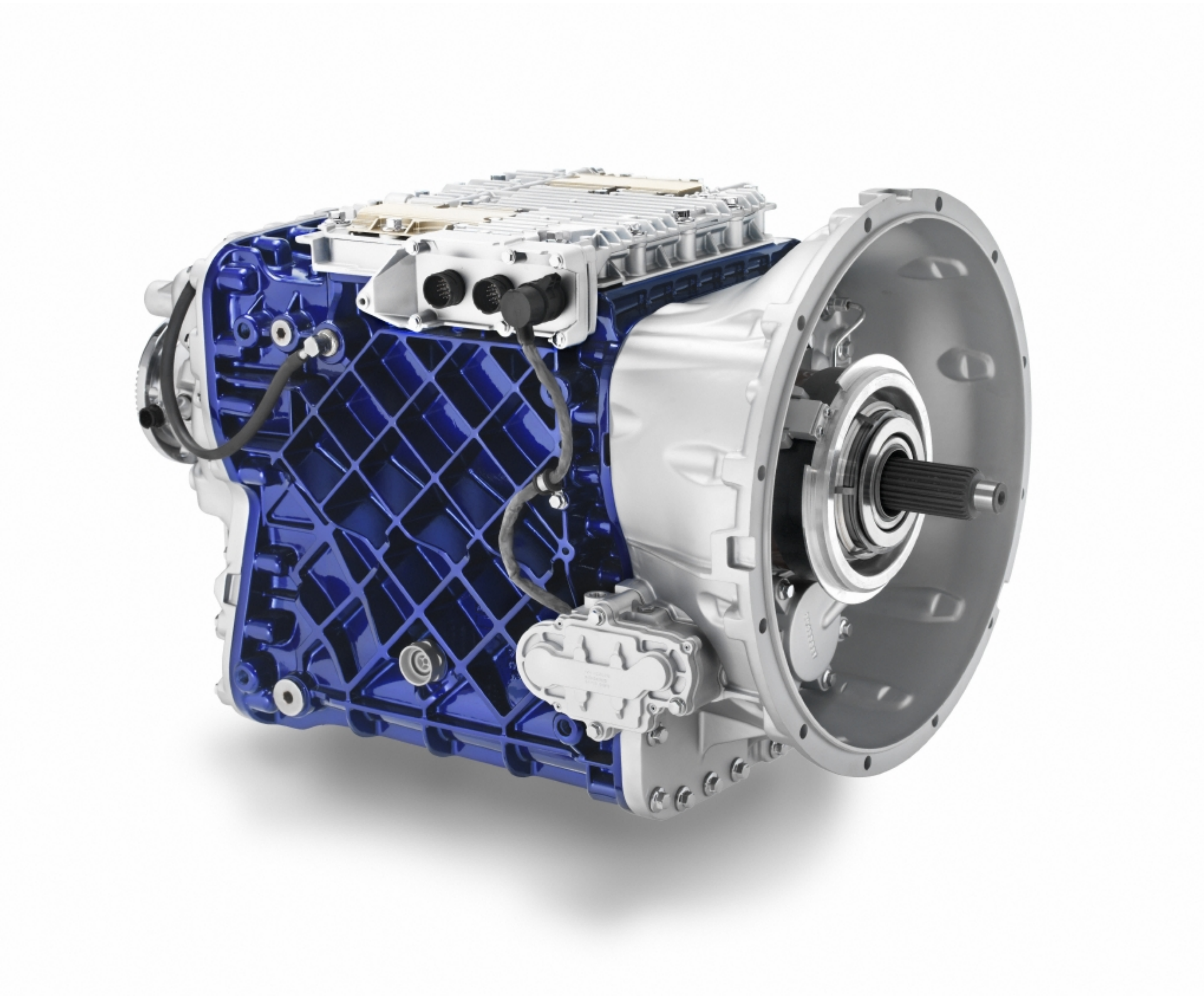

# Fuel Consumption for Gearshifts

Master's thesis in Automotive Engineering

NAREN RAGHAV HANASOGE JAGADEESHA
PRATHEEK SRINATH

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's thesis 2020:07
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Cover:
The image shown is an Automatic Mechanical transmission (AMT), which is popularly known by the name I-shift.

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# Abstract

The thesis work aims to quantify the effects of interesting variables such as engine speed, engine torque, vehicle mass, rear axle ratio, vehicle speed and road inclination on a gearshift event regarding fuel consumption and transport time. The cost of a gearshift is determined for gearshift between gear 11 and 12 in a AMT overdrive transmission. Firstly, the cost was calculated using simulations that are carried out in the Global simulation platform (GSP) by creating a DOE based simulation matrix where all the above mentioned interesting variables are varied.

The results obtained from these simulations are formulated in the form of thumb rules for the cost of a gearshift in terms of interesting variables. These thumb rules will be used to further develop better gear shifting strategies and also to develop further fuel-saving functions.

Secondly, testing on trucks was carried out to measure/estimate the cost of a gearshift. This was done to verify the obtained results from GSP simulations. Since time and resources were limited, the truck test is performed only on certain cases of simulation matrix which were available at the test facility. During truck testing the drive cycle called Borås-Landvetter-Borås cycle is used as this is the most suitable drive cycle which has long stretches of constant road inclination suitable for performing a gearshift at various cruising speeds as that was a requirement.

Keywords: Interesting variables, AMT overdrive transmission, Global simulation platform (GSP), DOE, Thumb rules, Truck testing

# Preface

Looking at the master thesis description published by Volvo for the first time, although it seemed vague for most parts, we understood that we would be working on the state-of-the-art Volvo I-shift transmission controls. Since our goal was to work on our thesis in the area of powertrain controls, it was a perfect fit for us.

Since we were excited about this thesis and wanted to know more about it, we discussed about the description of the thesis work with the one wrote the thesis-proposal at Volvo, Henrik Ryberg. Henrik was kind enough to explain what exactly the thesis work was about and the intricacies involved in it. This helped us to understand it better, only to raise our level of excitement. The fact that we could contribute in the development of intelligent and adaptive fuel saving functions for the Volvo I-shift transmission was the strong motivation for us to work on this particular topic. To add to the excitement, the thesis work also involved testing on trucks, which was a chance to experience things hands-on.

The stipulated amount of time for the completion of the thesis work was 20 weeks. As a result, after consulting supervisors from Volvo and Chalmers, a time-plan was chalked out. Due to various circumstances and reasons, the initial plan had to be modified throughout the process to make sure we were on-track.

This journey of 20 plus weeks of carrying out the master thesis work has taught us a lot. The fact that we had the opportunity to be stationed at Volvo Trucks and work along with the team at Volvo throughout this period on a topic which was near and dear to us has really been a dream come true. We could see and experience how it is like to be part of a multi-cultural team atmosphere working on a common mantra of development of the product. We also had the opportunity to meet, talk and exchange ideas with various people at Volvo and Chalmers which has definitely made us better engineers and human beings.

Good things come with challenges and this thesis work was no exception. There were many challenges that were encountered during this thesis work and we did not shy away from them. We faced each challenge with a positive mindset and we ended up learning valuable lessons each time, no matter what the outcome was. Since we were a team of two people working on the thesis, we believe we complemented and supported each other really well resulting in a smooth sail.

Finally, realizing our dream of working on the development of prowertrain control functions at Volvo and also getting an opportunity to be part of the process of transforming an idea into a product was a really satisfying experience.

# Acknowledgements

We would first like to express our heartfelt gratitude to Ingemar Arvidson, Henrik Ryberg and Robin Karlsson, the people at Volvo Group Trucks Technology who made this master-thesis a reality, giving us the opportunity to work on this thesis and extending their unconditional support during this period.

We have spent a lot of time with our supervisor at Volvo, Henrik Ryberg, engaging in very interesting and thought-provoking discussions from which we have learnt a lot. His expertise and patience to explain things in detail helped us to understand this thesis better. When it came to testing on trucks, his experience and driving skills made us feel testing on trucks was so simple only to realise that was not at all true. We would like extend our special thanks to him.

We would also like to thank Sixten Berglund, Daniel Jern, Manjnath Nagappa, Peter Templin, Jorild Mossljung, Mamadou Diaby, Robert Hjelte Ulmehag, Adam Lagerberg and Andreas Österdahl who are from different teams at Volvo for supporting us throughout and helping us with our questions time and again.

During the course of this thesis, we have had the privilege to visit various facilities of Volvo at Skövde, Volvo Trucks experience center at Torslanda which were exciting. We would like to thank group managers Ingemar Arvidson, Robin Karlsson and Sören Hansen for making this possible.
We wish to express our special thanks to our supervisor at Chalmers, Sven Andersson. His guidance and experience was very valuable to us in making this thesis a success. Also thanks to Jonas Sjöblom, program director of Automotive Engineering at Chalmers for arranging various administrative stuff. Last but not the least, we would like to thank our wonderful families and friends from all over the world who have continuously supported us during this journey making sure our spirits are high at all times.

