• 1x Battery A • 2x Motor B • 2x 2 speed gearbox • 2x Final gear units	2	

The illustrations explaining the configuration of the different concepts are provided in the Appendix (Chapter 14.2). The thumbnails of the same are provided in the table above.

The concepts were defined having in mind various factors such as simplicity, cost, and the characteristics of the components. Each concept is significantly different to each other, and they are defined so to understand the effects and study how the different concepts behave towards the control strategies. Emphasis was to avoid redundancy and on how effectively the components can be used.

Concept 1 and 3 share the fact that only one of the two axles of the dolly is driven, whereas in Concept 2 and 4, both the axles of the dolly are driven. This was defined so as to make use of the increased grip and traction offered when more axles are driven. As mentioned in the Powertrain sizing section, the introduction of a 2 speed gearbox into the concepts was to study the effect of the choice of two gear steps in the fuel consumption and performance during the different operation modes of the electric motor. The only difference between Concept 1 and Concept 3 is the inclusion of the 2 speed gearbox between the electric motor and the final gear unit. It is the same case with Concept 2 and Concept 4 as well.

8 Control Strategies

The control strategy for the hybrid powertrain is formulated with emphasis on rule based control methodology. The base functionalities were adapted from an existing HCU from a Volvo project. The functionalities which were then developed for this application were added in increments and they are as follows:

8.1 Hybrid powertrain control functionalities

There are three control blocks within the powertrain simulation model which have been dealt with in detail and extensively modified to implement the desired control strategies in the powertrain.

The Charge Balance Control block takes in data about the vehicle state and battery state, and thereby gives limits on the maximum and minimum SoC-based battery power. The Torque Abilities EM block requires inputs on the EM speed, EM current gear ratio, EM Power and torque limits, ESS power limits and auxiliary power consumption in order to set limits on the maximum and minimum EM torque that can be requested. Finally, the Torque Distribution Control block decides on how to split the torque demand between the ICE and EM, based on inputs of total powertrain torque demand, braking torque demand, and the EM and ICE torque limits.

All three control blocks have been adopted from the existing HCU. The Charge Balance Control block and Torque Distribution block have been extensively modified, whereas the Torque Abilities EM block has been left untouched.

8.1.1 Torque Distribution Control

This block controls the amount of torque demand distributed to the EM and ICE. The total powertrain torque demand is checked with the EM torque limit signals coming from the 'Torque Abilities EM' block, after which it is checked with the EM torque limit set by the 'SoC Control' blockThis control logic in this block is entirely new and differs greatly from the previous logic.

8.1.2 Torque Abilities EM

This control block outputs the final limits on maximum and minimum EM torque. It finds the power limit of the system by comparing those of the EM and ESS. The power limit is converted to a torque limit by dividing it with the real-time EM speed. This block has been adopted from the existing HCU and has been left unmodified.

8.1.3 Charge Balance Control

8.1.3.1 SoC Control strategy

The aim of the SoC control block is set the SoC window, as well as to govern the SoC level of the ESS by setting a SoC target and trying to match the current SoC with it. Since this hybrid powertrain doesn't have a charge-through-engine mode, the only way of charging the ESS is through regeneration. Also, the EM cannot be made to supply more torque than required to reach the required SoC, as the EM is directly connected to the driveline. Hence only an upper limit on the EM torque can be set. The two ways in which SoC target estimation has been done in this thesis have been described in the next section.

The blocks within the Charge Balance Control block were adopted from the existing model. However, the SoC Target block has been changed completely, due to application of a new method of calculating SoC target. Also, the SoC based Discharge/Charge limits block has been replaced with new control logic.

The SoC Target is converted into a power request by calculating a parameter called the SoC Ratio. Then, a look-up table is then used to provide the power request for a certain SoC ratio.

When SoC > SoC_{target} :

$$SoC_{ratio} = \frac{SoC - SoC_{target}}{SoC_{high} - SoC_{target}}$$

When SoC < SoC_{target} :

$$SoC_{ratio} = \frac{SoC - SoC_{target}}{SoC_{target} - SoC_{low}}$$

The SoC ratio calculated is fed as an input to the following lookup table, and the output is a percentage of the battery's maximum power capacity that is sent as a power request.

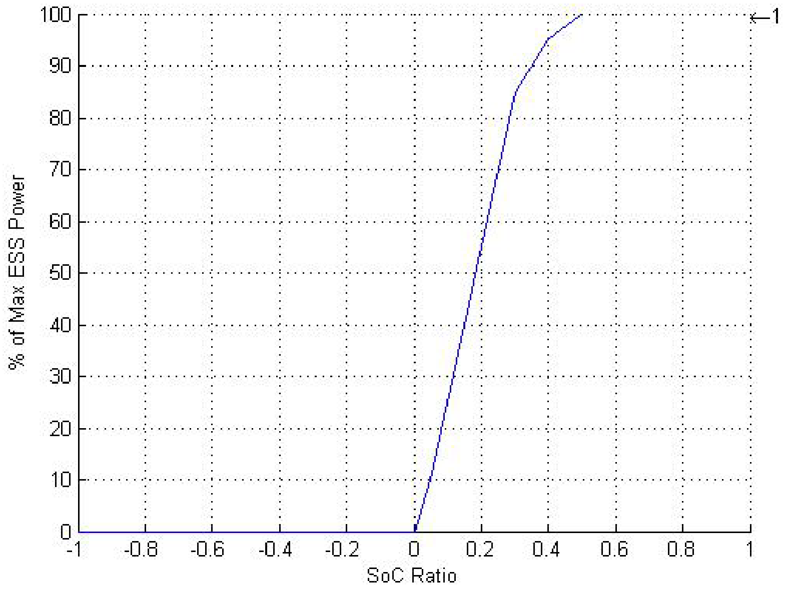


Figure 33: A Look-up Plot of % Max ESS Power versus SoC Ratio

8.1.3.2 Look-Ahead SoC Target Calculation

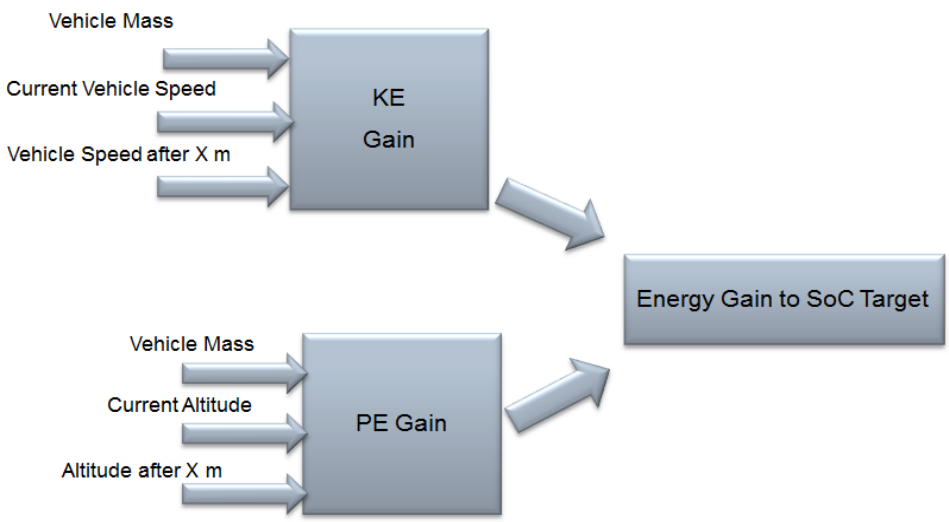


Figure 34: A flow chart depicting the Look-ahead SoC Target Calculation

This SoC control strategy aims to use knowledge of the future driving route in order to ensure that the vehicle fully utilizes opportunities to recover energy and store it in the battery without completely saturating it, such as when braking to a standstill or driving down a hill. It also aims at enabling the EM to assist the ICE with extra propulsion during demanding situations, such as driving up a hill.

The look-ahead strategy of estimating the SoC target uses information of the forthcoming driving route in order to calculate the kinetic and potential energy of the vehicle at a certain ‘X’ meters ahead from its current position. This is done by looking up the altitude and velocity of the vehicle at ‘X’ meters ahead, and then estimating the SoC Target based on the amount of total energy that will be lost or gained after ‘X’ meters. The look-ahead parameter X can be iterated for each driving route in order to reach an optimal value.

8.1.3.3 Predictive SoC Target Calculation

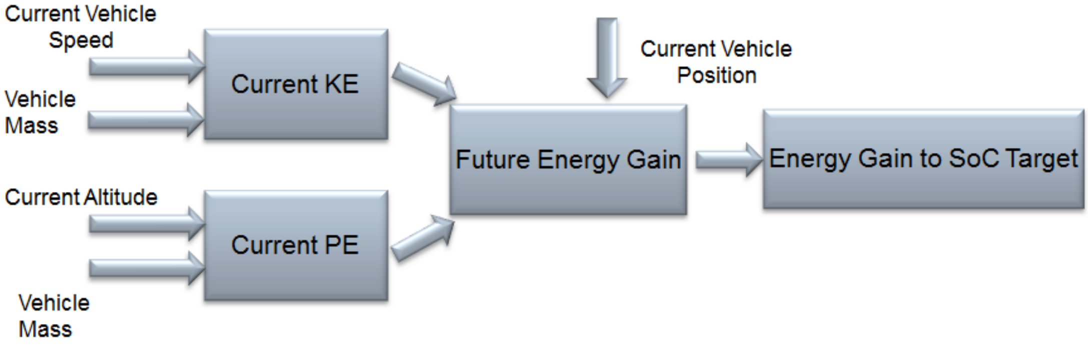


Figure 35: A flow chart depicting the Predictive SoC Target Calculation

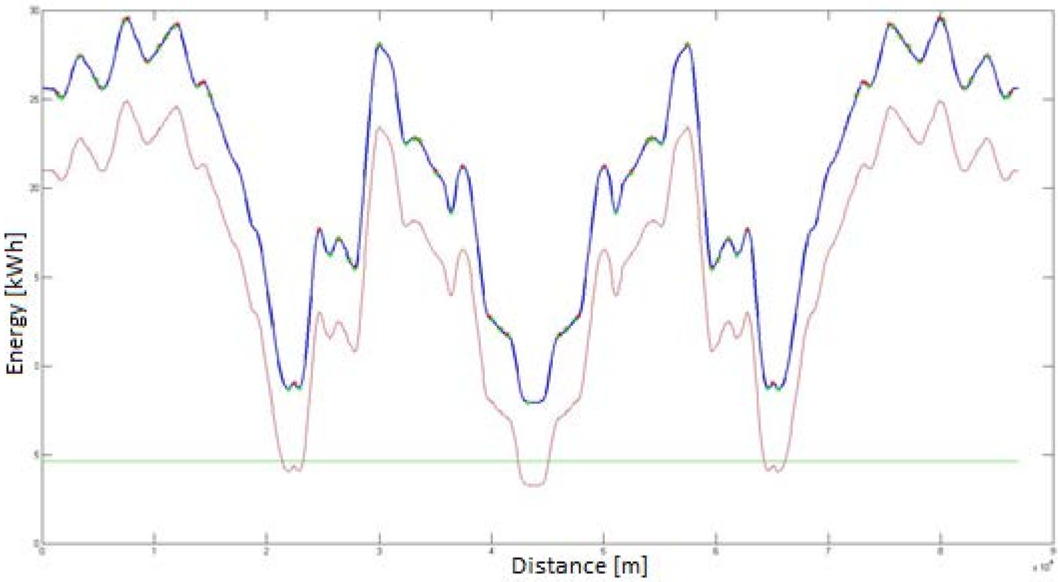


Figure 36: Energy Profile for the Borås-Landvetter-Borås driving cycle

This SoC control strategy is similar to the look-ahead type as it also aims at using knowledge of the future driving route to maximize energy recovery and assist the ICE whenever possible. However, instead of looking up the future vehicle speed and altitude at a certain distance X, it utilizes the energy profile of the entire driving route. Hence, complete information of the entire driving route must be known in advance at the start of the journey in order to implement this strategy. The energy profile is basically a plot of the kinetic and potential energy of the vehicle during the entire driving route. Then, the KE and PE of the vehicle at certain important points are identified on the energy profile, such as the start and end of hill, and the start and end of an acceleration/deceleration phase. In order to use this information, the energy of the vehicle at the next 'important' point is compared with the vehicle's current energy. The energy difference is calculated as a percentage of the battery's capacity, and thus converted into a SoC target using the two formulae below:

$$Future\ Energy\ Gain\ (kWh) = Future\ KE\ gain + Future\ PE\ gain$$
$$= m * \left(v_{future}{}^{2} - v^{2}\right) + m * g * \left(h_{future}{}^{2} - h^{2}\right)$$

$$SoC\ Target(\%) = SoC_{initial}(\%) - \left[\frac{Future\ Energy\ Gain\ (kWh)}{Total\ Battery\ capacity\ (kWh)}\right]$$

8.2 Sailing

This control strategy is designed to make use of the potential energy gained by the vehicle at the top of a hill. It is similar to the sailing concept described in section 2.3.1.2 of this report as it also keeps the driveline disconnected during a downhill phase, in order to prevent loss in kinetic energy due to engine friction losses. However, this strategy is not necessarily aimed at extending the coasting phase by keeping the EM propelling the vehicle above the target speed. The EM operation is directed only by the torque distribution control and the SoC control. The controller requires input signals of Current Road Angle, ICE torque Demand, and Current ICE Torque, and outputs the Clutch Disengagement Position to the TECU. This control strategy is entirely new and is not adopted from the existing HCU.

The control logic is explained in the flowchart below:

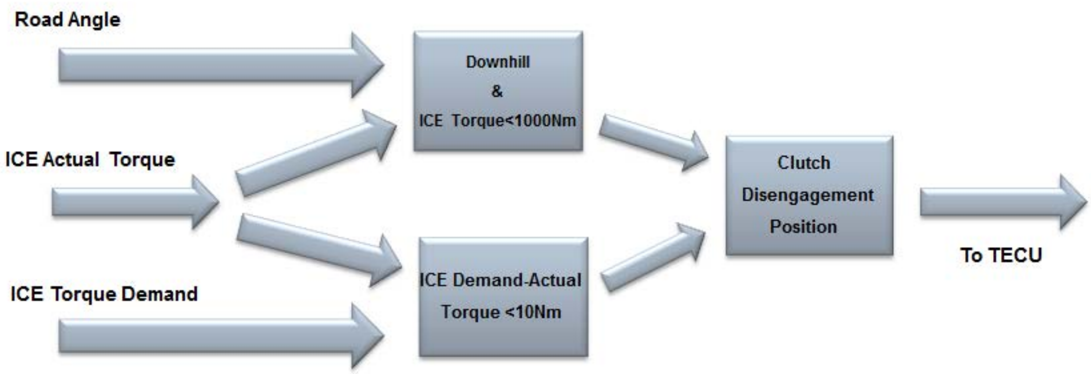


Figure 37: A flow chart depicting the Sailing control strategy

As seen in the above flowchart, the controller checks for three conditions that must be met in order to allow disengagement of the clutch:

1) <u>Current road angle must be negative:</u> Since sailing must be activated only while driving down a slope.

2) <u>ICE Torque Demand must be less than 100 Nm:</u> This condition must be met in order to make sure that sailing is activated only when there is negligible torque demand. In order to avoid frequent clutch disengagements which can affect vehicle performance, a certain optimal value for this must be reached, which was found to be 100 Nm after several iterations.

3) <u>Difference between ICE torque demand and actual ICE torque produced must be less than 10Nm:</u> This condition is required in order to prevent engine overspeeding when the clutch is disengaged.

On implementing this function, it was observed that it resulted in fuel consumption reduction only for a short and transient driving route, i.e. the MHD cycle (-1.2% f.c.). However, it lead to a slight increase in fuel consumption for the longer heavy duty driving routes such as the German Highway and BLB cycle (+1.2% f.c.). It was concluded that this was because of the frequent engaging and disengaging of the ICE at high output shaft speeds during cruising. Also, this function only reduces the engine inertia, and not the inertia of the transmission input shaft.

8.3 Ecoroll

The Ecoroll function was then considered as a replacement because of the problems caused by the sailing feature mentioned in the previous section. This function aims to reduce the inertia of the driveline by allowing the transmission input shaft to rotate freely (i.e. engaging the neutral gear). This is done while going down a hill with negligible torque demand from the ICE. This function was present in the existing HCU, but the conditions for activation have been changed.

This function is activated when the following conditions are met:

1. ICE Torque Demand < 100 Nm.
2. Vehicle Speed >= 60 km/h.
3. Gradient < 0.

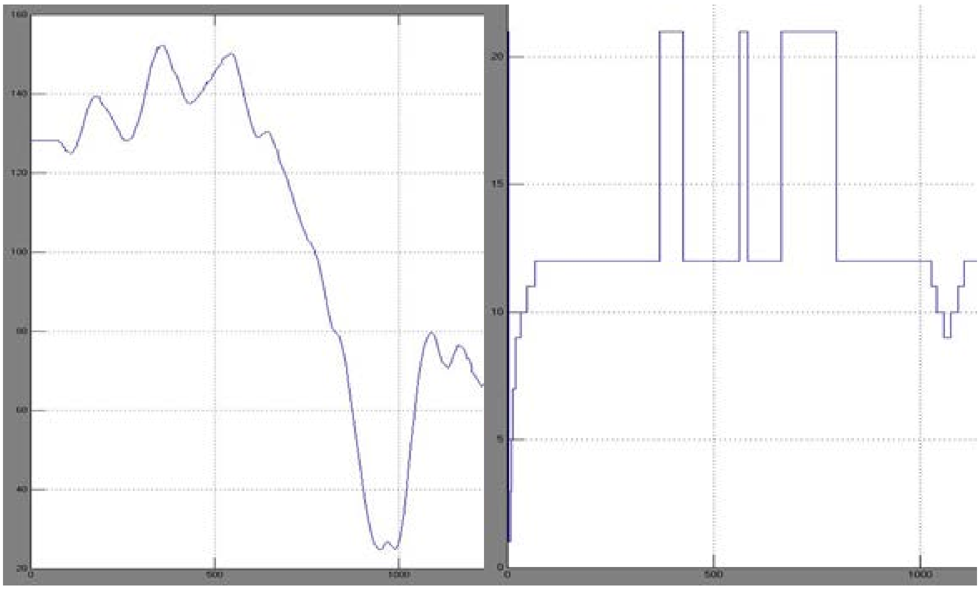


Figure 38: Altitude versus Time and Current Gear versus Time plots

9 Results

This chapter will present results from both longitudinal and lateral simulations that have been performed on the GSP and GSP+VTM models respectively. The results of the hybrid concepts have been compared with a conventional truck of 60tons and 32tons total weight.

The longitudinal simulations have been done on GSP models with different control strategies and powertrain concepts. Energy-related parameters such as fuel consumption, energy throughput of the ESS, regenerated energy have been calculated for two different driving routes. Also, performance-related parameters have been calculated, such as average speed, total trip time, vehicle speed error, and the number of gearshifts. The fuel consumption and performance results of the hybrid models have been compared with both a conventional model for the same vehicle configuration, as well as with results for existing hybrid models built at Volvo earlier.

The lateral simulations have been carried out in order to study the effect of electrification of the dolly axle(s) on the stability and performance of the vehicle during certain common maneuvers, such as lane-changing, taking a U-turn, and driving around a roundabout. Several lateral performance-based characteristics have been calculated for these maneuvers, and the results have been compared with the acceptable limits and with the results for the conventional model.

9.1 Longitudinal Simulations

In this chapter, various results related to fuel consumption, vehicle performance and drivability have been presented and compared for the Conventional vehicle and the Hybrid concepts. Please refer to Chapter 7 for more information on the hybrid concepts. It must be clarified that the Conventional vehicle in this case is a 60ton truck with the same ICE, length, and cargo capacity, unless stated otherwise. Please refer to Chapter 4 for more information on the conventional reference vehicle.

9.1.1 Fuel Consumption

9.1.1.1 Control Strategies

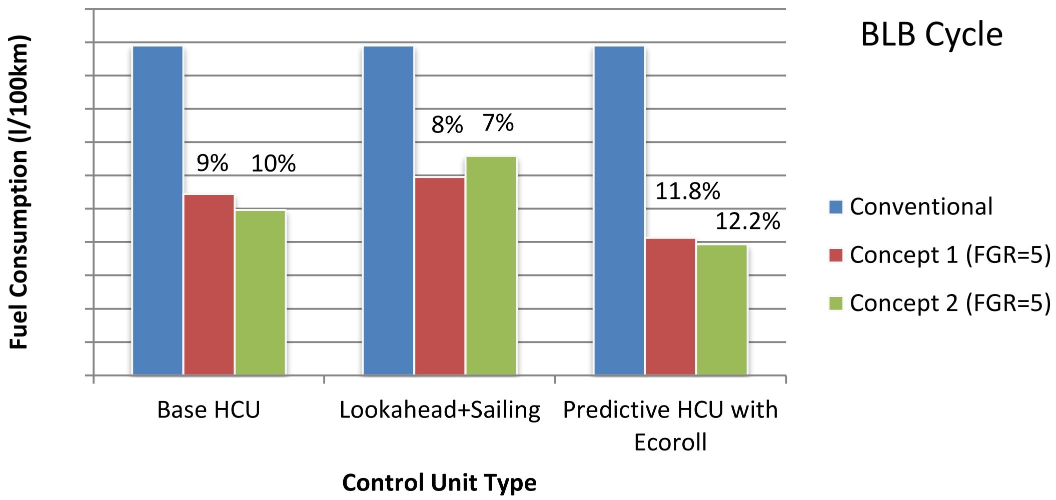


Figure 39: Fuel Consumption plots for various Control Strategies for the BLB cycle. The percentages represent fuel saving relative to conventional vehicle.

The HCU’s that have been compared in this section are the Base HCU, the HCU with Lookahead + sailing, and predictive HCU with Ecoroll.

It is observed in the figure 39 above for the BLB cycle that highest savings in fuel consumption were achieved for the predictive HCU with Ecoroll functionality, i.e. 11.8% and 12.2% for concepts 1 & 2 respectively. The base HCU taken from the Volvo project achieved a fuel saving of 9.1% & 10.1%. However, the fuel savings decreased to 8.15% & 6.7% on implementing the look-ahead & sailing function onto the base HCU. A possible reason for this is that the look-ahead distance was fixed as 1000m, and this parameter needs to be optimized for each driving cycle.

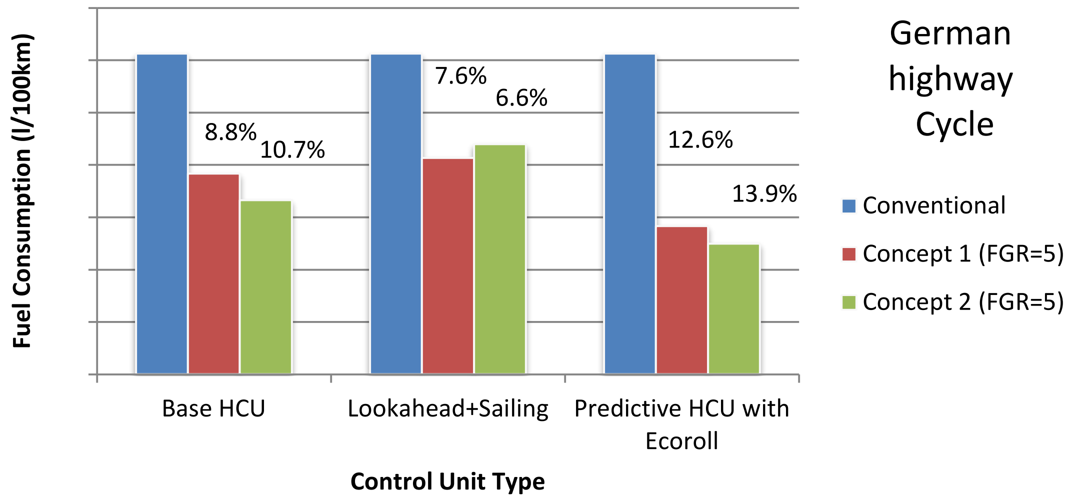


Figure 40: Fuel Consumption plots for various Control Strategies for the German highway cycle

As seen above, a similar result was achieved for the German Highway cycle as well, where the predictive HCU provided the highest fuel savings of 12.6% % 13.9%, and the Lookahead+Sailing HCU provided the least fuel savings of 7.6% & 6.6% for concepts 1 & 2 respectively.

9.1.1.2 Concepts

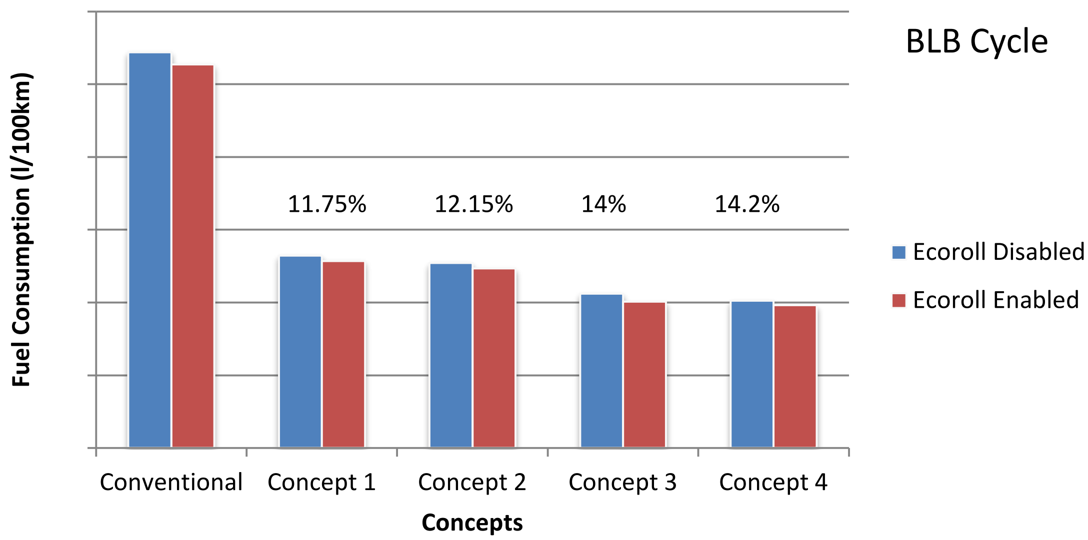


Figure 41: Fuel Consumption plots for various concepts for the BLB cycle

Concept 4 has provided the least fuel consumption, which is 14.2% less than the conventional model. Concepts 1 & 2, which have a direct final gear ratio from the EM to the wheels, provide about 2% less fuel savings as compared to concepts 3 & 4 which have a 2 speed gearbox.

The implementation of Ecoroll has resulted in an average increase in fuel savings of 0.44%, with the maximum effect seen in in the conventional model (0.69% more savings) and the least effect seen in concept 4 (0.29%).

Also, it is interesting to note that there is no significant difference in fuel consumption values between concept 1 and 2, and between concept 3 and 4. Hence, the addition of an additional EM has not contributed towards significant fuel savings (only 0.3% and 0.2% increase in fuel savings). The reason for this was found to be the power limit of the ESS. It was discovered that although the two EM's have a total capacity of 358kW, the ESS has a discharge limit of 170kW. This power limit translates to a torque limit on the EM's, as depicted in the figure below. The blue line represents the EM torque limit, and the green line is the torque limit due to the battery's maximum discharge power limit.

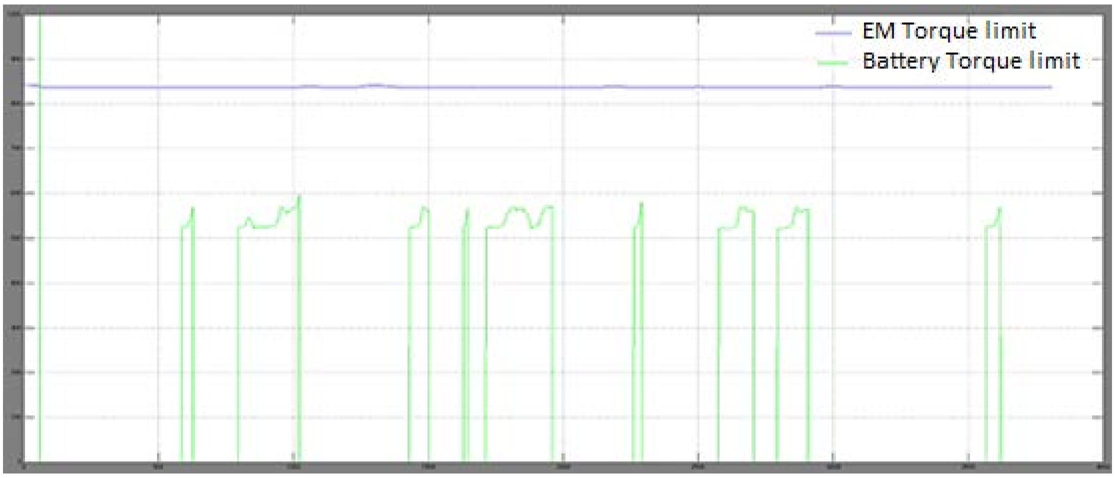


Figure 42: Plot of the Battery and EM Torque Limits versus Time

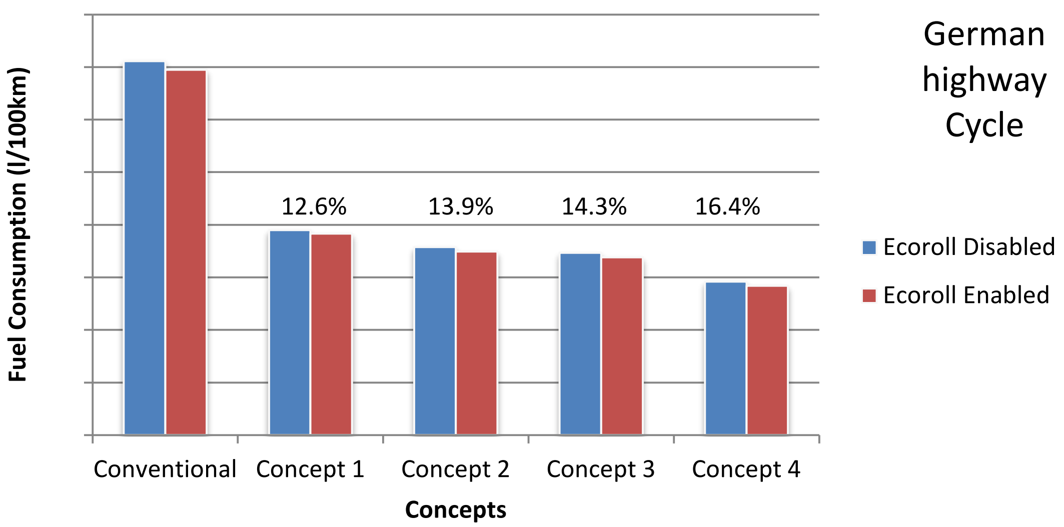


Figure 43: Fuel Consumption plots for various concepts for the German highway cycle

A similar trend is observed in the results for the German Highway cycle. However, the fuel savings values are greater for all concepts in this application. The effect of Ecoroll has resulted in an average increase in fuel savings of 0.41%, with the maximum effect seen on the conventional model (0.64%), and the least effect seen on concept 1 (0.29%). The difference in fuel savings between the two driving routes is especially more for concepts 2 and 4 which have 2 EM's (1.4% & 2.2% higher fuel savings as compared to the BLB cycle).

9.1.1.3 EM Final Gear Ratios

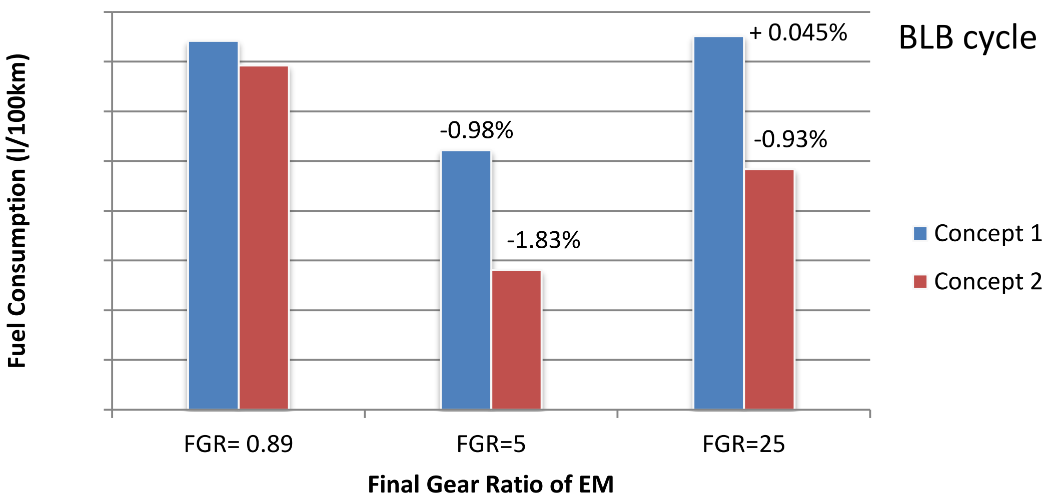


Figure 44: Fuel Consumption plots for various EM Final Gear Ratios for the BLB cycle

Several iterations were done in order to arrive at fuel consumption-optimized final gear ratio for the EM. It was found that in the driving cycles with more speed variations, the higher final gear ratios such as 10, 15 and 20 were found to give better fuel consumption, whereas in driving cycles with constant cruising speeds over larger distances, the lower final gear ratios such as 0.89, 2.5 and 5 gave better fuel consumption.

After comparing all the available final gear ratios in the inventory (FGR=0.89,2.5,5,10,15,20,22.8) with the base HCU models, three final gear ratios were short-listed for the later models with the predictive HCU, i.e. FGR=0.89,5,25. On comparing the results, it was found that a final gear ratio of 5 was best suitable for the BLB driving route. This can be observed from the above plot, as an FGR=5 results in a fuel consumption that is 0.98% & 1.83% lower than that with FGR=0.89. Also, an FGR=25 results in a 0.93% reduction in f.c. for concept 2, but a slight increase of 0.045% for concept 1. Hence, it is observed that an FGR=5 is most optimal for both concepts. There exists further scope for optimization of the final gear ratio but it was decided to continue with this result due to time constraints.

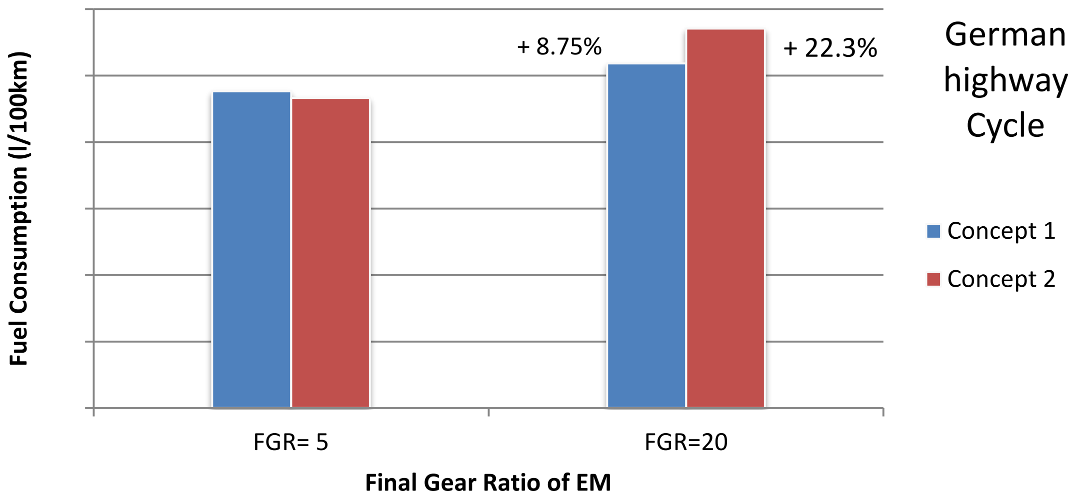


Figure 45: Fuel Consumption plots for various EM Final Gear Ratios for the German highway cycle

For the German Highway driving route, only two final gear ratios, i.e. 5 and 20 were shortlisted after initial iterations with the base HCU model. This is because the German Highway is a 6 hour long driving route and thus the number of iterations had to be reduced due to lack of computational time. It is observed that an FGR of 20 results in an 8.75% increase in f.c. for concept 1, and a 22.3% increase for concept 2. Hence, it was concluded that an FGR of 5 would be optimal for this application as well.