Naren Raghav Hanasoge Jagadeesha & Pratheek Srinath
Gothenburg, 2019

# Nomenclature

| | |
|---|---|
| **km/h** | kilometer per hour |
| **BLB** | Borås-landvetter-Borås |
| **GSP** | Global Simulation Platform |
| **ATI VISION** | Tool used to log signals in truck |
| **GUI** | Graphic User Interface |
| **TECU** | Transmission Electronic Control Unit |
| **ECU** | Electronic Control Unit |
| **SMT** | Synchronized Mechanical Transmission |
| **APS** | Automatic Power-Shifting Transmission |
| **AMT** | Automatic Mechanical Transmission |
| **AMT-PS** | Automatic Mechanical Transmission Power-Shift |
| **EMS** | Engine Management System |
| **DOE** | Design of Experiments |

Contents

# 1 Introduction

## 1.1 Background

Trucks run in various kinds of road profiles like highways, where the gradients of the roads are not as rough but fairly uniform and smooth when compared to rough terrains like mines and off-road conditions. The torque and speed requirements to propel a huge inertia like truck can vary significantly depending on the kind of road the truck is running on. Because of this significant variation of torque and speed requirements, a gearbox with enough number of gears which can satisfy these requirements is needed since the engine is essentially producing constant power at any particular engine speed or over a range of engine speeds [1][2]. As a consequence of these requirements, a gearbox in a truck usually has 12 to 14 gears. This also means that there are a lot of gearshifts involved between these 12 to 14 gears depending on the torque and speed requirement.

Depending on the type of gearbox involved, every gearshift comes with some loss associated with fuel and time for transport mission. Although these losses are very small in terms of one gearshift, it could be a significant number when looked at in terms of total distance travelled and cumulative number of gearshifts throughout the distance travelled.

### 1.1.1 Losses during a gearshift

This losses due to a gearshift [3][4] associated with fuel and time happens to due reasons listed as follows:

- During a gearshift, depending on the type of gearbox involved, there is power-interruption to wheels for a short period of time because of which the driver demand torque is not met and as a result, the vehicle speed will drop from the desired level.
  To compensate for this drop in vehicle speed following a gearshift, more fuel has to be burnt in order to reach the driver demand torque as soon as possible and ensuring the vehicle speed is reached back to the desired level as well. This additional burning of the fuel because of drop in vehicle speed results in some fuel loss [5].

- Due to the similar reason of drop in vehicle speed during a gearshift due to power-interruption to wheels, there is also a loss in time for the transport mission since the average speed for the transport mission will reduce slightly.

- Depending on the type of engine involved, the engine boost pressure will also reduce slightly during a gearshift and some fuel is lost in gaining back the lost boost pressure.

- Depending on the type of gearbox involved, there will be considerable friction loses in the clutches. This results in fuel loss associated with the friction losses in clutches.

### 1.1.2 Losses in AMT

In an AMT gearbox every time a gearshift happens there is power interruption to the wheels. As a consequence of this, there is power interruption for a short period of time during the gearshift event. During this period, the driver demand torque is not met and hence the vehicle speed will drop from the desired level (depending on the driving mode, this desired level is the cruise control set speed if the cruise control is switched ON or the input from driver pedal if the cruise control is switched OFF).

There are fuel losses due to gearshift [3][4] because the following reasons:

- There is power-interruption to wheels for a short period of time because of which the driver demand torque is not met and as a result, the vehicle speed will drop from the desired level. To compensate for this drop in vehicle speed following a gearshift, more fuel has to be burnt in order to reach the driver demand torque as soon as possible ensuring the vehicle speed is reached back to the desired level and in this duration, the engine runs in less efficient operating points making it to consume more fuel [5][1][2]. This additional burning of the fuel because of drop in vehicle speed results in some fuel loss.

- Due to the similar reason of drop in vehicle speed during a gearshift due to power-interruption to wheels, there is also a loss in time for the transport mission since the average speed for the transport mission will reduce slightly.

- The engine boost pressure will also reduce slightly during a gearshift and some fuel is lost in gaining back the lost boost pressure.

### 1.1.3 Motivation for the thesis work

Since the losses due to gearshift in an AMTPS are being modelled in a fuel saving function, it results in achieving appropriate gearshifts at optimum points of time depending on fuel savings.

The most commonly used gearbox type in heavy trucks in major parts of the world is AMT. So, to improve the gear selection strategy in AMT, resulting in optimum fuel consumption and fuel savings due to gearshifts, the first step is to quantify the losses happening during the gearshift. The losses involved during a gearshift in an AMT are fuel and time losses. Various factors and external variables contributing to these losses needs to be analysed and quantified since the losses in AMT are due to reasons mentioned in the section 1.1.2. The knowledge about losses can also then lead to development of a loss function.

The time losses needs to be examined during every shift and a comparison of fuel and time losses have to be made to understand the relative importance of each of the losses in order to weigh it accordingly.

It is therefore desirable to quantify the losses in an AMT gearbox in terms of fuel consumption and time taken for the transport mission. This will serve as a basis for designing fuel saving functions and to optimize the trade-off between running on most efficient gear and shifting to that gear at a good point. Once these losses are quantified, it can also be used for other purposes which could make the choice of gear selection better.

## 1.2 Objective

The objective of this thesis work is *to quantify the effect of different variables on a gearshift event in terms of simple rules-of-thumb regarding fuel consumption and time for transport mission.*

Examples of different variables are *road inclination, vehicle weight, engine speed, engine torque, etc.*

## 1.3 Deliverables

At the conclusion of this thesis work, the deliverables that are expected are as follows:

- Formulating simple rules-of-thumb by simplifying the existing simulation models on how different variables influence on a gearshift event regarding fuel consumption and time for transport mission.

- Summarizing report with recommendations.

As stated in the section 1.1.2, these deliverables will be used to improve the gear selection strategy and in the development of the AMT software.

## 1.4 Limitations

To limit the scope of this thesis work, the study has been carried out on certain specifications of components and some boundaries have also been imposed, such as:

- A 12-speed AMT overdrive gearbox is considered.

- A 16-liter EURO-6 Step D, Diesel engine truck is focused on, since it is the most commonly found engine with a 12-speed AMT overdrive gearbox.

- The focus is narrowed down only to the shift between the two highest gears (up-shift 11 to 12 and downshift 12 to 11 in this case), since these are the most oftenly occurring shifts during transport missions.
- For simplifying the analysis, only the road inclination's lower than that the vehicle speed can be maintained on both gear 11 and gear 12 is considered.

## 1.5 Work Procedure

An analytical approach was followed in the execution of this thesis work. The problem statement was broken down and divided into smaller stages and each stage was executed one by one as:

- ***Understanding the background of the thesis work:***

  In this phase, stress was laid upon reading the theory and concepts needed to get an in-depth understanding about the thesis work. Various literature's were studied for familiarization of many concepts, discussions and meetings with engineers and developers responsible for different products at Volvo helped in getting first hand information of many theories and ideas.

- ***Introduction to simulation platform and other tools:***

  Since the study required evaluation in the simulation platform *Global Simulation Platform (GSP)* based in Matlab/Simulink, it was important to have a good grip over GSP and the theory behind it. Reading documentation about GSP and attending some training's within Volvo helped to achieve this.

- ***Evaluation of the problem in simulation platform:***

  The evaluation of the study was done in the simulation platform, *'GSP'*, by setting up various simulation cases using design of experiments which resulted in reaching important conclusions.

- ***Evaluation of the problem by measurement in truck testing on-road:***

  The evaluation of the study was also carried out by measuring interesting signals on-road by testing in a truck. This process was carried out in order to make an attempt to verify the simulation results and to find out if that could be done by measurement in a truck.

- ***Evaluation of on-road test results and comparison:***

  The measurements obtained from the on-road tests were evaluated and compared with the results from simulation. Some important conclusions were made by this comparison.

# 2 Theory

## 2.1 Types of truck configuration

In this thesis work, the focus is to understand the effect of different variables on gearshift event, mass being one of them which has been varied according to the standards variants usually considered for various function development work also keeping legal limits in mind. The different types of truck configurations which are interesting for the thesis work are,

1. Tractor
2. Rigid truck
3. Rigid truck with light trailer
4. Rigid truck with heavy trailer

### 2.1.1 Tractor

A tractor is nothing but a prime mover which generates the power required for the vehicle to move which consist of powertrain and a cabin for the driver to manoeuvre or control the vehicle as shown in figure 2.1, a configuration of 8 x 4 is chosen which means out of 8 wheels 4 are powered. The overall mass of the tractor is 12000 kg which is one of the interesting variables considered which affects the fuel and time loss.