9.1.2 Energy Throughput

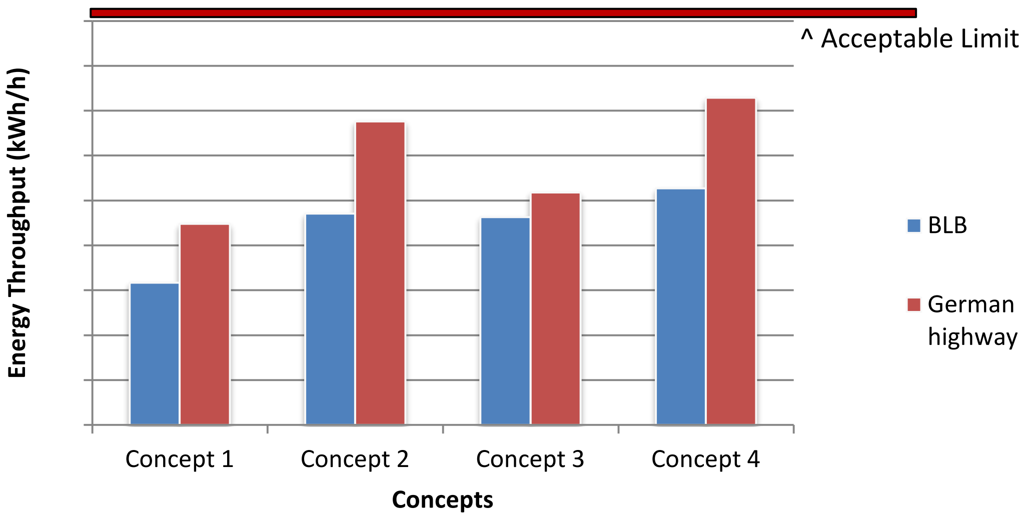


Figure 46: Energy Throughput values for different concepts for both BLB and German highway cycles

The energy throughput values have been normalized to kWh/h instead of an absolute value of kWh in order to compare the BLB and German Highway cycles, as they have very different lengths and time durations. It is observed that all the energy throughput values lie below the maximum threshold (i.e. 45kWh/h), and hence none of the concepts would cause excess degradation of the battery. Hence, it is clear that the

German Highway cycle results in higher battery usage, which can be attributed to the presence of stops and more frequent altitude variation in this driving route.

Also, it must be noted that the energy throughput is higher for the concepts with an additional EM, i.e. concepts 2 & 5. For the BLB cycle, the difference between concept 1 & 2 is 56% and between concept 4 & 5 is only 13%. For the German Highway cycle, the difference between concept 1 & 2 is 50% and between concept 3 & 4 is 44%.

9.1.3 Regenerated Energy

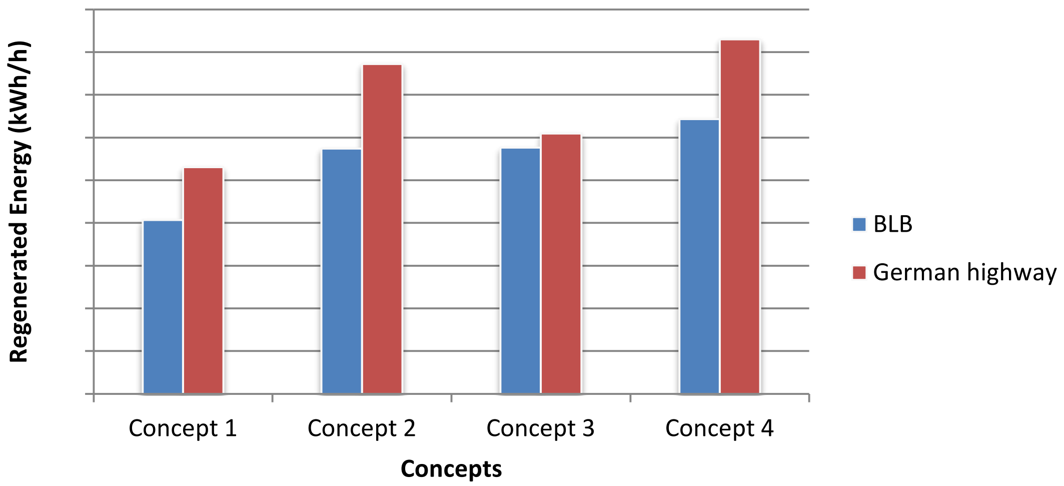


Figure 47: Regenerated Energy values for different concepts for both BLB and German highway cycles

The amount of energy regenerated have also been normalized to kWh/h instead of an absolute value of kWh in order to compare the BLB and German Highway cycles, as they have very different lengths and time durations. The German Highway cycle provides more opportunity for energy regeneration, which can be attributed to the fact that there are 4 stops that involve braking to a standstill, and also to the more frequent altitude variation in this driving route.

9.1.4 Performance & Drivability

9.1.4.1 Average Speed

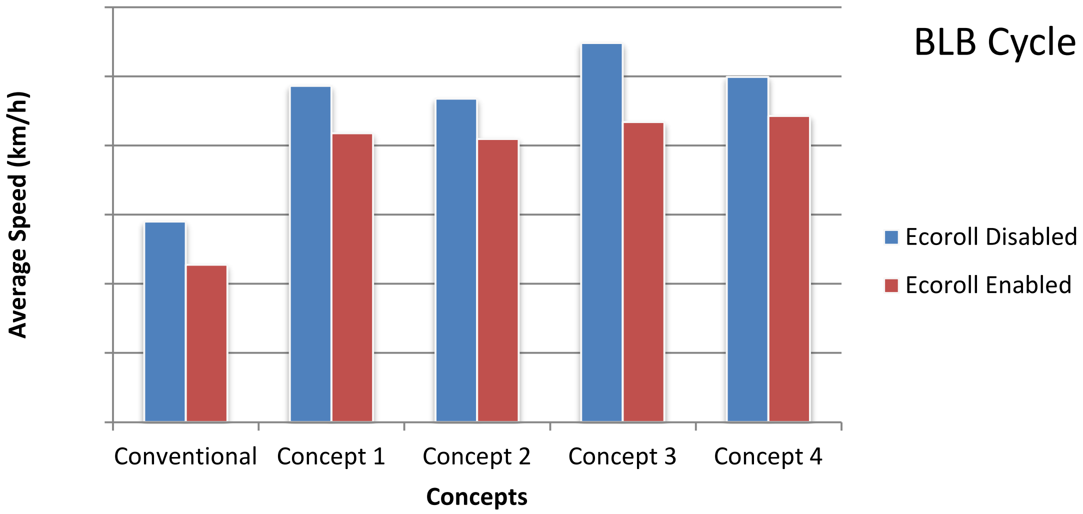


Figure 48: Average Speed of various concepts in the BLB cycle

The average speed for each concept has been determined in order to observe the effect of electrification on the drivability of the vehicle. Average speed has been chosen as a parameter to evaluate drivability as it gives an idea about how well the vehicle is able to keep up with the driver's demands, and whether it can reach the desired performance.

In the BLB driving route, it is observed that there has been an increase in average speed of 1 km/h (1.2% increase) due to electrification, and this value is consistent for all concepts. It is also observed that implementation of Ecoroll has resulted in a decrease in average speed of about 0.3 km/h (0.4% decrease) for both the conventional model and the hybrid concepts. The largest decrease in average speed due to Ecoroll has been observed for concept 4, i.e. 0.6 km/h.

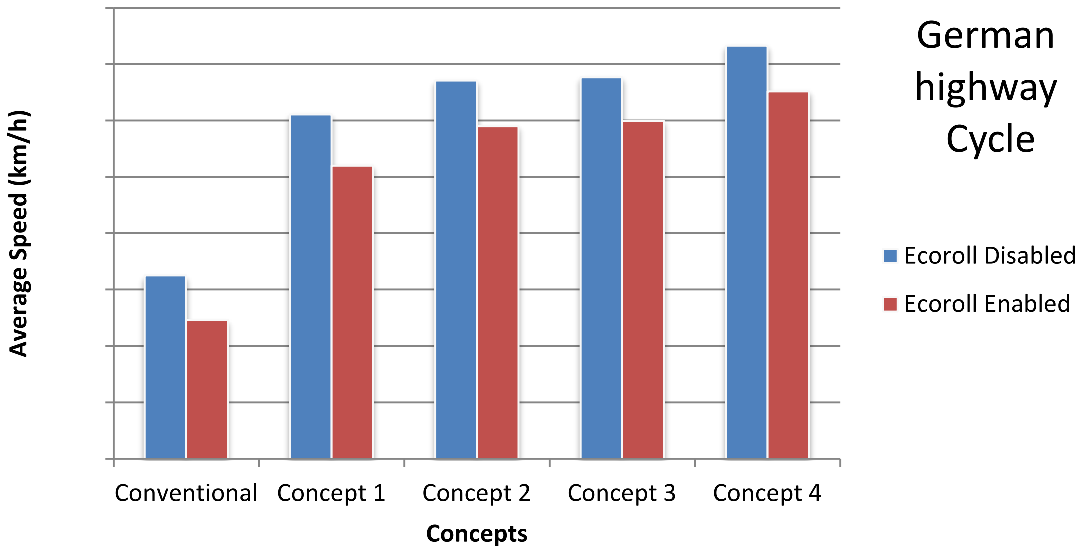


Figure 49: Average Speed of various concepts in the German highway cycle

For the German Highway driving route the average speed has increased by about 1.75 km/h (2.25% increase) due to electrification. The lowest increase has been for concept 1, i.e. 1.4km/h, and the largest has been for concept 4, i.e. 2 km/h. The decrease in average speed due to the Ecoroll functionality has been 0.4 km/h (0.5% decrease) and this value is consistent for all models.

9.1.4.2 Speed Error

Speed error is the difference in actual speed of the vehicle and desired speed. In this simulation model, the target speed set in the driver model (based on driving cycle data) is assumed to be the desired speed. This parameter has been calculated for both the conventional and hybrid models, for the Borås-Landvetter-Borås and German Highway driving route.

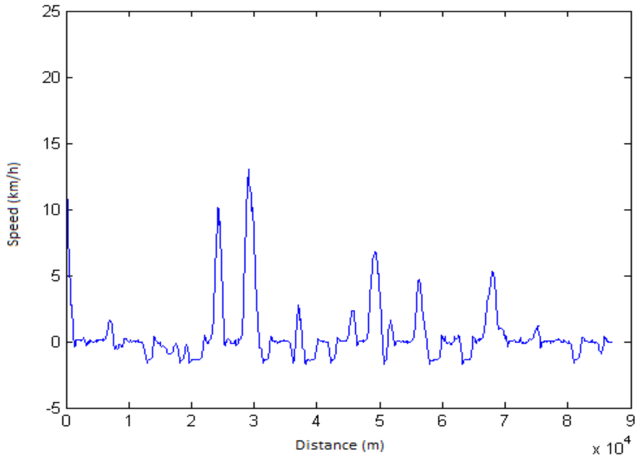


Figure 50: Speed Error versus Distance for the BLB cycle

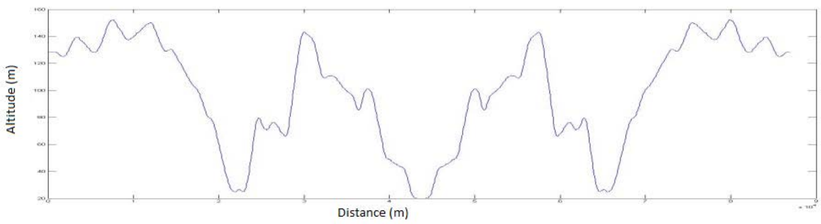


Figure 51: Altitude versus Distance for the BLB cycle

The speed error plot has been shown for the BLB cycle in the above figure. One can observe from the altitude profile that the speed error is significant when the vehicle is climbing a high gradient slope. This is because the vehicle reaches is maximum power limit in such high speed, high gradient scenarios and is thus unable to reach the desired speed. The maximum speed error is observed to be about 13 km/h.

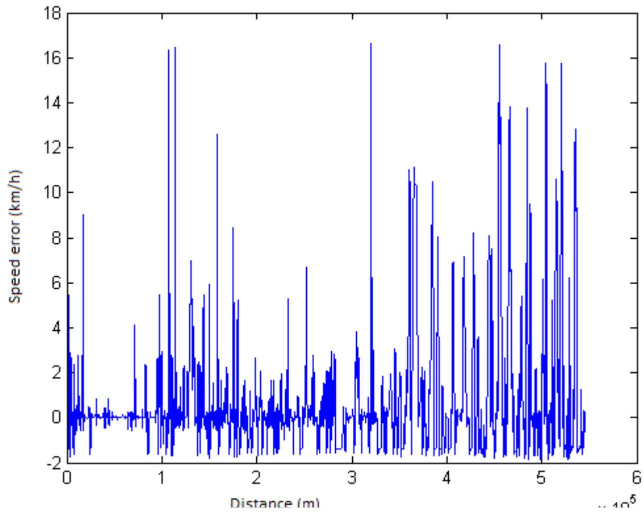


Figure 52: Speed Error versus Distance for the German highway cycle

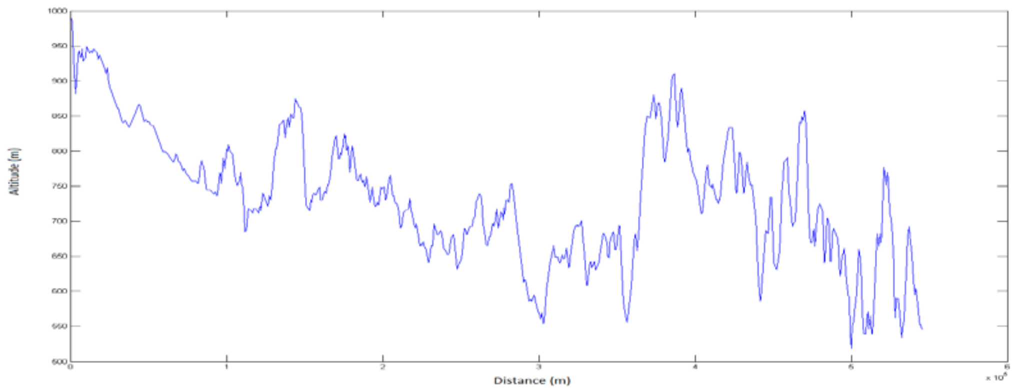


Figure 53: Altitude versus Distance for the sx45 cycle

The speed error plot has been shown for the German Highway cycle in the above figure. Again, the instances where the speed error is significant (greater than 5km/h) occur when there is a sudden increase of decrease in altitude. The maximum speed error is observed to be about 16 km/h.

Another term which is interesting with regards to drivability is Vehicle Speed Error Percentage. It can be defined as the percentage of time during the driving route during which the speed error is more than a minimum value, i.e. 5 km/h in this study. This term gives a reasonable idea about the fraction of time in the transport mission during which the powertrain is in lack of tractive power, or is overspeeding.

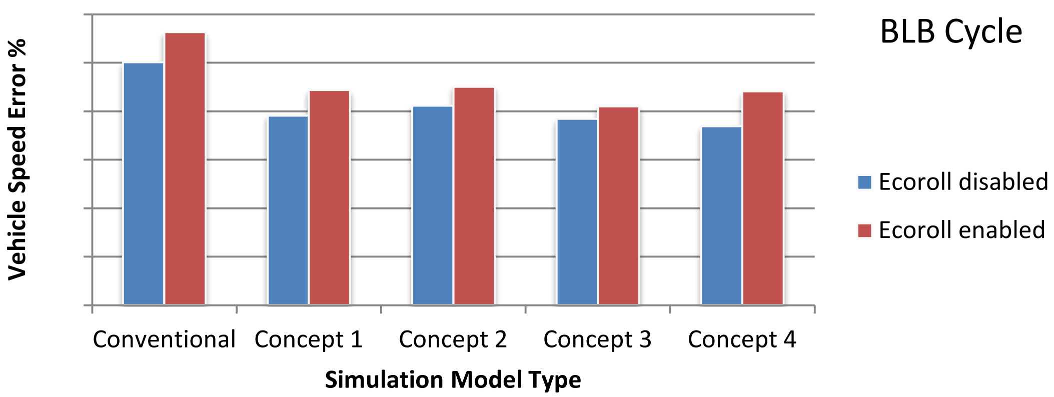


Figure 54: Vehicle Speed Error % for various simulation models in the BLB cycle

In the BLB cycle, it is observed that the vehicle speed error percentage is 11.24% for the conventional model with Ecoroll, whereas it is only 8.7% on average for the hybrid concepts. Hence, this parameter has decreased by 2.5% due to electrification. It must also be noted that the vehicle speed error percentage has increased by 1.2% in case of conventional and 1% in case of the hybrids due to the implementation of Ecoroll.