Figure 2.1: Volvo 8x4 tractor

### 2.1.2 Rigid truck

The name itself suggests that the tractor and trailer are one solid unit without any articulation point between the two, the rigid truck is capable of carrying a mass of 32000 kg. The configuration for the rigid truck is also 8x4 which can seen in figure 2.2,

Figure 2.2: Volvo 8x4 Rigid truck

### 2.1.3 Rigid truck with light/heavy trailer

Since the legal limit in Sweden for heavy vehicles is more than 32000 kg an additional trailer can be used to increase the load-carrying capacity, depending on the requirements a light trailer of 22000 kg or a heavy trailer of 32000 kg can be attached. These two different masses are common so in this thesis work, two different masses 54000 kg and 64000 kg are considered. The truck with trailer is shown in figure 2.3,

Figure 2.3: Volvo 8x4 Rigid truck with light/heavy trailer

## 2.2 Engine specifications

The specifications of the engine selected for this thesis work is listed in this section. Also, a typical engine with these specifications used in a Volvo truck is shown in figure 2.4.

- Displacement - 16000 cc
- Number of cylinders - 6
- Emission standard - EURO 6 step D
- Torque - 3500 Nm
- Power - 750 Hp

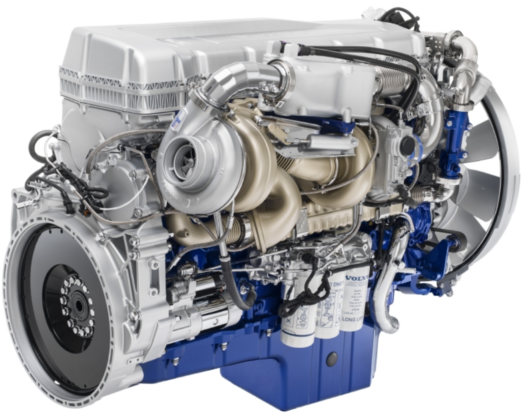

Figure 2.4: D-16 Euro 6 STEP D Engine

## 2.3 Types of Transmissions

There are different types of transmissions available at Volvo depending on the application,

1. Synchronized Mechanical Transmission (SMT)
2. Automatic Power-Shifting Transmission (APS)
3. Automatic mechanical transmission (AMT)
4. Automatic mechanical transmission power-shift (AMT-PS)

Nowadays, to have better fuel economy and reduce the carbon footprint on the environment the automatic transmissions are widely used where the operation can be controlled by the transmission electronic control unit (TECU). Various functions are being developed to improve the performance by using the latest technology to understand the road profile and run the vehicle in the best possible way to save fuel.

### 2.3.1 Synchronized Mechanical Transmission (SMT)

This gearbox has a wide range of gear ratios and well-balanced shift increments. This provides excellent starting traction while also permitting high average speeds. These type of gearbox is used to carry heavy loads up to 100 tonnes and a max torque of 2400 Nm. The robust design and longer oil change intervals reduce the operating costs and have a less environmental impact. The transmission is shown in the figure 2.5.

Figure 2.5: Synchronized Mechanical Transmission (SMT)

### 2.3.2 Automatic Power-Shifting Transmission (APS)

This transmission is also known by the name Powertronic. This gearbox is specially developed for heavy transport operations as it offers smooth, gentle gear changes without any interruption in power delivery and permits safe starts even in difficult conditions. This makes it ideal for demanding construction applications and urban transportation duties characterized by frequent stop-start driving. This is gearbox is capable of locking in all gears the figure 2.6 show the APS transmission.

Figure 2.6: Automatic Power-Shifting Transmission (APS)

### 2.3.3 Automatic Mechanical Transmission (AMT)

This is a most popular and widely used transmission at Volvo which is also known popularly by the name I-shift where I stands for Intelligent shift, this explains how to advance the transmission electronic control unit (TECU) is developed which has various functions. I-Shift is characterized by a fast gear changing system featuring minimum interruption in torque delivery during gear changing. Because the gearbox has such a large ratio span, it has the capacity for both high starting traction and high average speeds. I-Shift has advanced software with well-adapted gear change strategies.

The AMT transmission is shown in the figures 2.7 and 2.9. This transmission is capable of handling gross weight combination of 60 tonnes and capable of handling higher weights for certain application, manual gear changing and locking at different gear promotes higher driving flexibility also with 12 forward gears and 4 reverse gear it is suitable to transport applications in all segments, including special applications such as heavy haulage, refuse trucks and refrigerator trucks.

Figure 2.7: Automatic Mechanical Transmission (AMT)

### 2.3.4 Automatic mechanical transmission power-shift (AMT-PS)

The first dual-clutch transmission for a heavy-duty truck which is also called I-shift Dual clutch. With Dual Clutch there is a smooth and fast gear changing without torque and power loss giving an extremely good driving comfort, a unique and fast gear changing system called power-shift makes it possible to perform most single-step shifts with no interruptions in power and torque delivery during a gear change. The large ratio coverage of the gearbox provides high starting traction and low fuel consumption. The advanced software has well-adapted gear change strategies. I-Shift Dual Clutch handles up to 60 tonnes of gross combination weight and can handle higher weights for certain applications, the transmission is as shown in figures 2.8 and 2.10.

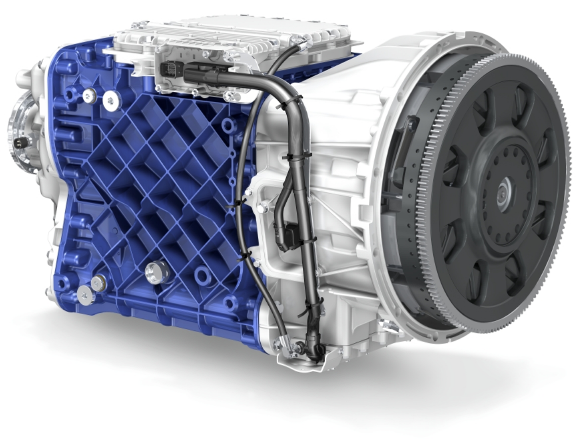

Figure 2.8: Automatic mechanical transmission power-shift (AMT-PS)

## 2.4 Comparison between with AMT and AMT-PS

The main difference between AMT and AMT-PS is the presence of dual-clutch in AMT-PS which helps it in smooth transitions between gear changes without any loss of power or torque to the wheels which makes the driving experience more comfortable. In AMT there is always an interruption of power to the wheels for a short duration which causes the speed to drop, so after every gearshift there is an additional fuel burnt to regain the speed which was before the gearshift event.

To have a deeper understanding, the advantages and dis-advantages for both AMT and AMT-PS are listed in the table 2.4

Figure 2.9: AMT

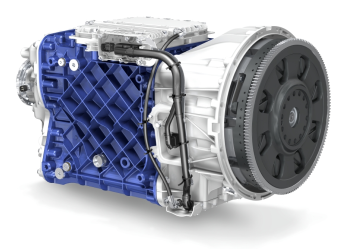

Figure 2.10: AMT-PS

| Automatic Mechanical Transmission (AMT) | Automatic Mechanical Transmission Power - Shift (AMT-PS) |
|---|---|
| There is an interruption of torque and power to the wheel during gear changes, which compromises the smoothness of the ride and experience to the driver. | Smooth ride experience and faster gear changes without any torque and power loss to the wheel, giving an extremely good driving comfort. |
| When a gear change is made without any loss in power to the power-shifting but it is not possible due to a single clutch. | Power-shifting is the main take away from this transmission due to the presence of two clutches, but skip shifts cannot be power-shift. |
| The construction of this transmission is simple as there is only one clutch. | Sue to the presence of two clutches the complexity increases. |
| The cost is comparatively low. | The cost increases as this is more advanced and complex. |
| During every gearshift, there is loss in vehicle speed and time. | There will be some frictional loss during a gearshift in AMT-PS. |

Table 2.1: Comparison between AMT and AMT-PS

## 2.5 Real truck driving Experience

Since the advantages and operation of AMT and AMT-PS are completely understood, the power interruption between gearshifts in AMT and power shift in AMT-PS have to experienced practically in order to have a better idea. Two different trucks, one with AMT and another with AMT-PS transmission were driven in the BLB driving cycle. During the journey in the truck with AMT, there were many instances where the gearshifts can easily be distinguished as the speed of the vehicle will drop due to power interruption. When the truck with AMT-PS was driven, better comparison could be made as the gear changes were seamless and the driving experience was smooth since the power from the engine was uninterrupted during gear shifts.

After the practical driving experience of both the trucks, one can observe the power interruption in AMT leading to speed drop which has a significant effect on the fuel consumption because when there is vehicle speed drop, additional fuel is burnt to regain the the vehicle speed. A better gear shifting strategy can be developed if the amount of fuel lost during gearshifts and amount of fuel saved by running on the upcoming gear is known.