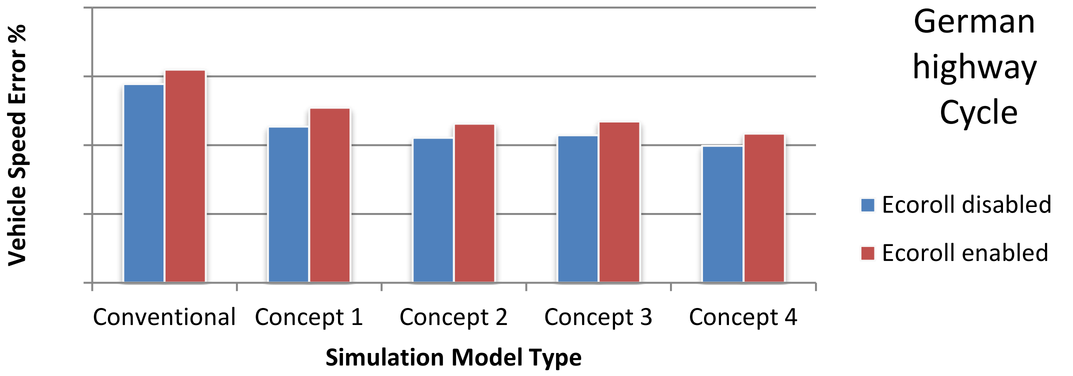


Figure 55: Vehicle Speed Error % for various simulation models in the German highway cycle

In the German Highway cycle, the vehicle speed error percentage is 15.5% for the conventional model with Ecoroll, whereas it is only 11.7% on average for the hybrid concepts. Hence, this parameter has decreased by 3.8% due to electrification. It must also be noted that the vehicle speed error percentage has increased by 1.1% due to the implementation of Ecoroll in both the conventional model and hybrid concepts.

It can thus be concluded that the vehicle achieves lower performance and drivability in the German Highway cycle as compared to the BLB cycle, as it has a higher maximum speed error (3km/h more) and higher vehicle speed error percentage (3% more).

9.1.4.3 Number of Gearshifts

Number of gearshifts has also been considered as an indicator of drivability, as a higher number of gearshifts causes torque interruptions, noise and vibrations, which in turn cause additional disturbance to the driver.

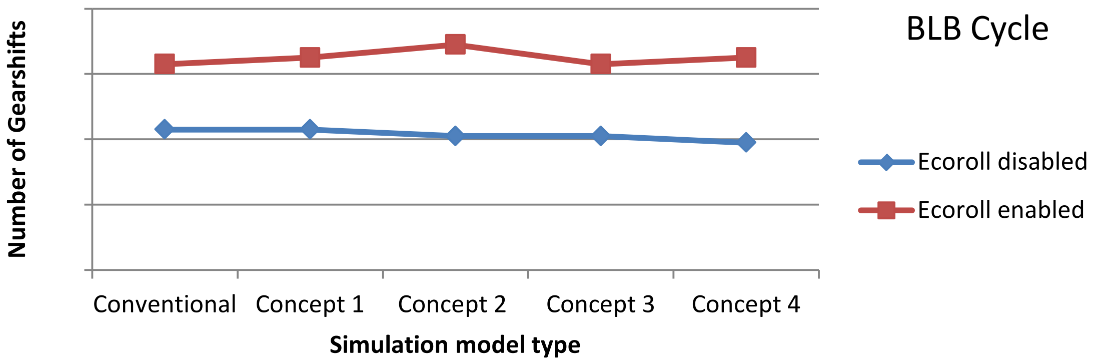


Figure 56: Number of Gearshifts of various simulation models in the BLB cycle

The average number of gearshifts has increased from 41 with Ecoroll disabled to 65 with Ecoroll enabled (58% increase). This is because the Ecoroll functionality causes to current gear to change to neutral when it is activated. Also, there is no change in the number of gearshifts due to electrification. It must be noted however that the highest number of gearshifts has been observed for Concept 2.

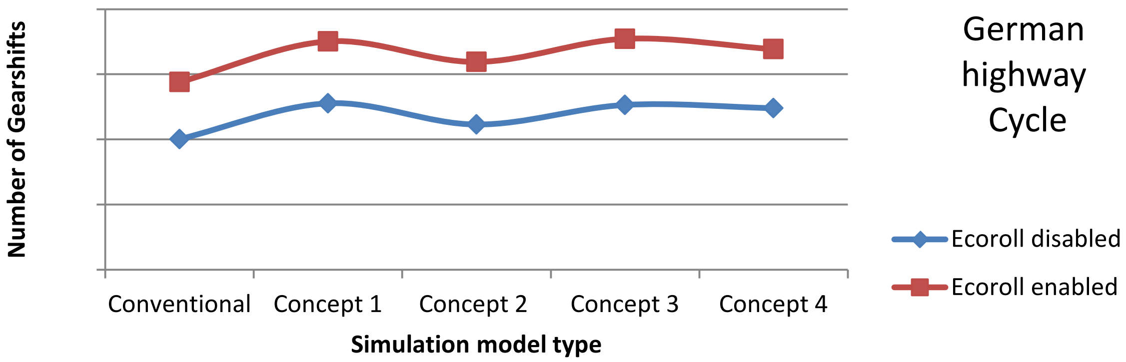


Figure 57: Number of Gearshifts of different simulation models in the German highway cycle

For the German Highway cycle, the average number of gearshifts has increased by 40% with Ecoroll enabled compared with Ecoroll disabled. The effect of electrification has resulted in an average increase in the number of gearshifts with Ecoroll enabled (20% increase). Interestingly, the lowest number of gearshifts has been observed for Concept 2 for this driving route, which is contrary to the result for the BL driving route.

9.1.5 Comparison with 32ton conventional truck

A comparison of fuel consumption and performance will be done between the hybrid 60ton truck model, and the conventional 32ton truck model in this section. This is because the purpose of hybridization is to reduce the fuel consumption per mass of cargo transported per kilometer of distance travelled. A direct comparison of fuel consumption in terms of l/100km is not done, as this would obviously be more for a 60ton truck as compared to a 32ton one, despite the hybridization.

Maximum Payload on the A-double 60ton hybrid truck: 24000+10000 = 34000kg.

Maximum Payload on the Rigid 6x4 32ton conventional truck: 20000kg.

9.1.5.1 Fuel Savings

In this section, the savings in fuel in terms of litres per mass of cargo transported has been presented for the transport missions, i.e. Borås-Landvetter-Borås as well as German Highway. Also, the monetary savings in terms of SEK per mass of cargo transported have been presented.

9.1.5.1.1 Borås-Landvetter-Borås Cycle

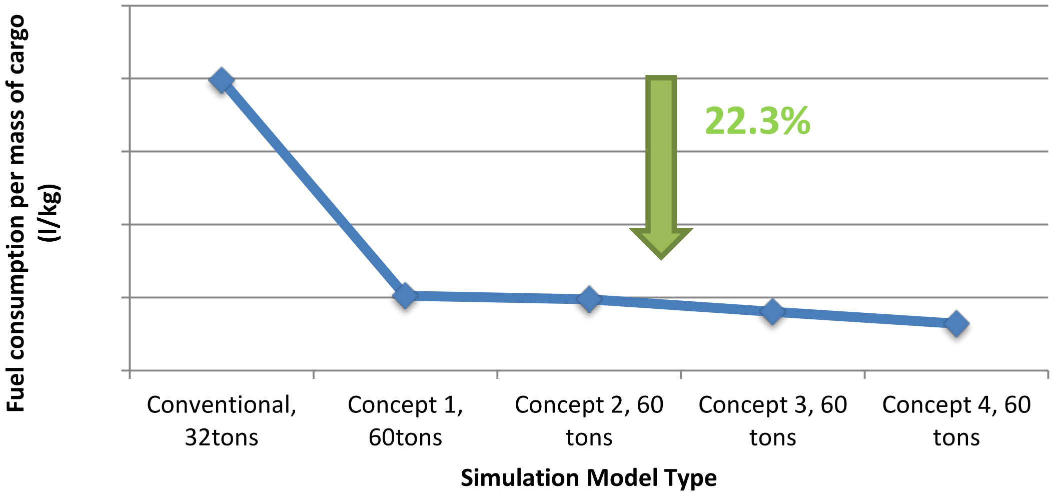


Figure 58: Fuel Consumption per mass of cargo for various concepts in the BLB cycle

The fuel consumed per mass of cargo transported has been calculated to be 1.4 l/kg for the conventional 32 ton truck. For the hybrid 60 ton truck, this parameter varies from 1.1l/kg to 1.06l/kg. Hence, on average there is a decrease of 22.3%, i.e. 0.3 l/kg. The maximum fuel saving occurs for Concept 4, i.e. 23.85%, and the minimum for Concept 1, i.e. 21.12%. Assuming the fuel price as 14.52 SEK/l, [13] the cost savings per kg of mass transported was also calculated. The average fuel cost savings was found to be 4.5 SEK/kg of mass transported, as seen in the plot below.

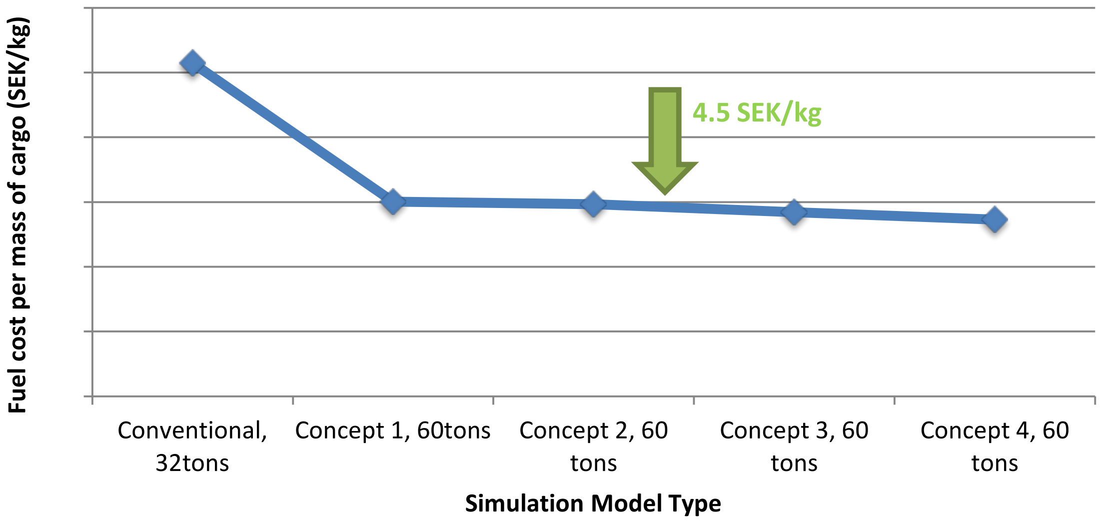


Figure 59: Fuel Cost per mass of cargo for various concepts in the BLB cycle

9.1.5.1.2 German Highway Cycle

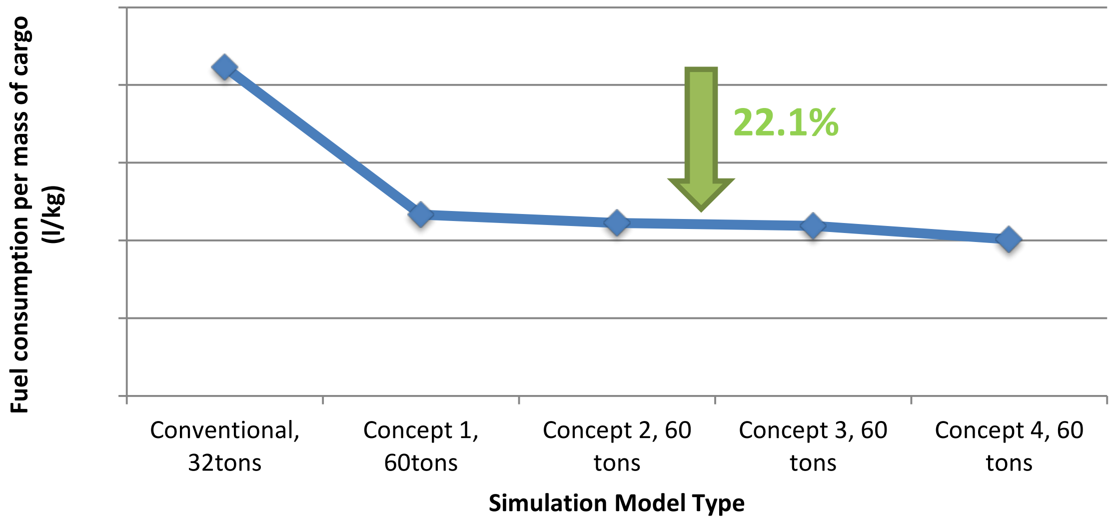


Figure 60: Fuel Consumption per mass of cargo for various concepts in the German highway cycle

For the German Highway driving route, the fuel consumed per mass of cargo transported has been calculated to be 9.23 l/kg for the conventional 32 ton truck. For the hybrid 60 ton truck, this parameter varies from 7.33 l/kg to 7 l/kg. Hence, on average there is a decrease of 22.1%, i.e. 1.93 l/kg. The maximum fuel saving occurs for Concept 4, i.e. 24%, and the minimum for Concept 1, i.e. 20.56%. The average fuel cost savings for this transport mission was found to be 29.6 SEK/kg of mass transported, as seen in the plot below.

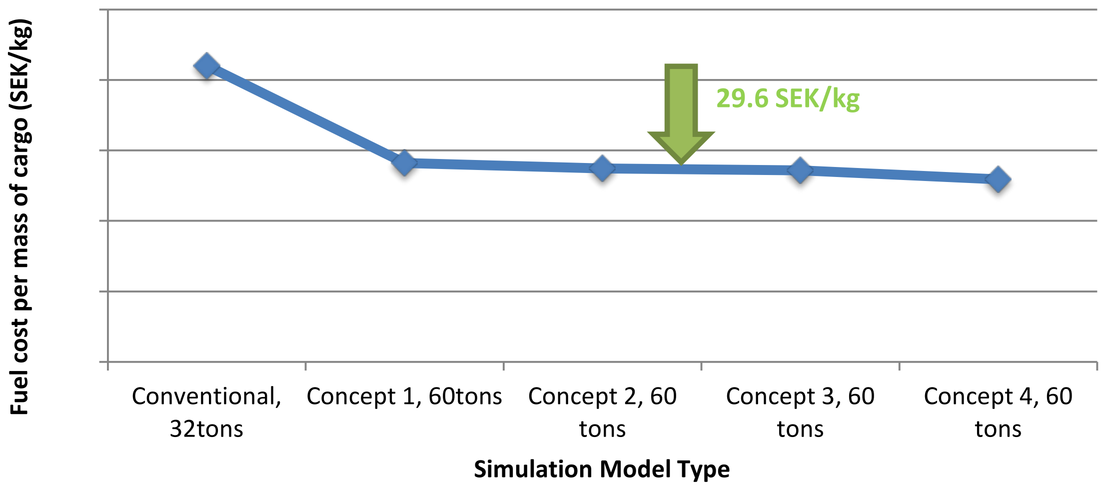


Figure 61: Fuel Cost per mass of cargo for various concepts in the German highway cycle

9.1.5.1.3 Fuel Savings Comparison between both driving cycles

This section determines which type of driving route is more suitable for fuel savings per mass of cargo transported with the 60ton A-double hybrid truck, as compared to the 32ton 6x4 rigid conventional truck. Hence, the results have been calculated in the unit of percentage savings in fuel/fuel cost per kg of cargo mass per km of distance travelled.

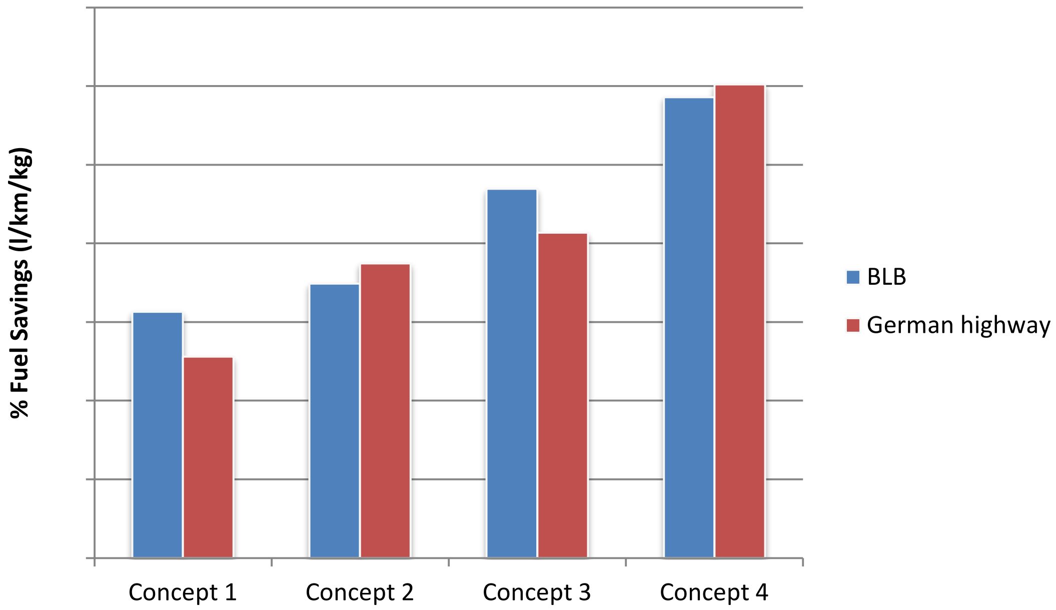


Figure 62: Fuel Consumption comparison between both driving cycles

The maximum fuel savings (%) per kg per km is slightly higher for the German Highway cycle (24.02%) than the BLB cycle (23.85%), but the average fuel savings are slightly higher for the BLB cycle. It is observed from the plot above that there is greater variation in percentage of fuel savings/kg/km between the concepts for the German Highway cycle (Δ3.4%) than the BLB cycle (Δ 2.7%).