## 2.6 Gear selector

The gear selector [6] in Volvo truck is attached to the driver's seat and can be folded away to aid passage but only when transmission is in neutral. The gear selector inhibitor prevents unintentional gearshifts, the gear selector has four positions,

- R - Reverse
- N - Neutral
- A - Automatic
- M - Manual

The E/P (Economy/Performance) button is used when higher engine speed is required between gear changes. The system returns to economy mode when the performance program is no longer required. Gearshift can inhibited but pressing and holding the inhibitor switch, the vehicle can be driven in manual mode but the number of gearshifts allowed is indicated by the arrows in the display. The gear selector used in Volvo tucks is shown in figure 2.11.


Figure 2.11: I-shift Gear selector

## 2.7 Vision tool

During truck testing on real roads, signals from various ECU's are monitored using a tool called Vision. Various signals required for the thesis work are selected in Vision which can be seen live when the vehicle is being driven. Using this, the gearshift can be made at the required distance from the reference point in the drive cycle as per the shift plan. Also, the data saved during the test run can be analysed again in vision.

## 2.8 Various signals monitored

There are various signals monitored during simulations in GSP environment and some of the important signals are explained in brief,

1. **Transmission shift in process:**
   This signal is used to identify an ongoing gearshift which is indicated by the number 1, which can be seen in the figure 2.12.

2. **Speed Request:**
   This signal exists only during a gearshift that is when TECU controls the engine instead of EMS, a request is made by TECU to increase the engine speed during an up-shift in a standard AMT to match the upcoming gear speed.

3. **Torque Request:**
   This is signal gives information to the engine during the gearshift sequence as how much torque has to generated based on the road inclination and driver demand, the signal is expressed always as percentage of Indicated torque.

4. **Torque speed request mode:**
   This is signal helps to identify the request made by TECU to the Engine during gearshift sequence where,

- 1 - Indicates Speed Request
- 2 - Indicates Torque ramp down
- 3 - Indicates Torque ramp up

## 2.9 Gearshift sequence

The gearshift is indicated by the signal called transmission shift in process which turns 1 indicating that TECU is controlling the engine until the end of gearshift sequence. The gearshift sequence for a up-shift is further broken down into three phases which are,

1. **Engine torque ramp down:**
   In this phase the TECU controls the engine and reduces the generated engine torque to zero by controlling the amount of fuel injected, this phase is indicated by the number 2 in transmission request mode signal. The figure 2.13 shows the indicated torque in percentage being dropped to zero towards the end of this phase. Also, note that the clutch is completely closed in this phase.

2. **Engine speed request:**
   This phase exists only during an up-shift where the engine speed has to be increased to match the upcoming gear speed. After the torque ramp down phase is complete the indicated torque is zero and now the clutch starts to disengage. The desired engine speed is obtained, the engine speed varies for various gears and by changing the fuel-injected or by using engine and counter shaft brakes the requested engine speed is achieved. This phase is indicated by number 1 in the figure 2.13 and the secondary y-axis indicates the requested engine speed by TECU.

   Note: The clutch starts to disengage in the torque ramp down phase as per the figure 2.12, this is due to a minor error in the signal obtained.

3. **Engine torque ramp up:**
   After the desired engine speed is achieved the gearshift is made, which is followed by engaging the clutch. The engine torque is increased as per the driver demand, this phase is indicated by number 3 in the figure 2.13. During these three phases the vehicle speed drops which is quite certain in a standard AMT.

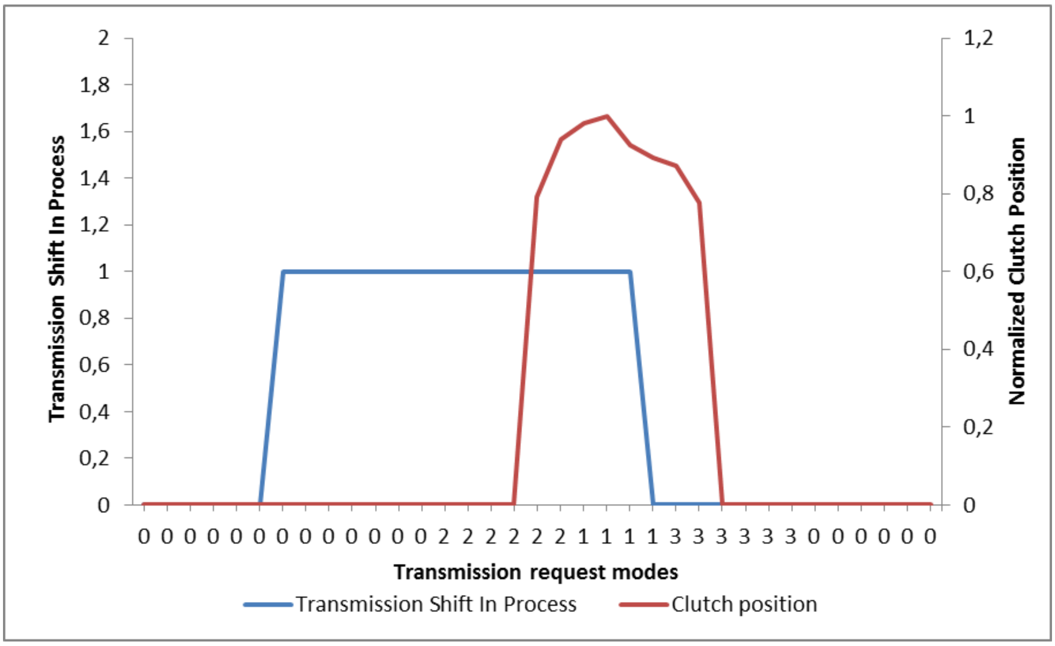


Figure 2.12: Transmission shift in process for up-shift

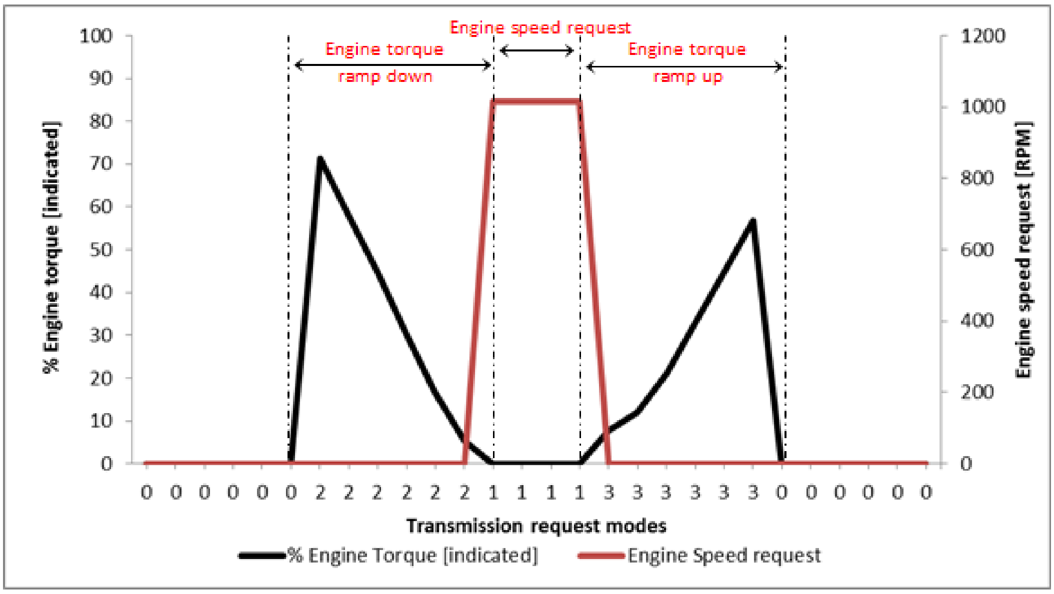


Figure 2.13: Gearshift sequence for up-shift

## 2.10 Driving cycle

The most commonly used driving cycle at Volvo is the Borås-Landvetter-Borås cycle (BLB cycle) as it has some of constant inclination road stretch suitable for the thesis work. As the thumb rules are formulated by simulating for different variables such as vehicle mass, rear axle ratio, vehicle speed and road inclinations which have to be verified. To verify the results tests on real roads are conducted, to perform the test in BLB cycle various road inclinations are filtered and since this is a real road it is quite hard to find a perfect constant inclination stretch so a tolerance band for inclination had to be defined and the inclination should be within the band for a minimum of 10 seconds for a gearshift to take place and vehicle speed to return to the set speed.

Based on the following conditions the entire BLB cycle [2.14] is filtered using a Matlab code to generate the stretches of constant inclinations which forms the shift plan, using the shift plan gearshifts are made and the data from the vehicle is analysed using Vision.