9.1.5.2 Performance Comparison

9.1.5.2.1 Average Speed

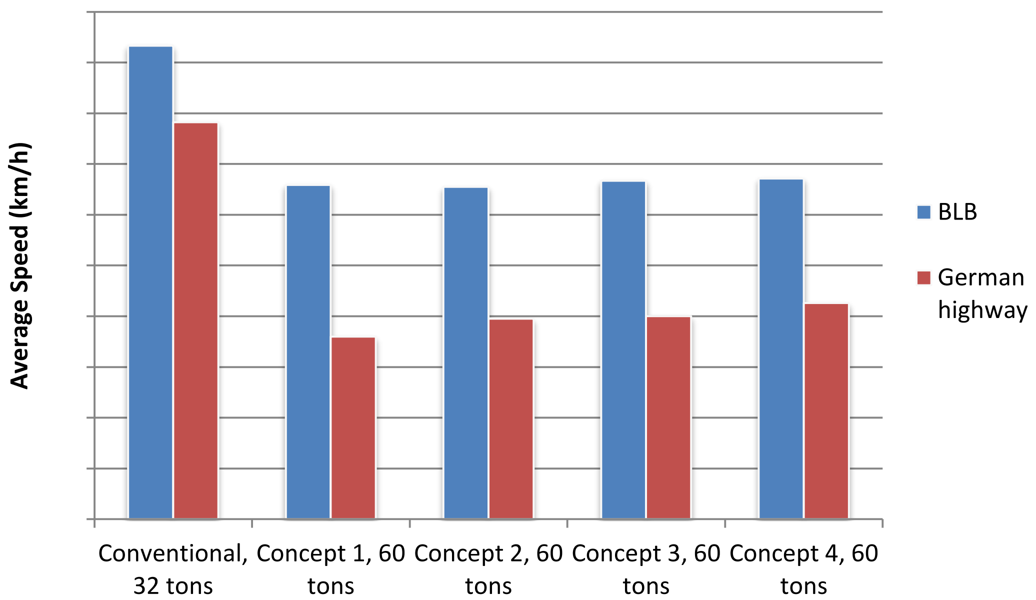


Figure 63: Average Speed of various concepts for both cycles

There has been a considerable drop in average speed when comparing a conventional 32 ton truck with the hybrid 60 ton concepts. In the BLB driving route, the drop in average speed due to electrification is about 2.7 km/h (3.2%). In the German Highway route, the average speed drop due to electrification is about 3.9 km/h (4.7%). Hence, there is a greater drop in performance in the German Highway driving route as compared to the BLB route.

9.1.5.2.2 Speed Error

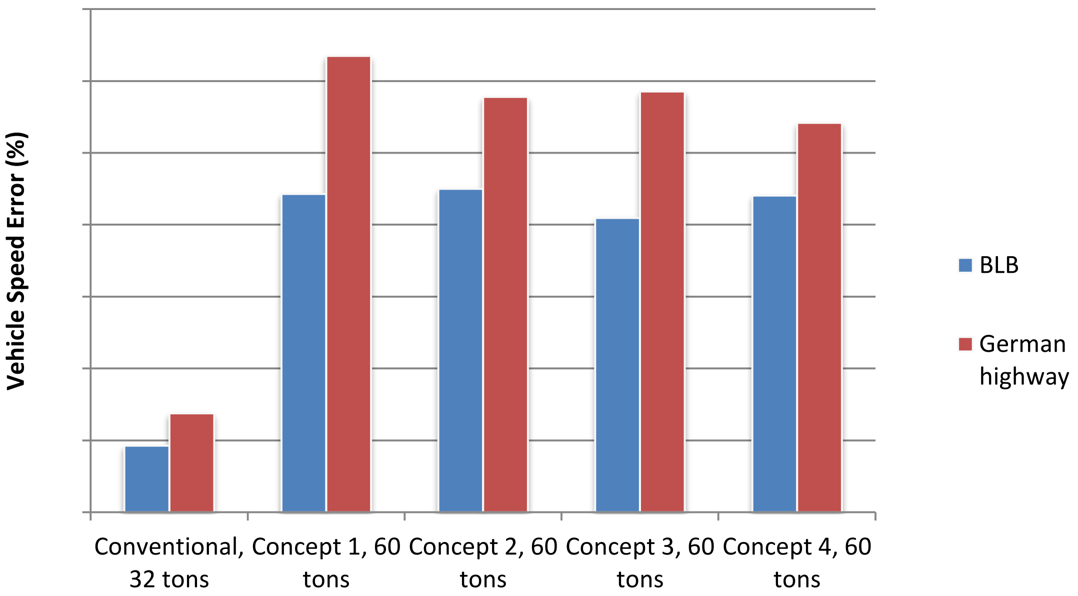


Figure 64: Vehicle Speed Error % of various concepts for both cycles

In the BLB cycle, the speed error is more than 5 km/h for only 1.85% of the total time. However, this vehicle speed error percentage is higher for the hybrid concepts, a value of 8.75% on average (i.e.6.9% higher than conventional). The vehicle speed error for the conventional 32ton model is 2.75% for the German Highway cycle, and 11.7% for the hybrid concepts on average (8.9% higher than conventional).

The speed error at different times during the driving routes can be seen in the two plots below, where the red line represents the Concept 4 60ton model and blue line represents the conventional 32ton model. It is noticed that the speed errors are greatest during uphill and downhill scenarios.

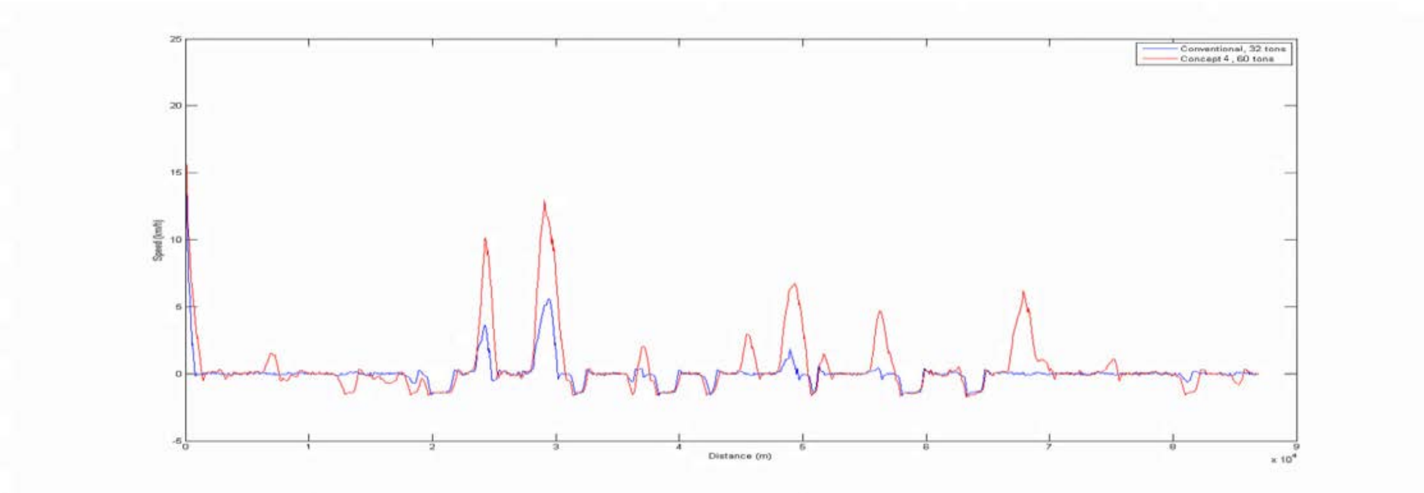


Figure 65: Speed Error for Conventional and Concept 4 models in the BLB cycle

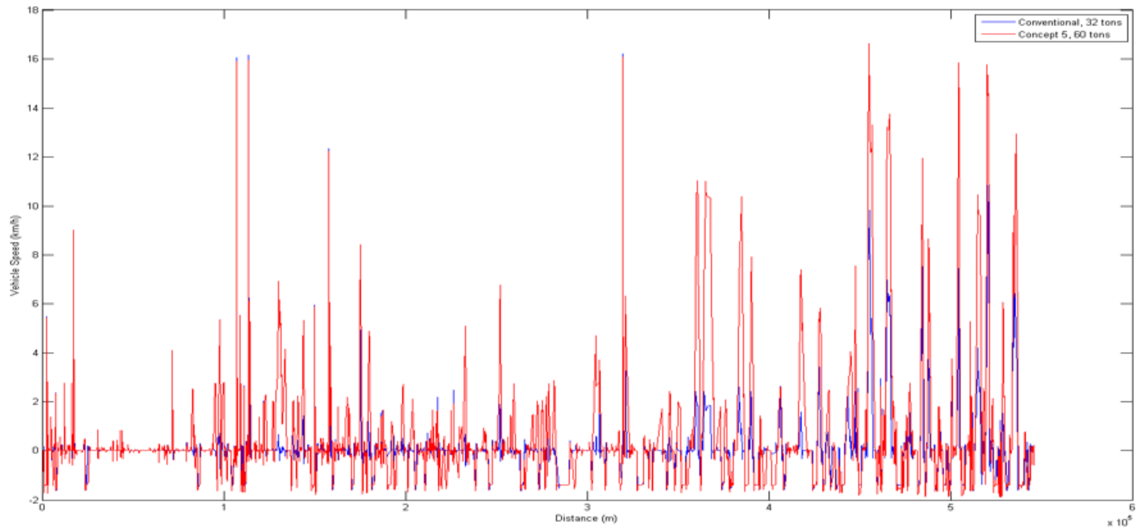


Figure 67: Speed Error for Conventional and Concept 5 models in the German highway cycle

9.1.5.2.3 Time taken to complete driving route

This parameter has been calculated, as it related to the cost-efficiency of the transport mission. A delay in transporting goods from one point to another can lead to an increase in labour costs, and further costs down the logistics chain. The following figure depicts the time delay in transportation of goods for various concepts of the hybrid Double-A combination 60 ton truck, as compared to the conventional 32 ton truck.

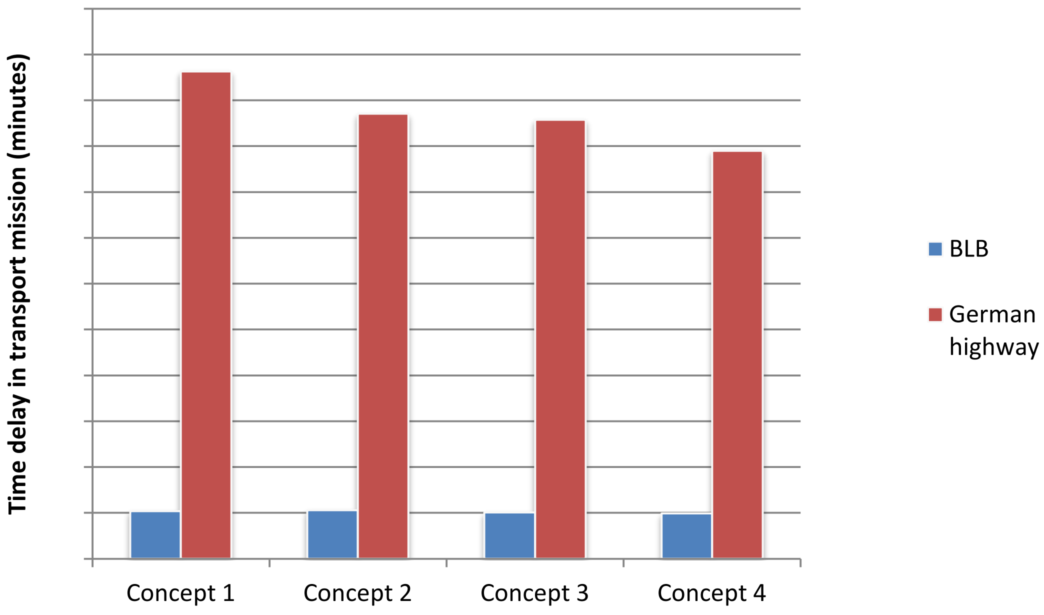


Figure 67: Time delay for different concepts in both BLB and German Highway cycles

Hence, it is observed above that there occurs a time delay of about 2 minutes for the BLB transport mission which is about 1 hour long (3.3%). The time delay for the German Highway transport mission is more significant, i.e. up to 21 minutes (5%). Although 21 minutes is a small fraction of the total transport time, it can lead to significant increase in labour costs and costs related to subsequent logistical delays. It must also be noted that Concept 4 provides the least time delay, i.e. 1.98 minutes and 17.8 minutes for BLB and German Highway cycles respectively.

9.2 Lateral Simulations

9.2.1 High Speed Turn

This maneuver consists of a constant radius turn at a steady speed of 90 km/h with about 0.2g of maximum lateral acceleration. The two main parameters to be observed during this maneuver are High Speed Steady-state Offtracking and Turn Radius.

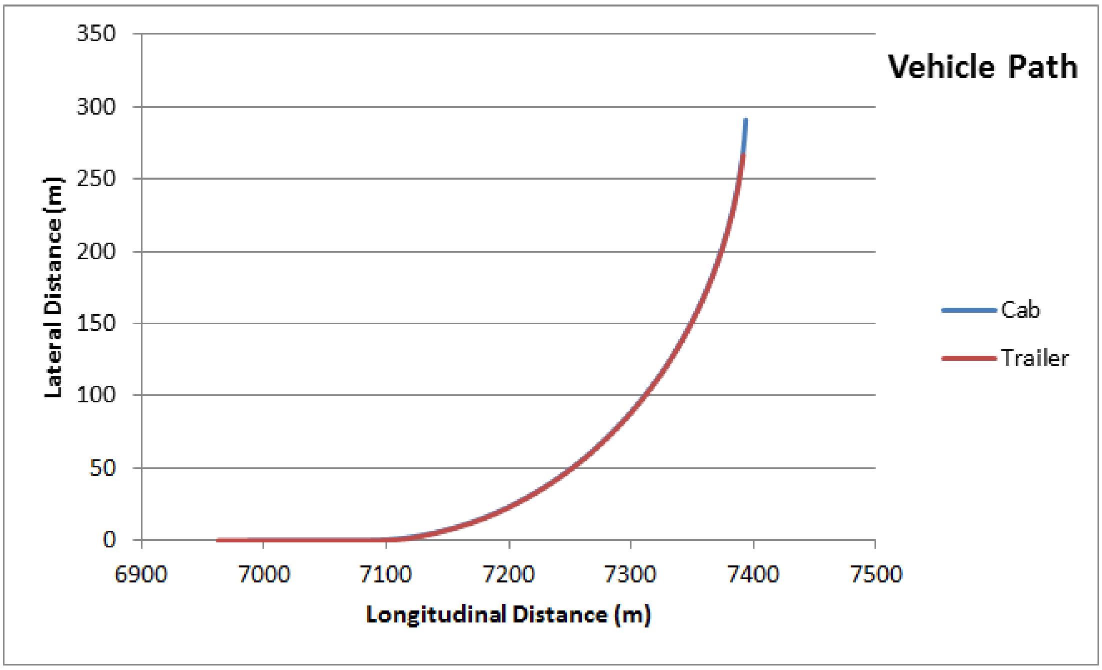


Figure 68: Vehicle Path of Concept 1 during a High Speed Turn maneuver

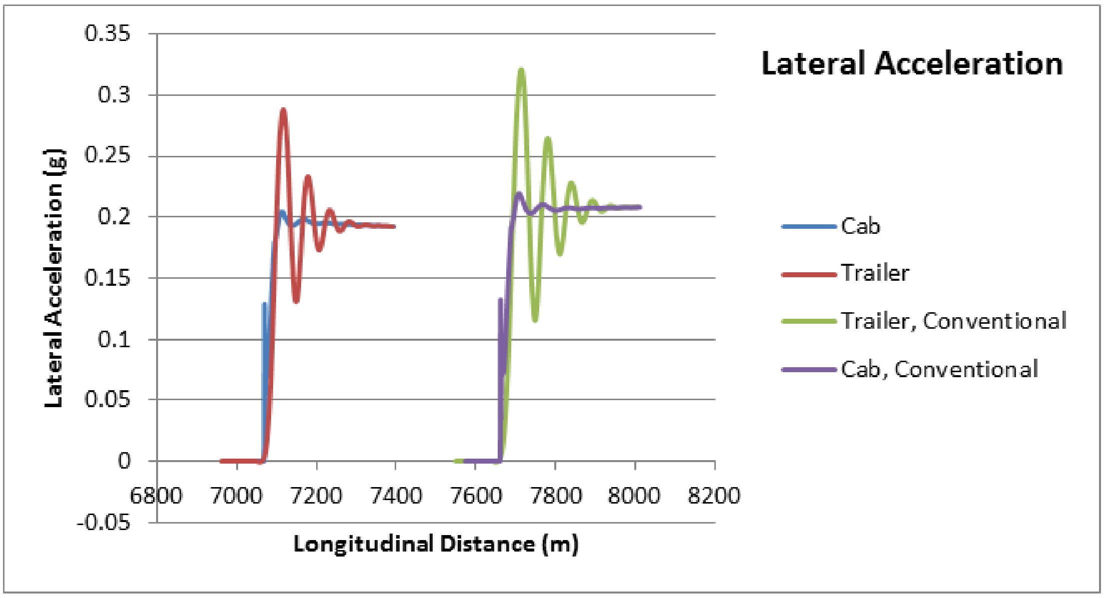


Figure 69: Lateral Acceleration vs. Longitudinal Distance for both Conventional and Concept 1

Table 9: High Speed Maneuver parameters for both Conventional and Concept 1

Parameter	Acceptable Value	Conventional	Concept 1
HSSO (m)	0.44	0.7472	0.7034
Turn Radius (m)	319	349.65	324.15

9.2.2 High Speed Lane Change

This is a typical lane change maneuver during highway driving at a constant speed of 80 km/h. The steering input was set such that it results in a maximum lateral acceleration of 0.2g, with a steering frequency of 0.4 Hz. The main output parameter of interest in this maneuver is High Speed Transient Offtracking (HSTO).