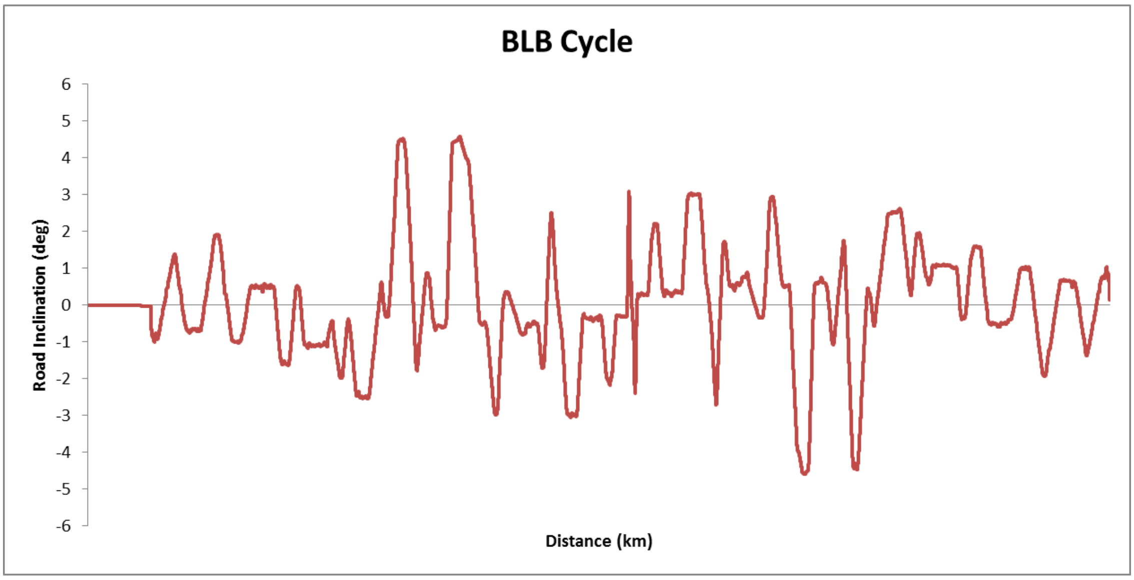


Figure 2.14: Borås-Landvetter-Borås drive cycle

## 2.11 Global Simulation Platform (GSP)

The Global Simulation Platform is a library of simulink models that Volvo has developed. This was used as the tool for simulation in this thesis work.

The GSP is a forward calculating model, meaning that as the name suggests, forward calculating model always looks ahead from the ”trucks perspective” and is operating in real-time. It is exactly how the truck is operating in real life. The control system receives data from sensors and is later sending data to actuators which execute a “physical” action. In a model like this, it is possible to include software in the loop (SIL), since the events in the simulation environment will occur and be controlled just as they are when the software is used in the truck. This will however make the model more computationally heavy.

Whereas, a backward calculating model is not controlled of what lies ahead in time, from the perspective of the truck, instead it already has all the information about what is about to happen. So let’s say that we know that the truck will approach an uphill of a certain inclination after a certain distance. Then the model will use the altitude of the hill and where the hill starts in order to determine how much torque the engine needs and when that torque needs to be applied. This means that a back calculating model is not simulating a real-time event, and therefore it is not possible to run a SIL-simulation with such a model. These models are however usually faster than a forward calculating model.

If there is a transport mission with a particular drive cycle, in a forward calculating model, it is possible to simulate the vehicle actively, meaning the desired speed can be demanded via the driver (accelerator pedal) at each instant, whereas in a backward calculating model, the desired speed at each instant need to be input before the simulation and cannot be controlled actively during the simulation.

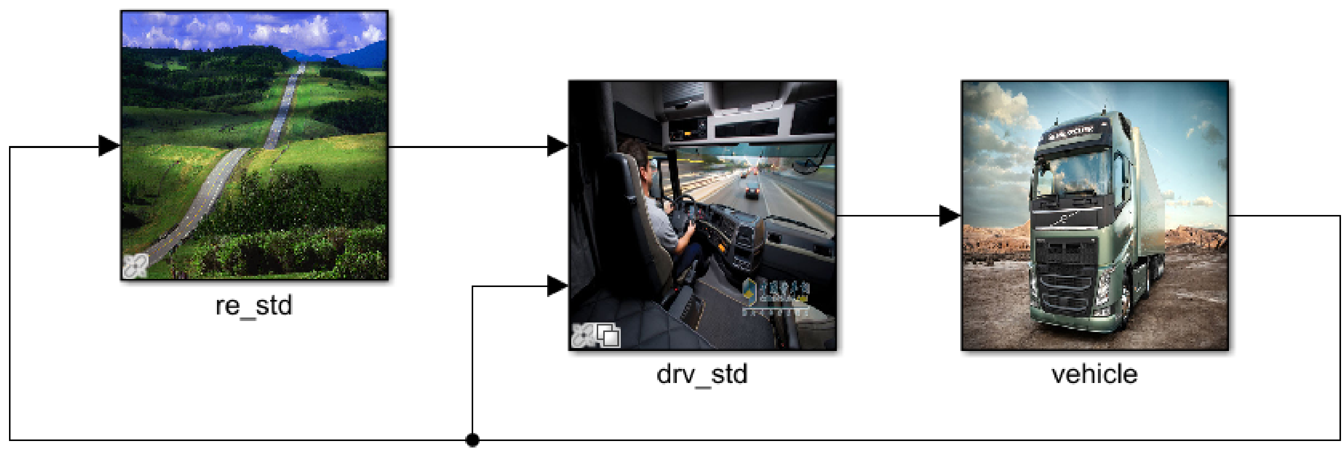


Figure 2.15: Global simulation platform (GSP)

The GSP essentially consists of three main models as shown in the figure 2.15:

1. Road model [re_std]
2. Driver model [drv_std]
3. Vehicle model [vehicle]

The road model consists of the road details the vehicle needs to be simulated on and also the environment details such as properties of the surrounding air, etc. The driver model consists of the driver input to the vehicle like the gear lever input, accelerator pedal, brake pedal and various other inputs. Finally, most importantly, the vehicle model consists of the models of all the powertrain, drivetrain and chassis components.

Since GSP is a forward calculating model, SIL models can be used here. In this thesis work, since the focus was more on engine and transmission, SIL models were initially used for both engine and transmission. The SIL models for engine and transmission were called vEMS (virtual engine management system) and vTECU (virtual transmission electronic control unit) respectively. When the SIL models for both engine and transmission was used in the vehicle model, it was observed that some parameters like the engine indicated torque, vehicle speed took a long time to be stable after a gearshift was triggered (indicated by red point in the figure 2.16) which is unusual. Hence, a light engine model which is more stable was instead used throughout the thesis work.

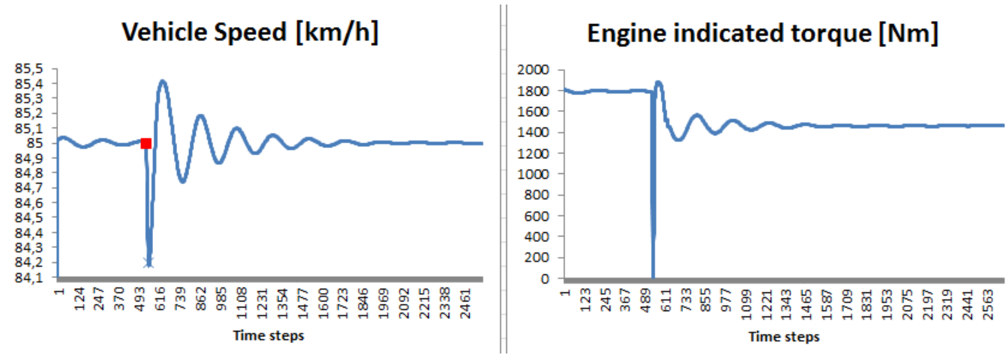


Figure 2.16: Instability of vehicle speed and engine indicated torque after a gearshift is triggered (indicated by red dot)

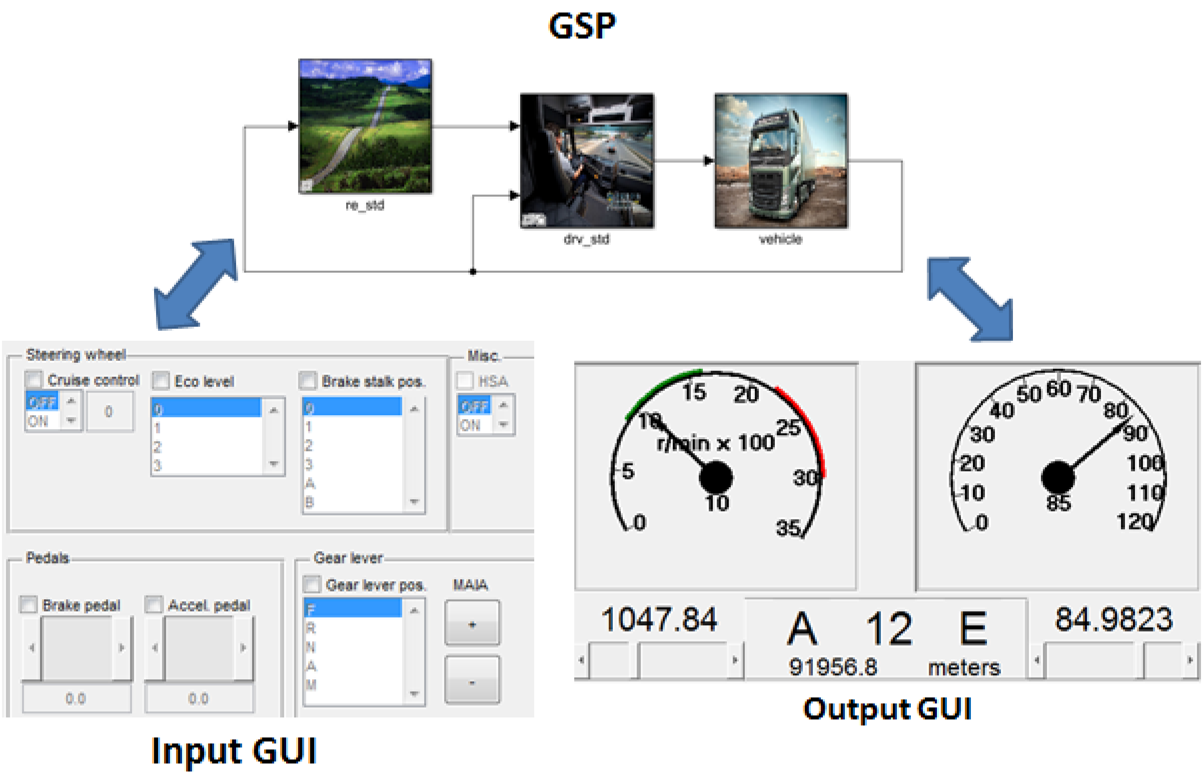


Figure 2.17: Driver GUI integrated with GSP

As shown in the figure 2.17, a driver GUI was integrated with GSP. Using this GUI, various vehicle inputs like accelerator pedal, break pedal, gear position, Eco level etc. could be specified. In this thesis work, this GUI was used to trigger gearshifts. In the output GUI, various outputs like the engine speed, vehicle speed, gear number, etc. could be visualized directly.

# 3 Methodology

With all the insight gained about transmissions and simulation platform we now move on to the actual procedure to estimate the losses in terms of fuel and time during a gear shift in AMT transmission.

## 3.1 Brainstorming of interesting variables

The study begins with analyzing various variables that influence the gearshift in terms of fuel and time. As we know the fuel consumption for an engine is determined by the engine map that has engine speed and engine torque as inputs and fuel consumption values as output.

With this analogy, we can vary the engine speed by varying the cruising speed (up to allowed maximum legal speed) and also changing the rear axle ratio which is discussed in detail section3.1.1. The demand torque or the load on the engine is dependent on how much load it has to carry or in other words, the weight of the truck itself. As the road inclination changes, there will be an additional effect on the weight which is given by the equation,

$$Weight = Mass * gravity * sin(\theta) \tag{3.1}$$

Higher the road inclination higher is the torque demand and during negative inclination, the torque demand falls and the weight itself acts as a driving force. However, tires also play a role in modifying the engine speed but for this thesis work the tires used are 315/80-22.5 (outer radius of 0.522m) which will not be changed throughout.

Since the engine used for the work is turbocharged which gives rise to another parameter that is boost pressure, let us consider a gear shift sequence during which the torque inside the engine falls down as the clutch is disengaged and the fuel mass burnt will also reduce relatively, the boost pressure is dependent on the amount of fuel burnt and variation of the boost pressure will affect the engine's capability, so the effect of this has to be studied in detail.

Finally summing up, all the different variables which need to be studied are,

1. Engine speed
2. Engine torque
3. Vehicle mass
4. Road inclination
5. Rear axle ratio
6. Vehicle speed
7. Boost pressure

To understand the effect of these variable several gear shifts were triggered using the driver GUI model and all these signals were monitored which helped to narrow down the focus only to the variables which have an impact on fuel and time. Each variable is discussed further in detail,

### 3.1.1 Interesting variables in detail

1. Engine speed:
   As the loss in fuel and time is limited to only 11th and 12th gears, the engine runs at different speeds while running on 11th and 12th gear and it varies with different rear axle ratio and cruising speed of the vehicle. The different engine speeds obtained by changing the rear axle and vehicle speed for 11th and 12th are shown in the tables 3.1 and 3.2. The overdrive gear box has lower gear ratio for 12th gear which lowers the engine speed

| Various cases | 11th gear ratio | Rear axle ratio | Vehicle speed (km/h) | Engine speed (RPM) |
|---|---|---|---|---|
| 1 | | 2.85 | 75 | |
| 2 | | 2.85 | 80 | |
| 3 | | 2.85 | 85 | |
| 4 | | 3.09 | 75 | |
| 5 | | 3.09 | 80 | |
| 6 | | 3.09 | 85 | |
| 7 | | 3.4 | 75 | |
| 8 | | 3.4 | 80 | |
| 9 | | 3.4 | 85 | |

Table 3.1: Various cases of Engine speed for 11th gear

| Various cases | 12th gear ratio | Rear axle ratio | Vehicle speed (km/h) | Engine speed (RPM) |
|---|---|---|---|---|
| 1 | | 2.85 | 75 | |
| 2 | | 2.85 | 80 | |
| 3 | | 2.85 | 85 | |
| 4 | | 3.09 | 75 | |
| 5 | | 3.09 | 80 | |
| 6 | | 3.09 | 85 | |
| 7 | | 3.4 | 75 | |
| 8 | | 3.4 | 80 | |
| 9 | | 3.4 | 85 | |

Table 3.2: Various cases of Engine speed for 12th gear

*Note: The values of engine speeds cannot be listed due to confidentiality agreement.*

2. Rear axle ratio:

   In a vehicle the power is transferred from the engine to the wheels through the differential, the differential in the rear axle has a bevel gear which meshes with propeller shaft the gear ratio of this bevel gear or generally referred as rear axle ratio is designed according to the application or customer needs. For a vehicle to have larger torques at wheels higher gear ratios are selected and vice-versa.

   By varying the rear axle ratio the engine speed is altered which affects fuel consumption, so this is one of the interesting variables to look at. In trucks, there are several rear axle ratios available to select. Since the time was limited to perform various experiments with different rear axle ratios, three different rear axle ratios were chosen which would give a good variation of engine speed and thus fuel consumption.

   The tires used for the analysis are discussed in the section 3.1, the different rear axles chosen in the estimation of losses are,

   - 2.85
   - 3.09
   - 3.40

   For a vehicle running at a cruise speed of 80km/h, increasing the rear axle ratio in steps would result in considerable increase in the engine speed as per the relation,

$$Vehiclespeed = \frac{Enginespeed}{Rearaxleratio * gearratio} \tag{3.2}$$

3. Vehicle speed:

   For the thesis work the speeds defined are based on the legal limits and speeds with which other on-road tests are conducted at Volvo. Based on this 80 km/h speed is defined for and the speed of the vehicle cannot be maintained at 80 km/h for heavier trucks during uphill the focus has been widened to a additional vehicle speeds of 85 km/h and 75 km/h. The variation in the engine speed for different gears are accounted in the table 3.2.

4. Engine Torque:

   Engine torque is main variable which affects the fuel and time loss, higher is the engine torque higher is the time required to reach back after a gear shift. Since the demand on the engine is because of the two main variables those are road inclination and vehicle mass which will be discussed in detail further.

5. Vehicle mass:

   When it comes to heavy vehicles like a truck the demand on the engine is mainly due to the vehicle mass due to cargo it is carrying. However, there is a limit to the legally allowed weight and that is 64 Tonnes and truck is not always loaded to its maximum mass so in order to get a complete picture various other masses have been included which are most commonly used by customers in the market. The different masses considered for the thesis work are

   - 12 Tonnes - Tractor without any cargo
   - 32 Tonnes - Rigid truck
   - 54 Tonnes - Rigid truck with a light trailer
   - 64 Tonnes - Rigid truck with a heavy trailer

6. Road inclination:

   To simplify the analysis as it gets complicated if variable inclinations are considered, because then there will be variable demand torque for variable inclinations, and it is difficult to define when the gearshift event end. Engine demand torque depends on the load that varies due to the change in inclination given by the relation,

$$Weight = Mass * gravity * Sin(\theta) \tag{3.3}$$

   Although the road inclination of maximum 6 percent are regarded as good highways [7] but for our analysis the inclinations in which speed cannot be reached back to the set cruising speed after a gearshift were considered to be invalid, even inclinations in which set cruising speed cannot be reached were also considered invalid.