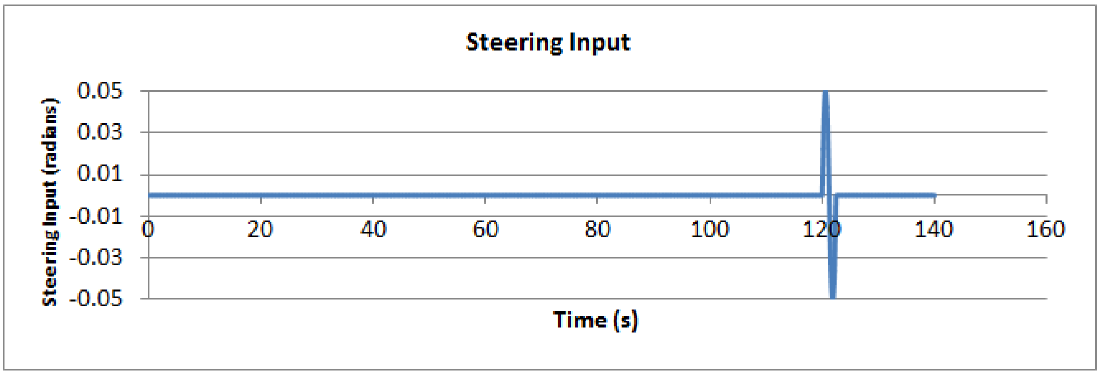


Figure 70: Steering Input versus Time for High Speed Lane Change maneuver

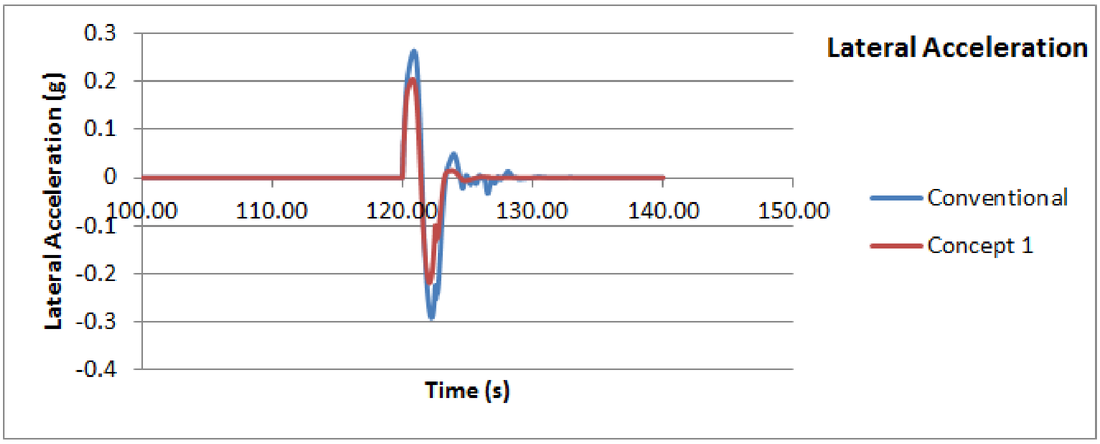


Figure 71: Lateral Acceleration versus Time for High Speed Lane Change maneuver

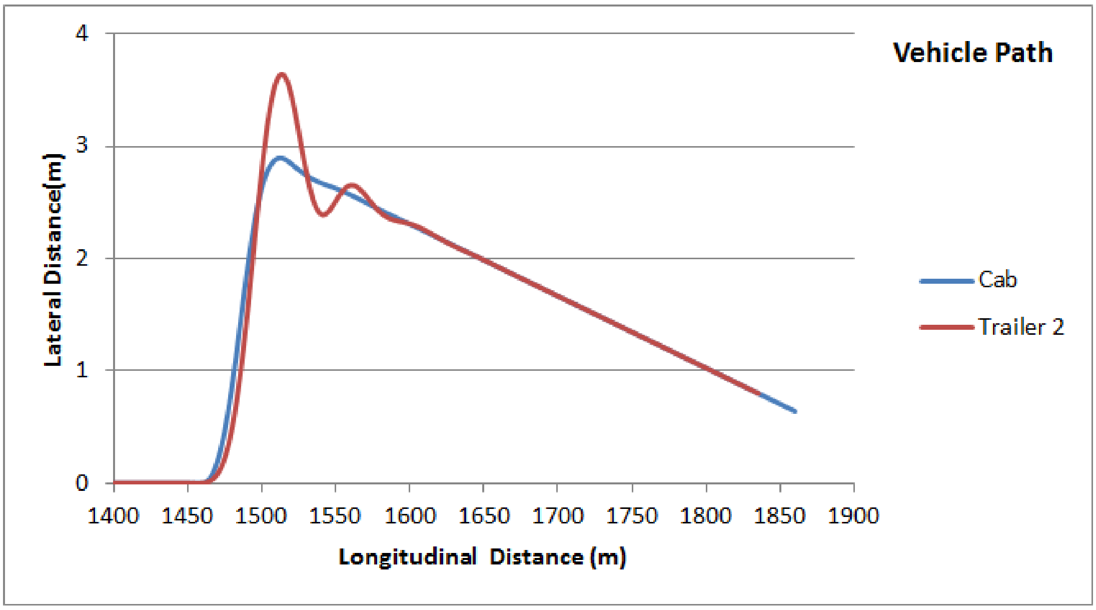


Figure 72: Vehicle Path for High Speed Lane Change maneuver

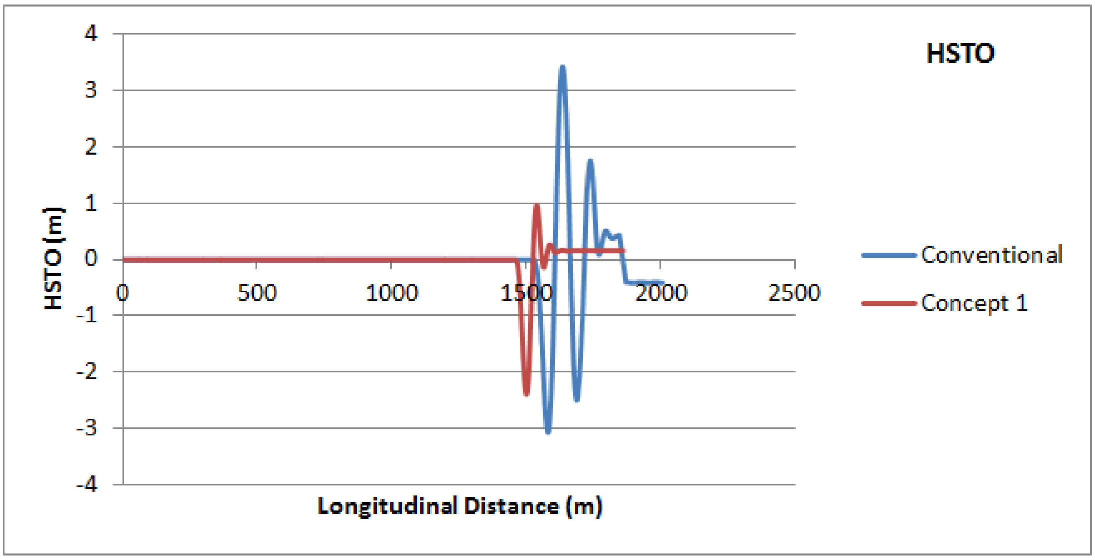


Figure 73: High Speed Transient Offtracking versus Longitudinal Distance

Table 10: HSTO values for the High Speed Lane Change maneuver

Parameter	Acceptable Value	Conventional	Concept 1
HSTO (m)	0.54	3.4	0.95

9.2.3 Low Speed Roundabout Maneuver

This maneuver replicates a typical low speed U-turn around a roundabout at a constant speed of 10 km/h. The main parameters to be studied are articulation angle, outer path, and low speed swept path width.

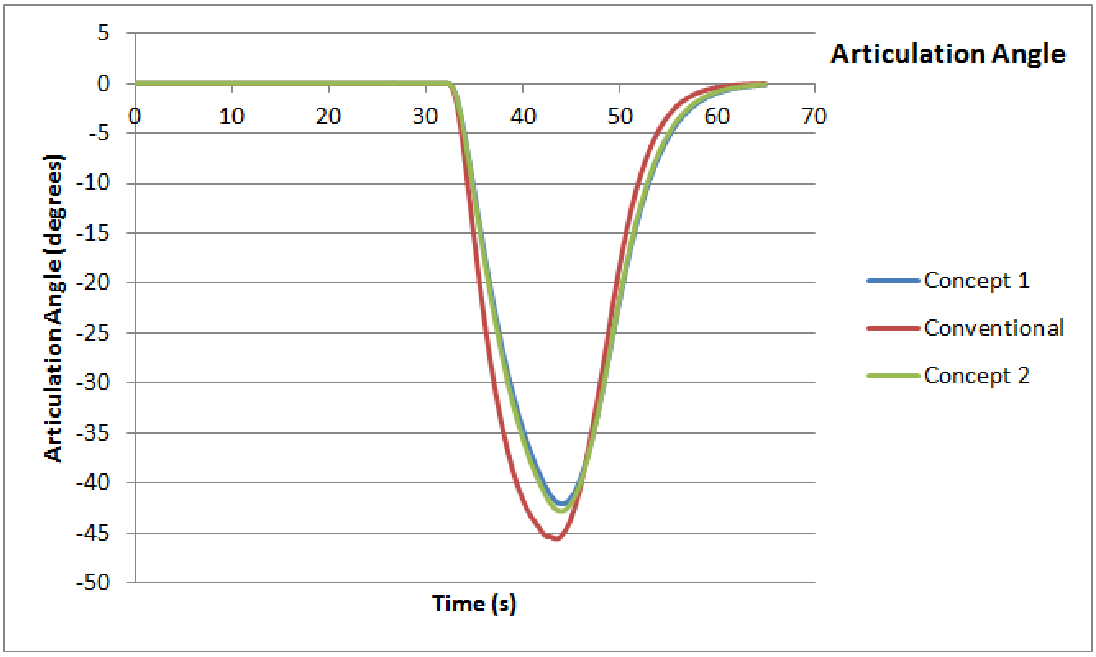


Figure 74: Articulation Angle versus time for the Low Speed Maneuver

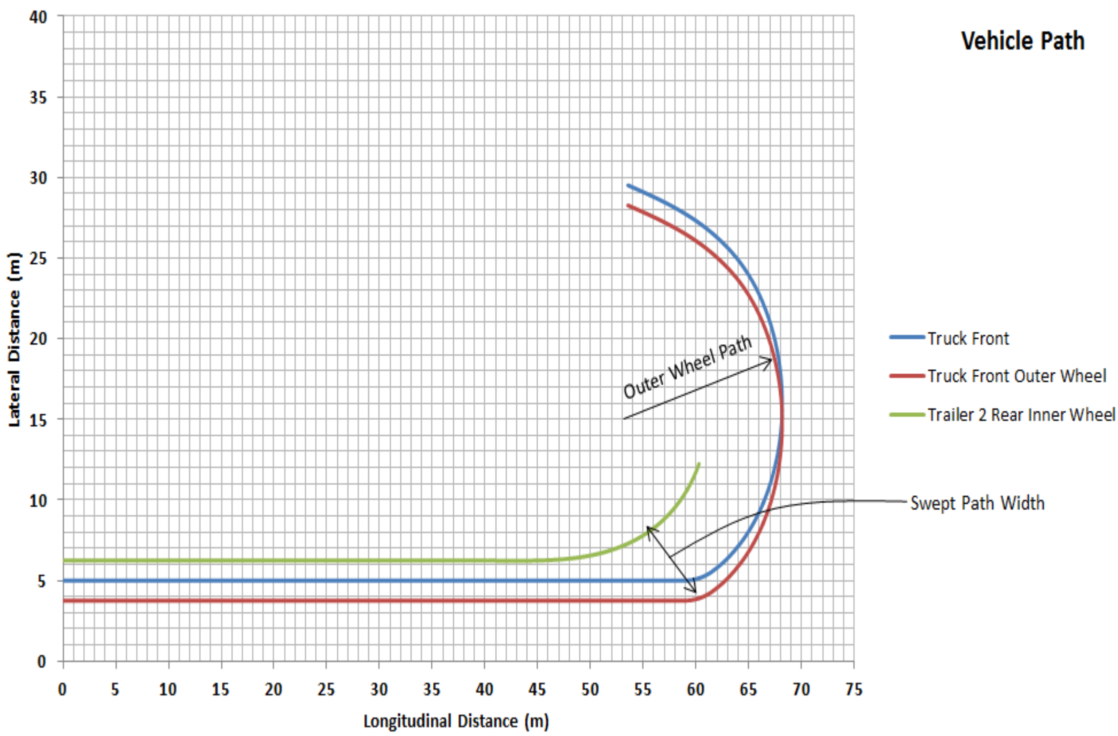


Figure 75: Vehicle Path for the Low Speed Maneuver

Table 11: Output parameters for the Low Speed Maneuver

Parameter	Acceptable Value	Conventional	Concept 1	Concept 2
Swept Path Width (m)	8.21	7.65	6.4	6.3
Outer Path	12.5	11.25	11.25	11.25

9.2.4 Custom Roundabout Maneuver

This is a custom maneuver which was carried out in order to observe how the vehicle behaves in a worst-case scenario. The vehicle turns at a constant speed of 30 km/h around a roundabout. The parameter observed here in the articulation angle.

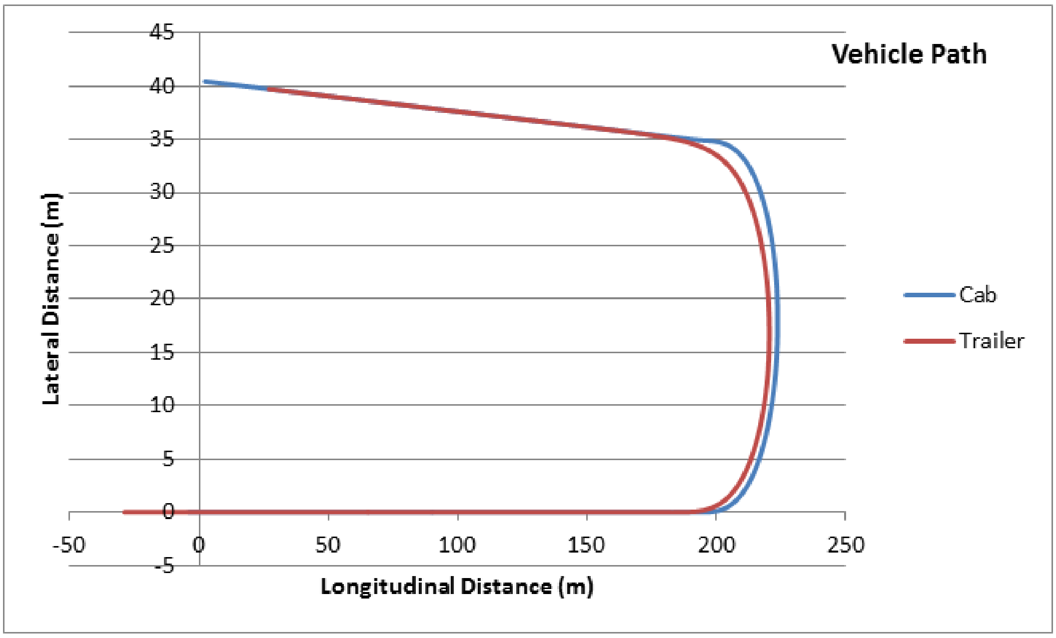


Figure 76: Vehicle Path of Concept 1 during the custom maneuver

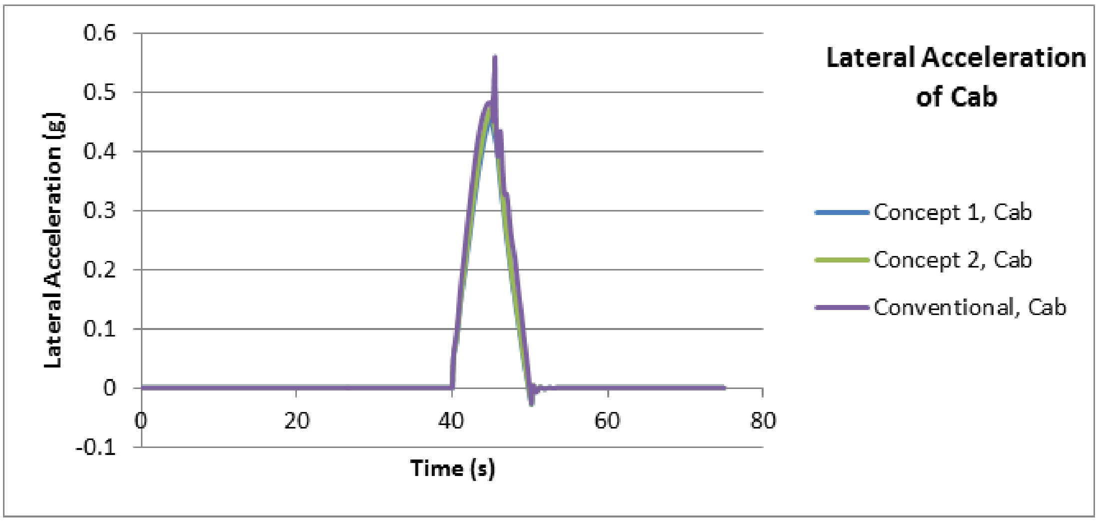


Figure 77: Lateral Acceleration versus Time of Cab during the custom maneuver

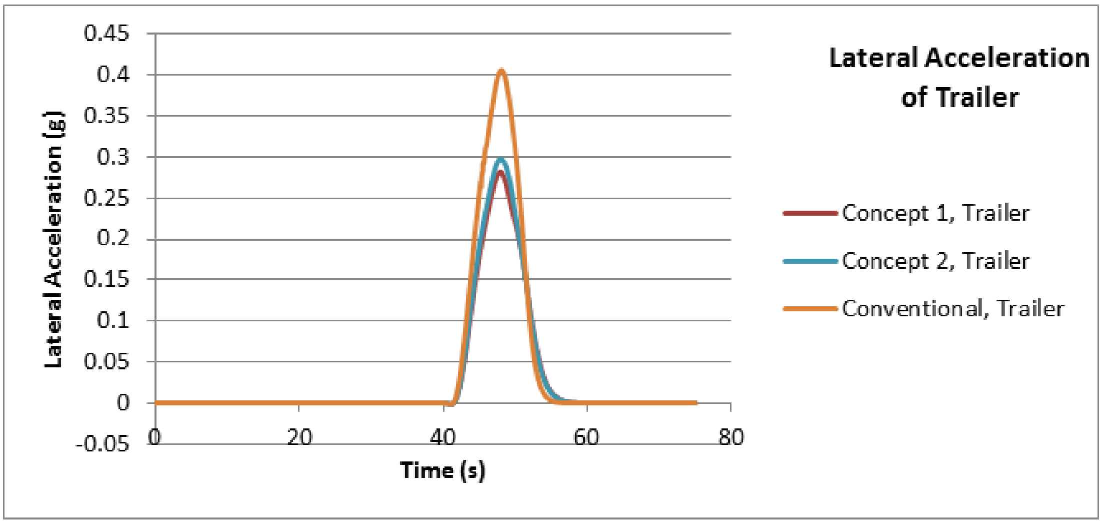


Figure 78: Lateral Acceleration versus Time of Trailer during the custom maneuver