   In order to carry out the test on real roads, a long stretch of constant inclination is needed, unfortunately these kind of roads were not available within the test facility, the commonly used test track data were analyzed and found out that Borås-landvetter-Borås (BLB) route had constant inclination road stretches for a longer duration. A longer duration is needed as the speed recovery time for heavier trucks after a gear shift is large, various constant inclination roads listed in the table 3.1 are created in GSP environment for simulations.

| Road inclination (%) |
|---|
| -6 |
| -5 |
| -4 |
| -3 |
| -2 |
| -1 |
| -0,5 |
| 0 |
| 0,5 |
| 1 |
| 1,5 |
| 2 |
| 3 |
| 4 |
| 5 |
| 6 |

Figure 3.1: Various constant road inclinations

7. Boost Pressure:

   Nowadays all the engines are becoming more fuel-efficient by downsizing and by downsizing there is always a need for the additional charging methods to get necessary power output. In most of the diesel engines, the general practice is to introduce a turbocharger, which increases the boost pressure. With higher boost pressure, a large amount of fuel can be burnt and more power can be generated.

   Since most of the truck engines are equipped with a turbocharger which is driven by the exhaust gases, during a gear shift the engine is momentarily disconnected from the transmission and the engine speed has to be reduced in order to reduce the clutch wear which means the fuel mass burnt will also be small and this reduces the turbocharger performance because of less exhaust generated.

   After the gearshift is completed, the large amount of fuel has to be burnt to meet the demand torque however it is limited by low boost pressure provided by the turbocharger and the effect of this maybe interested in the analysis.

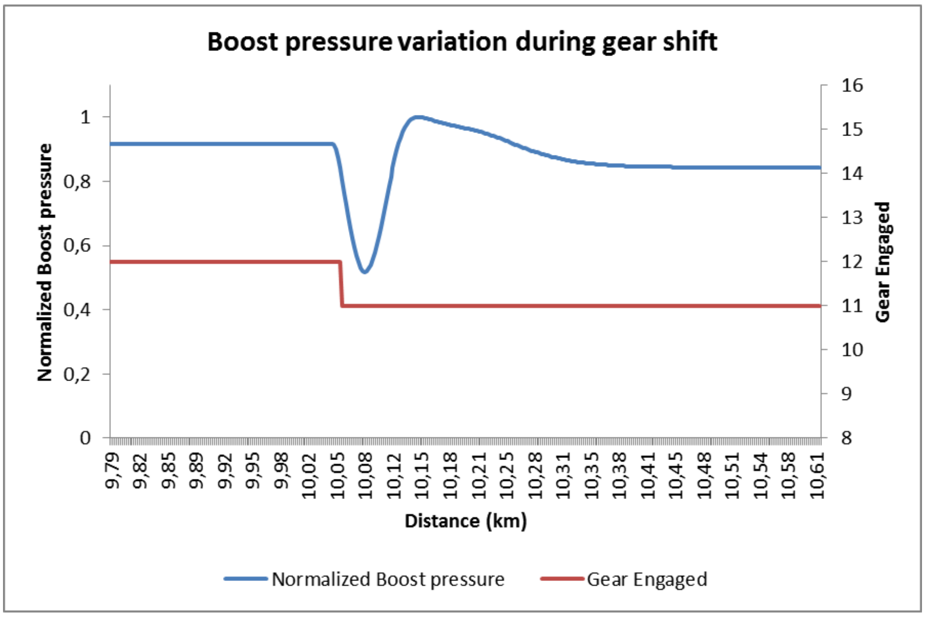


Figure 3.2: Boost pressure variation during a gear shift

### 3.1.2 Why boost pressure is disregarded as an input variable

The boost pressure generated by the turbocharger varies during gear shift due to the lower mass of fuel burnt, the variation can be seen in the figure3.2.

There are some advanced techniques used in the Volvo engines which do not use additional fuel to regain the boost pressure, which makes it clear that boost pressure does not have any effect on fuel during a gear shift.

Now coming to time loss, boost pressure has no additional effect on the time as the boost pressure will be completely recovered well before the vehicle speed is recovered back to cruising speed (which is considered as the end of the gearshift). After this study on for various cases boost pressure can be disregarded as an interesting variable.

### 3.1.3 List of Interesting variables

After excluding boost pressure as an interesting variable, the final list of the variables with all the values considered for simulation are shown in the figure 3.3.

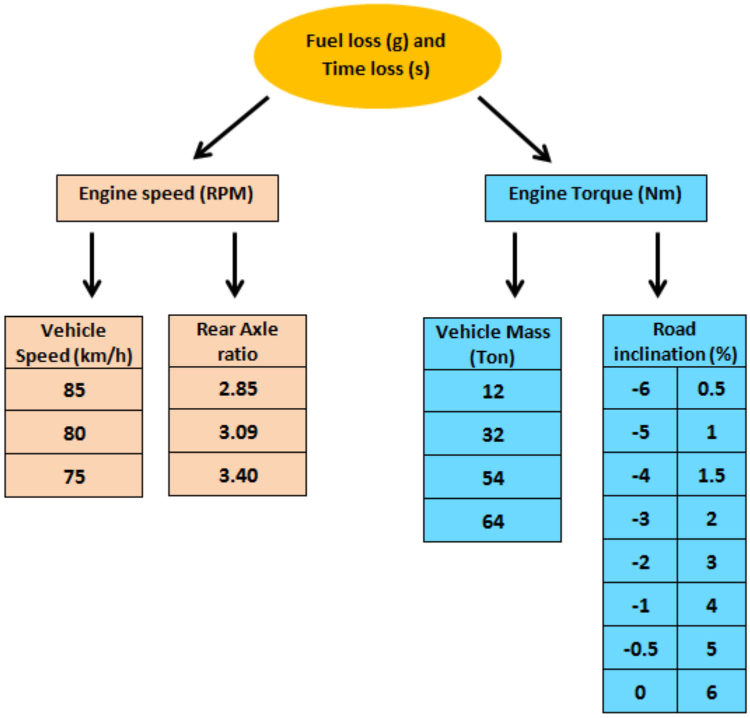


Figure 3.3: Interesting variables

### 3.1.4 Design of experiments (DOE) based simulation matrix

Since there are four different variables which are vehicle speed, rear axle ratio, vehicle mass and road inclination and two different responses a design of experiment based simulation matrix is created with each parameter being varied at a time in order to understand their effect on fuel and time. There are 432 different cases of simulation for gearshifts from 12th to 11th, similarly 432 cases for gearshifts from 11th to 12th.

## 3.2 Determination of losses during gearshift in simulation platform

After coming up with a DOE based experiment table based on various variables, these different experiments have to be set up in simulation platform in order to determine the required losses from simulation.

As stated in previous section, the simulation platform used in the present study is *'GSP'*, which is based in Matlab/Simulink.

### 3.2.1 GSP Simulation setup

Setting up the simulation model in GSP involves setting up three main models inside GSP, namely:

- Road and environment model
- Driver model
- Vehicle model

The initialization that was done in each of these models as required by the study are as follows:

- ***Road and environment model:***
  In this model, the kind of road on the which vehicle tests needs to be simulated is defined. Also, external environment conditions such as the properties of surrounding air, etc. are also defined.

While defining the kind of road, details that are input are the altitude, latitude and longitude, density of air and the desired vehicle speed (in case of driving in cruise control mode).

It is important to note that these details are specified for equal intervals of vehicle distance. That means the road created is in terms of distance based.

The road altitude and other details that are specified throughout the distance for which the vehicle travels, is then used to estimate the road inclination within the GSP model. Based on different road inclinations, different demand is placed on the engine, resulting in generation of different engine torques.

For the purpose of this study, roads with stretches comprising constant road inclination at a constant vehicle speed was required. This was in order to maintain steady state conditions in terms of constant torque demand and consequently constant vehicle speed. This meant that different engine torques could be achieved by simulating on roads with different constant inclinations in different cases.

As a result of this requirement, different stretches of roads with different constant inclinations were created by specifying the inclination at respective vehicle distances. From these specified values of road inclination at particular vehicle distances, the altitude is estimated as shown in the figure 3.4 according to equation 3.4:

$$Altitude = VehicleDistance * sin[tan^{-1}(roadinclination)] \tag{3.4}$$

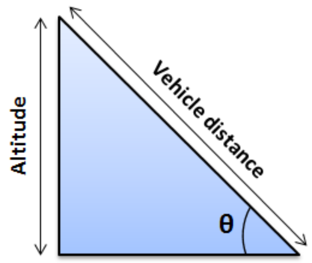


Figure 3.4: Calculation of altitude from vehicle distance and road inclination

The resulting altitude data is then given as an input to GSP. Using this, the road inclination data is estimated in the GSP.
In addition to these constant inclination roads, some other standard road stretches like BLB (Borås-Landvetter-Borås) were also used.

- ***Driver model:***

  The driver model serves as an interface between driver and the vehicle in GSP. In the driver model, there are different driver behaviour strategies based on whether the driving mode is cruise control or controlled by the pedal by the driver.
  For all the cases in this study, the vehicle is simulated in the cruise control mode.

  While in the cruise control mode, there is an imaginary driver in the driver model, where some strategies are modelled in order to mimic the response of a driver. Events like acceleration, deceleration, gearshifts, braking, etc. are automatically controlled by the driver according to the strategies in the driver model.