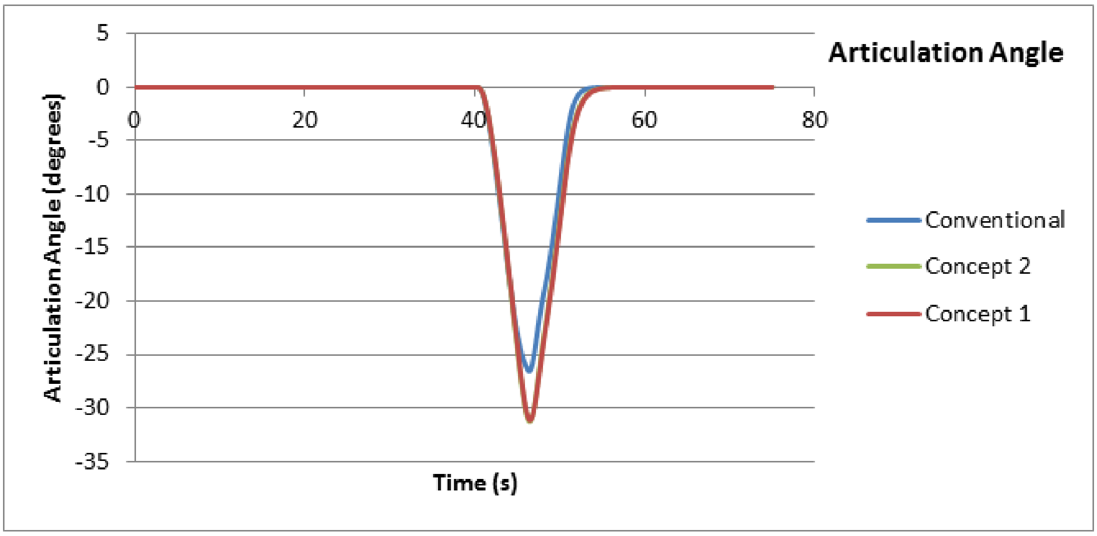


Figure 79: Articulation Angle versus Time during the custom maneuver

10 Discussion

In this chapter, the results from chapter 9 will be analyzed in further detail. The discussion will mainly focus on fuel consumption, but the vehicle's lateral and longitudinal performance will also be analyzed.

10.1 Longitudinal Simulations

10.1.1 Fuel Consumption

The predictive HCU with Ecoroll functionality has provided the lowest fuel consumption for both the BLB and German Highway cycles. The fuel consumption values had been compared between the base HCU, Lookahead+sailing HCU and the predictive HCU with Ecoroll for only Concept 1 and 2, as they were the only concepts developed at that stage of the thesis. An interesting outcome has been that the addition of the Lookahead+sailing functionality to the base HCU resulted in an increase in fuel consumption. The reason for this was that the look-ahead distance would need to be further optimized, as the fuel consumption greatly depends on this parameter, and the optimal value for this parameter is different for each driving route. The sailing feature in this functionality also led to an increase in fuel consumption due to highly frequent engaging/disengaging of the clutch.

Regarding the comparison of the hybrid concepts, it was found that Concept 4 provided the least fuel consumption in both the BLB and German Highway cycles, with a fuel saving of 14.2% and 16.4% respectively. This can be attributed to the fact that it has both an additional EM as well as a 2 speed gearbox for each EM. Concepts 3 and 4 have outperformed Concept 1 and 2 due to the application of a 2 speed gearbox between the EM and wheels, instead of a direct final gear reduction. Hence, there has been a jump in fuel savings of 2.15% between Concept 1 and 3, and of 2.05% between Concept 2 and 4. The 2 speed gearbox has enabled the EM to work efficiently in both high torque and high speed situations, as well as regenerate more energy.

The addition of an extra EM however has not led to any significant fuel savings. The increase in fuel savings has been a mere 0.3% between Concept 1 & 2, and 0.2% between Concept 3 & 4. The reason for this is that the additional EM has not been utilized as much as expected due to a power limit enforced by the ESS. Although the two EM's together are capable of producing 840Nm torque and 358kW of power, they were limited to a maximum of about 600Nm torque and 170kW by the ESS.

Regarding final gear ratios of the EM, it was discovered that an FGR of 5 provided the highest fuel economy for both the BLB and German Highway cycle. This is because both cycles involve constant high speed driving and therefore require a low gear ratio. An FGR=0.89 however did not provide the best result, as the routes also involve driving up high gradient inclines, and a low ratio would enable the EM to assist the ICE significantly in such situations. Hence, an FGR of 5 provided a good tradeoff between the need to drive at high speeds and the need to drive up inclines with more torque demands.

Lastly, it must also be noted that all fuel consumption values were significantly lower for the German Highway cycle as compared to the BLB cycle. This can be attributed to the fact that the German Highway cycle involves 4 complete stops to a standstill, whereas the BLB cycle has none. The German Highway cycle also has more frequent changes in altitude, which leads to more regeneration and discharge of electrical energy. For example, the amount of energy regenerated in the German Highway cycle is 22% more than the BLB cycle for Concept 4, which has led to 2.2% more fuel savings.

10.1.2 Energy throughput

The energy throughput values were determined in order to know if the electrification would lead to a possible degradation of the ESS. An approximate figure of 45 kWh/h was obtained for the maximum permissible energy throughput. The maximum value achieved in the simulations was 36 kWh/h. Hence, it is safe to conclude that the ESS would not be degraded faster than normal during operation in the two driving scenarios concerned. The energy throughput was significantly higher (up to 40% higher) in the German Highway cycle than the BLB cycle, which is because the German Highway route involves 4 stops to a complete standstill, and more frequent altitude variation, which leads to more frequent charging and discharging of the ESS.

10.1.3 Regenerated energy

This parameter was calculated in order to know both the regeneration capability of the driving routes, as well as the capability of the various concepts. It was found that the amount of energy regenerated per hour was 30% more in the German Highway cycle as compared to the BLB cycle. This is because the German Highway cycle involves 4 stops to a complete halt as well as more frequent altitude variations. It was also observed that the energy regeneration significantly increased due to the addition of a 2 speed gearbox. The increase was more between Concept 1 and 3 (40%) which have a single EM than between Concept 2 and 4 (18%) which have two EM’s. Also, the addition of an EM led to a significant increase between Concept 1 and 2 (35%) which have a direct gear reduction, but a lesser increase between Concept 3 and 4 (11%) which have a 2 speed gearbox.

10.1.4 Performance & Drivability

Four parameters have been analyzed in order to evaluate the performance and drivability of the vehicle: Average speed, Speed error, vehicle speed error percentage and number of gearshifts.

The average speed has increased by 1 km/h (1.2%) and 1.75 km/h (2.25%) due to the effect of electrification in the BLB and German Highway cycles respectively. This is because the EM has assisted the ICE for propulsion when sufficient charge was available in the ESS. The implementation of the Ecoroll functionality has however led to a decrease in average speed of 0.3 km/h (0.4%) and 0.4 km/h (0.5%) in the BLB and German Highway cycles respectively. This is because the Ecoroll function allows a 5 km/h deviation from the desired speed while coasting.

The maximum speed error was found to be 13 km/h for the BLB cycle and 16 km/h for the German Highway cycle. The vehicle speed error percentage was about 3% more for the German Highway cycle than the BLB cycle. This is because German Highway is a more demanding cycle, as it involves complete stops as well as more altitude changes. Electrification of the dolly has led to a decrease in the vehicle speed error percentage by 2.5% and 3.8% in the BLB and German Highway cycle. Also, activation of the Ecoroll function has led to an increase in the vehicle speed error percentage by about 1% in both cycles, as it allows for more variation from the target speed.

The number of gearshifts has increased by 58% and 40% for the BLB and German Highway cycles due to activation of Ecoroll. This is because Ecoroll causes the transmission to shift from the current gear to the neutral gear in order to reduce inertia and enable coasting. Electrification has not caused any significant increase in number of gearshifts in the BLB cycle, but has led to an increase of 20% in the German Highway cycle. This could be because German Highway is a much longer cycle, and a long duration is required to observe this effect. Interestingly, Concept 2 has recorded the least number of gearshifts in the BLB cycle and the highest number of gearshifts in the German Highway cycle.

10.1.5 Comparison with 32ton conventional truck

A comparison of fuel consumption and performance has been done between the 60 ton hybrid models with a 32 ton conventional truck. The reason for this is that the purpose of electrification of the truck is to increase the cargo carrying capability of the truck from 32 to 60tons, and to reduce the amount of fuel consumed per mass of cargo transported. A direct comparison in terms of l/100km has not been carried out, as it is evidently much higher for a 60ton truck than a 32 ton one.

It was found that the amount of fuel consumed per mass of cargo transported has decreased by 22.3% and 22.1% for the BLB and German Highway cycles respectively. This translates to a monetary fuel cost saving of 4.5 SEK/kg of cargo and 29.6 SEK/kg of cargo for the BLB and German Highway cycles respectively. Concept 4 provides the highest savings and Concept 1 the lowest for both cycles. Also, it must be noted that the average fuel savings are higher for the BLB cycle over all concepts, but the German Highway cycle provides the maximum fuel saving percentage [13].

Regarding performance, it was found that the vehicle speed error percentage was 6.9% and 8.9% higher in case of the 60ton hybrid vehicle than the 32ton conventional vehicle for the BLB and German Highway cycles respectively. The maximum speed error is 13 km/h and 16 km/h for the 60ton hybrid, as compared to only 6km/h and 11km/h for the 32ton conventional model in the BLB and German Highway driving routes correspondingly. Hence it is evident that the performance and drivability has been compromised in the 60ton hybrid concepts as compared to the 32ton conventional due to the addition of extra payload. The average speed has also dropped, by 2.7 km/h (3.2%) and 3.9km/h (4.7%) for the 60ton hybrid as compared to the 32ton conventional for the BLB and German Highway cycles respectively. This translates to an extra 2 minutes (3.3%) spent to complete the BLB transport mission, and an additional 21 minutes (5%) to complete the German Highway route. This time delay due to reduced performance could lead to significant increase in labour and logistical costs which should be accounted for when a cost-benefit analysis is made.

10.2 Lateral Simulations

10.2.1 High Speed Turn

The maximum lateral acceleration of the cab in Concept 1 is about 0.2g, which was the desired value. However, it is observed that when the same maneuver is performed with the conventional model, the lateral acceleration is higher than 0.2g.

The High speed steady-state offtracking value was higher than the acceptable value according to the PBC requirements for both the conventional model and Concept 1. It was also observed that the HSSO for Concept 1 (0.7472m) was 6% lower than the conventional model (0.7034m).

The radius of the high speed turn should be within 319m for a 0.2g turn according to the PBC requirements. However, it was higher than that value for both Concept 1 and the conventional model. The radius was about 25m smaller for Concept 1 than the conventional model.

Thus it can be stated that the hybrid Concept 1 model is more stable in the High Speed Turn maneuver as it has a lower lateral acceleration and lower HSSO than the conventional model. It also has a smaller turn radius than the conventional for the same speed and steering input.

10.2.2 High Speed Lane Change

It is observed that the lateral acceleration of Concept 1 is exactly 0.2g, as the steering input was set in order to reach this value. However, the conventional model has a higher maximum lateral acceleration for the same steering input and frequency, i.e. about 0.25g.

The High Speed Transient Offtracking values for both models are much higher than the acceptable value according to the guidelines. It must be observed that the HSTO value for the conventional model is more than 3 times that of Concept 1.

Hence it can be stated that Concept 1 is much more stable than the conventional vehicle in this High Speed Lane Change maneuver, as it has a lower maximum lateral acceleration and HSTO value for the same steering input and longitudinal velocity.

10.2.3 Low Speed Roundabout Maneuver

The maximum articulation angle value of the conventional vehicle is slightly higher than 45 degrees, and is hence at the limit of acceptance according to the guidelines. However, the articulation angle for Concept 1 and 2 is considerably lower than the conventional vehicle (about 42 degrees for both) and thus within the acceptable limit of 45 degrees. It is interesting to note that there is no significant difference between the maximum articulation angle of Concept 1 and Concept 2, despite the fact that Concept 1 has a single driven axle and Concept 2 has two driven axles. Also, it can be stated that hybridization has led to a decrease in articulation angle for this low speed maneuver. However, the reason for these findings must be determined by further investigation of how the torque affects the vehicle dynamics in this manner.

The swept path width is within the acceptable limit for both the conventional vehicle and hybrid concepts. The swept path width for Concept 1 and 2 is significantly lower

(1.35m lower) than the conventional vehicle. Also, the outer path of both the conventional and hybrid vehicles was about the same for all (~11.25m) and well within the acceptable value of 12.5m. Hence it can be stated that hybridization of the combination leads to a lower footprint of the vehicle during a low speed turn around a roundabout.

10.2.4 Custom Roundabout Maneuver

It was observed that the maximum lateral acceleration of the cab is much higher for the conventional vehicle than the hybrid concepts, as it peaks to a value of about 0.57g, whereas the maximum value is only about 0.47g for Concept 1 and 2. A similar difference of about 0.1g between the hybrid and conventional vehicles is observed in the maximum lateral acceleration of the second semitrailer. The maximum value is about 0.3g for the hybrid concepts, whereas it is about 0.4g for the conventional vehicle.

The articulation angle however is lesser in the case of the conventional vehicle than the hybrid concepts. It has a maximum value of about 31 degrees for Concept 1 and 2, whereas the maximum value for the conventional vehicle is about 26 degrees. This could be attributed to the ‘jack-knifing effect’ that is caused by having propulsion from a rearward axle while negotiating a U-turn around a roundabout.

11 Conclusions

The Concept 4 electric dolly with Predictive HCU (with Ecoroll) is the final recommendation based on the fact that it provides maximum fuel saving potential. However, Concept 3 is the most cost effective solution since it has the least components and it provides nearly the same reduction in fuel consumption.

Further discussions and findings from the results on different aspects of longitudinal and lateral simulations have been summarized below. Regarding the fuel consumption of the vehicle, the main conclusions that have been drawn are:

- Predictive HCU with Ecoroll functionality has provided the least fuel consumption.
- The Lookahead+sailing control strategy resulted in an increase in fuel consumption as compared to the base HCU. The look-ahead distance parameter needs to be optimized for each driving route in order to achieve better results. The sailing feature caused too frequent interruptions to torque flow through the clutch, hence reduced fuel efficiency and drivability.
- Concept 4, i.e. the model with 2 EM’s and a 2 speed gearbox connected between each EM and axle provided the best fuel savings (14.2% & 16.4%) for both the BLB and German Highway cycle.
- The replacement of a direct gear reduction with a 2 speed gearbox for the EM resulted in a significant decrease in fuel consumption (~2%).
- The addition of an extra EM has not led to considerable fuel savings (only ~0.2%). This is because the EM’s were limited by the maximum power discharge limit of the ESS. Hence a higher power capacity ESS or an additional ESS of the same capacity is required in order to utilize the additional EM.
- An EM final gear ratio of 5 turned out to be the most optimal option for both the BLB and German Highway cycles from the list of available final gear ratios in the inventory.
- All the hybrid concepts provided lower fuel consumption values for the German Highway cycle than the BLB cycle. This can be attributed to the more frequent altitude changes and the presence of complete stops in the German Highway driving route.

Regarding energy throughput, the main conclusions were:

- The maximum energy throughput value was for Concept 4 in the German Highway cycle, with a value of 36 kWh/h. This is much lower than the recommended maximum limit of 45 kWh/h, and hence it can be concluded that the electrification implemented will not lead to abnormal degradation of the ESS for the two driving routes that have been tested.
- The energy throughput values were about 40% higher for the German Highway cycle than the BLB cycle, which can be explained by the stops and more frequent altitude variations in this cycle.

Regarding the amount of energy regenerated, the main conclusions were:

- The amount of energy regenerated per hour was 30% more in the German Highway cycle than the BLB cycle.
- The replacement of the EM final gear reduction with a 2 speed gearbox led to an increase in the amount of energy regenerated per hour of up to 40%.

- The addition of an EM led to a maximum increase of 35% in the amount of regenerated energy per hour.

The main conclusions derived related to vehicle performance and drivability were:

- Electrification of the dolly led to an increase in average speed of 1 km/h (1.2%) and 1.75km/h (2.25%) in the BLB and German Highway cycles respectively.
- The maximum speed error at any instance was determined to be 13 km/h for the BLB route and 16 km/h for the German Highway route.
- The percentage of time when the vehicle exceeds a speed error of 5 km/h was found to be 3% more in the German Highway cycle than the BLB cycle.
- Electrification of the dolly has led to a decrease in the vehicle speed error percentage of up to 2.5% and 3.8% in the BLB and German Highway driving routes respectively.
- Electrification has not caused any significant increase in number of gearshifts in the BLB cycle, but has led to an increase of 20% in the German Highway cycle.
- Activation of Ecoroll caused a decrease in average speed of about 0.3 km/h (0.4%) and 0.4km/h (0.5%) in the BLB and German Highway cycles respectively.
- Ecoroll activation has also caused the number of gearshifts to increase by 58% and 40% for the BLB and German Highway cycles respectively.
- Interestingly, Concept 2 has recorded the least number of gearshifts in the BLB cycle and the highest number of gearshifts in the German Highway cycle.

Comparison of the hybrid concept results with that for the 32ton conventional truck has resulted in the following conclusions:

- The amount of fuel consumed per mass of cargo transported has decreased by 22.3% and 22.1% for the BLB and German Highway cycles respectively.
- Taking into account current fuel prices, the monetary fuel cost savings due to dolly electrification have been 4.5 SEK per kg of cargo and 29.6 SEK per kg of cargo for the BLB and German Highway cycles respectively, as compared to the 32ton conventional truck.
- The average fuel savings are higher for the BLB cycle over all concepts, but the German Highway cycle provides the maximum fuel saving percentage.
- Regarding performance, it was found that the vehicle speed error percentage was 6.9% and 8.9% higher in case of the 60ton hybrid vehicle than the 32ton conventional vehicle for the BLB and German Highway cycles respectively.
- The maximum speed error is 13 km/h and 16 km/h for the 60ton hybrid, as compared to only 6km/h and 11km/h for the 32ton conventional truck in the BLB and German Highway cycles correspondingly.
- The average speed has also dropped, by 2.7 km/h (3.2%) and 3.9km/h (4.7%) for the 60ton hybrid as compared to the 32ton conventional truck. This translates to an extra 2 minutes (3.3%) spent to complete the BLB transport mission, and an additional 21 minutes (5%) to complete the German Highway route. This time delay due to reduced performance could lead to significant increase in labour and logistical costs which should be accounted for when a cost-benefit analysis is made.

The following conclusions were derived from the lateral simulations:

- Hybridization has led to an increase in vehicle stability and performance in the high speed maneuvers, i.e. in High Speed Turn and High Speed Lane Change.
- The maximum articulation angle and swept path width has reduced due to electrification of the dolly axle(s) in the Low speed Roundabout Maneuver, thus leading to a smaller vehicle footprint. The torque produced at the dolly axle(s) during the maneuver must be studied in order to determine the reason for this effect of hybridization.
- The hybrid concepts are also more stable in the Custom Roundabout Maneuver, but have a larger articulation angle due to the additional propulsion from the rear.

12 Future Work

- Cost-benefit analysis required for all concepts.
- Updated VTM model with dolly dimensions and steerable dolly.
- Effect of extra electrified axle on vehicle dynamics in high speed maneuvers.
- Effect of 2speed gearbox on vehicle dynamics.
- Optimizing the Look-ahead horizon for the Sailing strategy.
- Improving simulation performance of GSP+VTM models.
- The effect of hybridization on startability and gradeability of the vehicle combination to be studied with simulations on the GSP+VTM models.
- Integrated Control Unit that uses vehicle dynamics data to limit powertrain.

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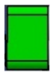
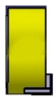
14 Appendices

14.1 Concept Study

14.1.1 Legend

For sections 14.2.2-14.2.5.

	**2 Speed Gearbox**
	**Final Gear Ratio Unit**
	**Electric motor**
	**Energy Storage System**

14.1.2 Concept 1

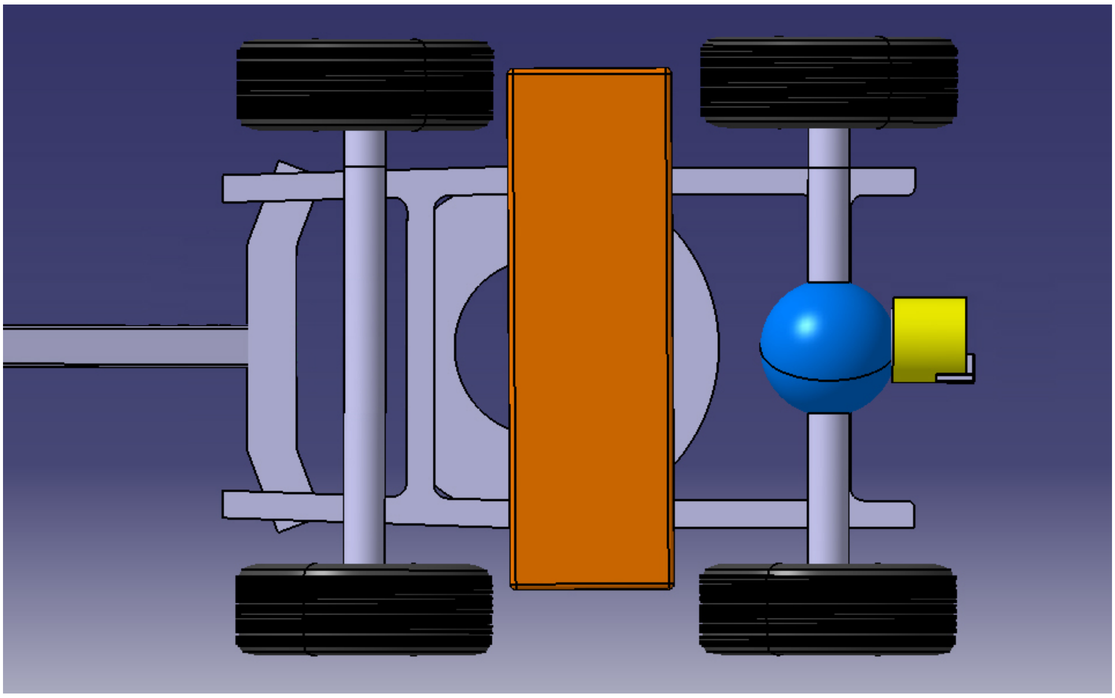


Figure 80: Concept 1 bottom view

14.1.3 Concept 2

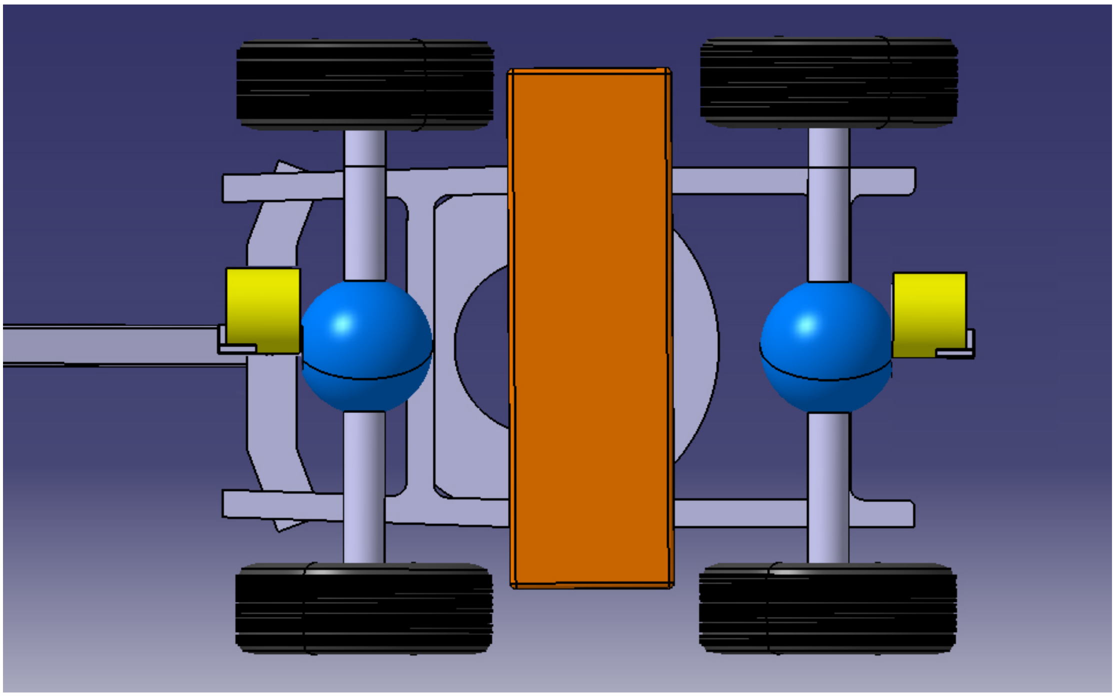


Figure 81: Concept 2 bottom view

14.1.4 Concept 3

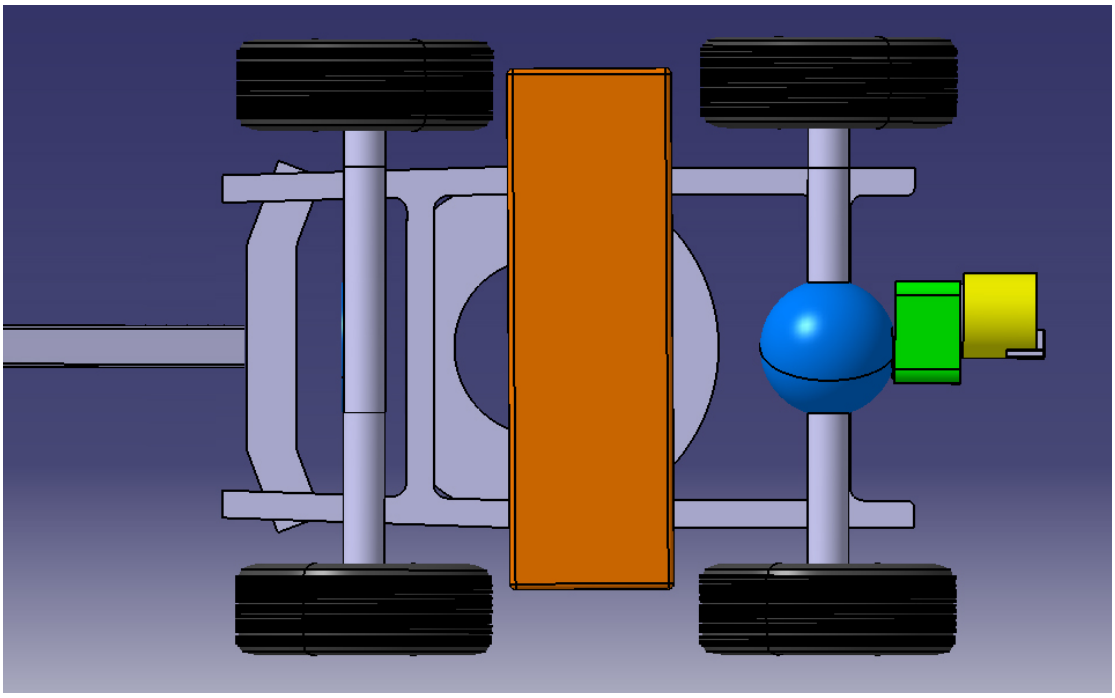


Figure 82: Concept 3 bottom view

14.1.5 Concept 4

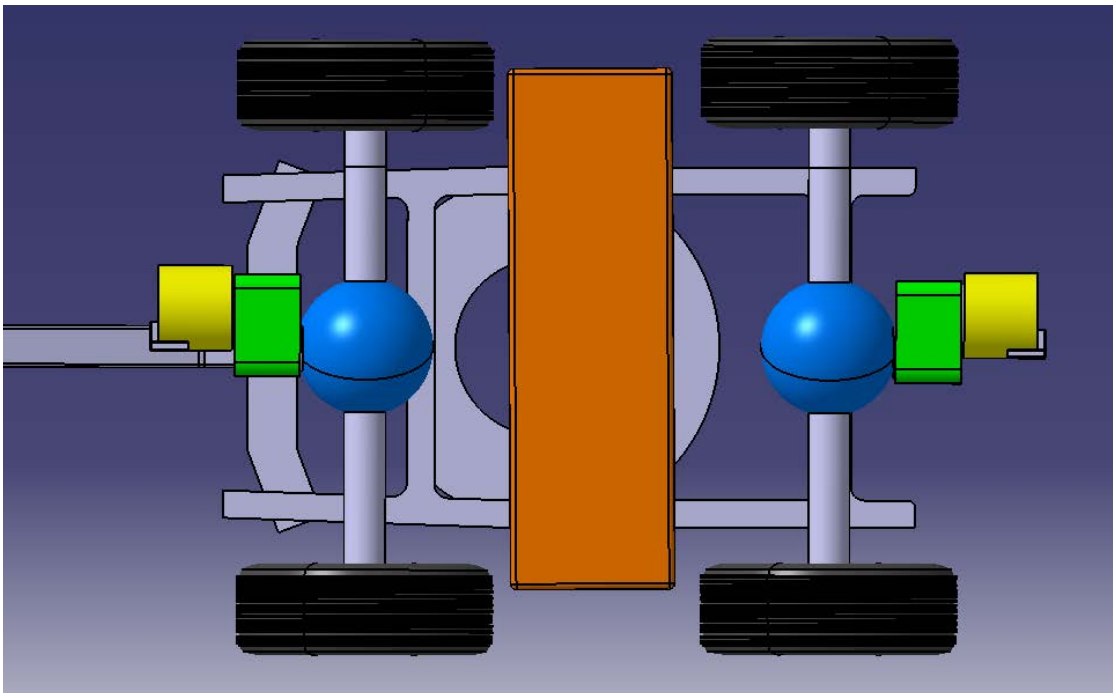


Figure 83: Concept 4 bottom view

14.2 Packaging feasibility study

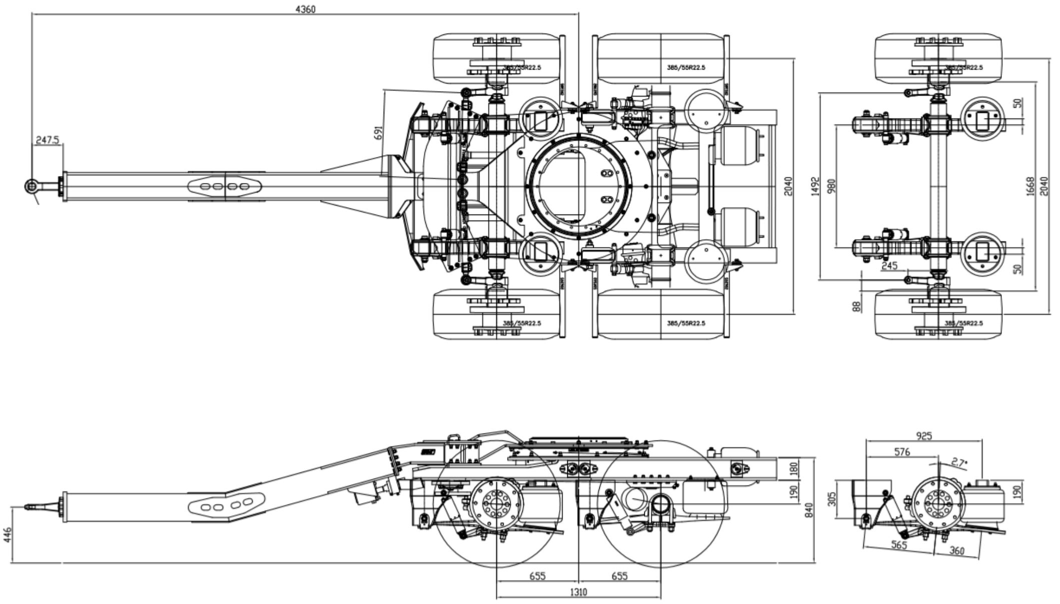


Figure 84: 2D drawing of the dolly

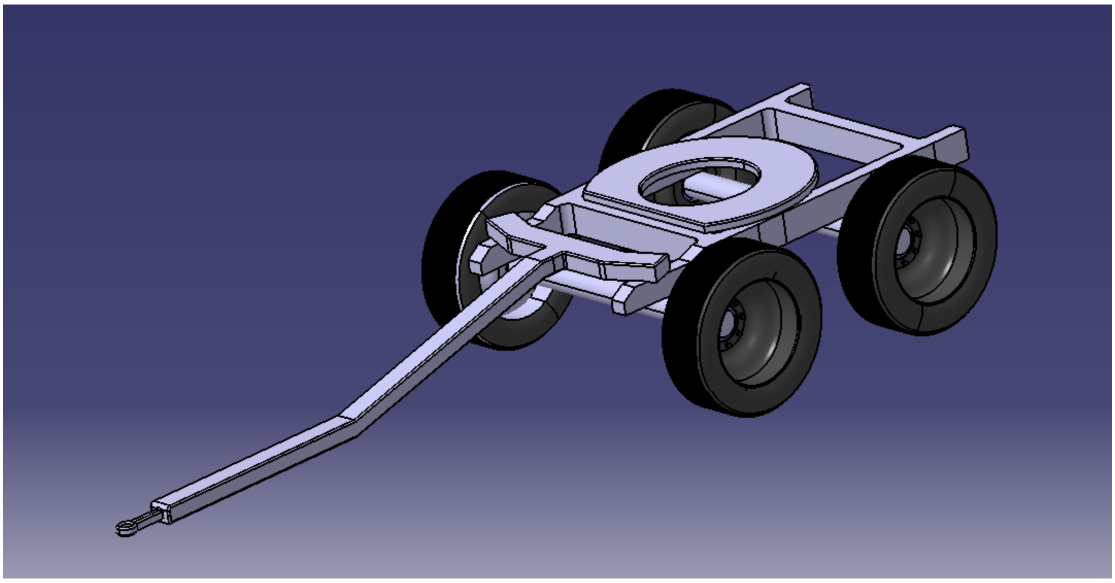


Figure 85: 3D drawing of the dolly using CATIA