  However, it is also possible to drive in the pedal mode, during which all the events like acceleration, deceleration, gearshifts, braking, etc. are controlled by the driver. In the simulation platform, the driver can communicate with the vehicle by means of a *'Graphical User Interface (GUI)'* which has controls for various events as shown in the figure 2.17.

  Since the requirement of this study required studying losses during gearshifts, it was essential to be able to shift the gears at any point of time to test in various conditions. This meant that the gearshifts were to be able to be triggered as and when required. For this purpose, the *'Driver GUI'* as seen in figure 2.17 was used as it had controls for gearshift.

  Basically, the *'Driver GUI'* communicates both with the user who controls the simulation (or driver who controls the vehicle), and the vehicle control units. The input from the user is received by the *'Driver*

*GUI'* transferring it to the vehicle control units, where the action required by the user is taking place as shown in figure 3.5. This way, it was possible to trigger the gearshifts at any desired point of time throughout the simulation duration.

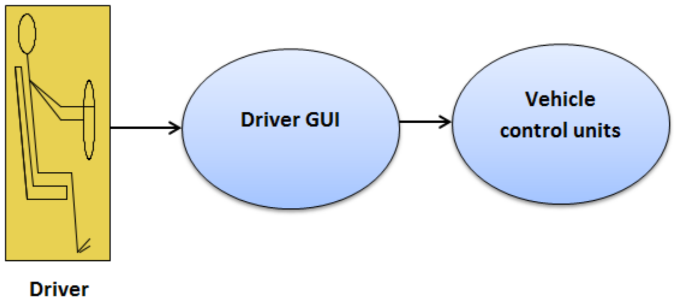


Figure 3.5: Driver GUI communication with driver and vehicle control units

The *' Driver GUI'* was used to trigger a gearshift when one experiment case was simulated at once. But, when a host of experiments for various cases of different variables were simulated together in a *'batch simulation'*, then the *'Driver GUI'* cannot be used because the simulation then takes place in the background without the pop-up of *'Driver GUI'*.
In this case, to trigger a gearshift, a *'signal generator'*, as shown in figure 3.6 is used, which sends out signals to specific vehicle control units at specified points of time in the simulation, where a gearshift is desired to happen.

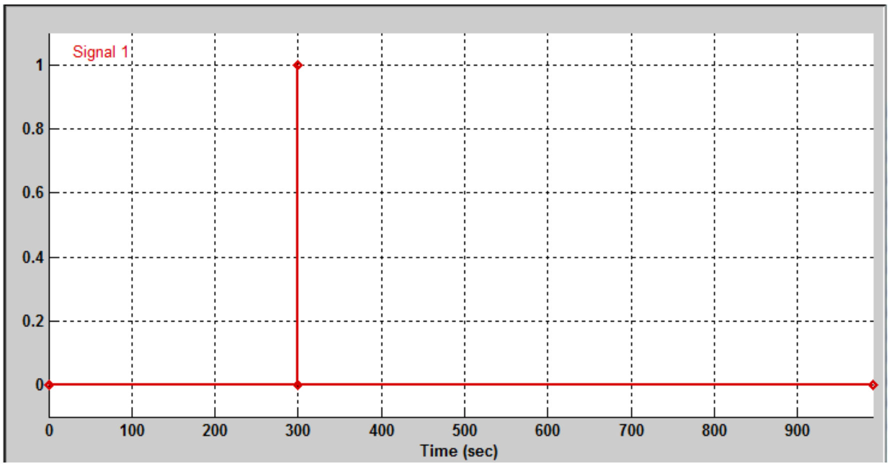


Figure 3.6: Signal generator to trigger specific events at specific points of time

The procedure that was followed to trigger a gearshift while driving in cruise control mode is as follows:

- While driving on road with constant inclination, at steady state (a state of constant vehicle speed, constant engine torque and engine speed), shift in the mode of gear selection from automatic to manual using *'Driver GUI'* is made, just before a particular gearshift is desired.
- When the driving mode is manual, the required gearshift is triggered using *'Driver GUI'*.
  In the previous step, the mode of gear selection was changed from automatic to manual to ensure that after triggering a gearshift, it is desired that the state of the selected gear remains the same and no other unintended gearshifts take place due to automatic mode.
- After the gearshift has happened at the particular point where it was desired, the simulation is continued in the same state without any further gearshifts until the end.

- ***Vehicle model:***

  Vehicle model is the model in which all the subsystems like engine, clutch, transmission, chassis, wheels, etc. are modelled as described in the section 2.11.

  The main focus for this work is on the transmission control unit, *'TECU'* since it contains the software which controls the gear selection in a Volvo truck. Focus is also laid on the engine control unit, *'EMS'*, since it contains the software which controls the engine in a Volvo truck. While evaluating the losses due to gearshifts, values from many signals in TECU, EMS and other units within the vehicle model are used as reference.

  The signals which were used are described in the table 3.3.

| **Signal names** | **Signal description** | **Unit** | **Control unit from which the signal is taken** |
|---|---|---|---|
| distance_m | Vehicle Distance | m | Chassis and Frame plant model |
| speed_mps | Vehicle Speed | m/s | Chassis and Frame plant model |
| fuelFlow_mgps | Total fuel flow | mg/s | EMS |
| TransmissionShiftInProcess | Transmission Shift In Process | - | vTECU |
| currGear | Transmission current gear | - | vTECU |
| CAN_EECU_EngineSpeed | Engine Speed | RPM | vTECU |
| Ind_Torque_Value | Engine Torque | Nm | EMS |
| driverDemandIndTorque_Nm | Driver Demand Torque | Nm | EMS |
| CAN_EECU_BoostPressure | Boost Pressure | kPa | vTECU |
| TorqueSpeedRequestMode | Torque Speed Request Mode | - | vTECU |

| **Signal names** | **Signal description** | **Unit** | **Control unit from which the signal is taken** |
|---|---|---|---|
| TorqueRequest | Torque Request | % of Engine torque | vTECU |
| SpeedRequest | Speed Request | RPM | vTECU |
| TRA_E_CLUTCH_posRaw | Clutch Position | - | vTECU |
| CAN_VMCU_ccSetSpeedJ1939 | Cruise control set speed | km/h | vTECU |
| debug_inclination | debug inclination | % | vTECU |

Table 3.3: Description of the different CAN signals used in different control units

  Once the simulation platform is setup with all the required inputs, a particular case from the list of experiments is simulated. The resulting values from various signals in the vehicle model are evaluated. All the signals are sampled from GSP at a sampling time of 100 ms (0.1s).

### 3.2.2 Simulation scenario

As described in the section 3.1.4, there are several experiments that needs to be carried out based on various variables involved. To be precise, there are 864 experiments that needs to be simulated including gearshifts from gear 11 to gear 12 and gear 12 to gear 11.
Considering one such instance of experiments with specific values of variables such as:

- Gearshift from 11 to 12
- Road inclination = constant road of 1%
- Vehicle mass = 32 T
- Vehicle Speed = 85 km/h
- Rear axle ratio = 3.09

These are the values of variables which will be used to initialize the simulation. Once the simulation is started, a gearshift from 11 to 12 is triggered as described in the section 3.2.1.

The simulation needs to be run again with the same set of values for all the variables, but now completely in gear 12 without triggering any gearshifts.

Once these processes are simulated, the results from the simulation are evaluated with the help of signals as described in section 3.2.1 to determine the losses in terms of fuel consumption and time.

### 3.2.3 Loss calculation methodology from simulation

Before describing the loss calculation methodology used in this work, it is important to state the definition of few terms used for loss calculation from simulation.

**Definition of specific terms:**

- ***Steady state:***

  Steady state is defined as the state of constant torque demand and constant vehicle speed. Since the simulations are carried out on roads with constant road inclinations, the vehicle will have a constant demand torque at the wheels to maintain a constant vehicle speed set by the cruise controller.

  The definition of steady state is important to clearly distinguish and identify dynamic states such as gearshift event, during which the steady state conditions will no longer hold good. Since these dynamic events like gearshifts are for a very short duration, clear demarcation needs to be done to identify them.

- ***Gearshift event:***

  The gearshift event is the duration from when the gearshift is triggered till the effect of gearshift ends. The start of the gearshift event is indicated when the signal TransmissionShiftInProcess as described in the table 3.3 starts to be active (takes the value 1), which happens when the gearshift is triggered by the driver or the transmission control unit (TECU). This is also the time at which the transmission control unit (TECU) starts controlling the engine, by issuing torque and speed requests and is indicated in the CAN signals described in table 3.3.

  As a result of this variation in engine torque, the vehicle speed starts to drop below the cruise control set speed. The effect of the gearshift event is considered to end when the vehicle speed recovers back and reaches the set speed again.

  In other words, the gear shift event starts when there is deviation from the steady state and ends when the steady state is reached again.

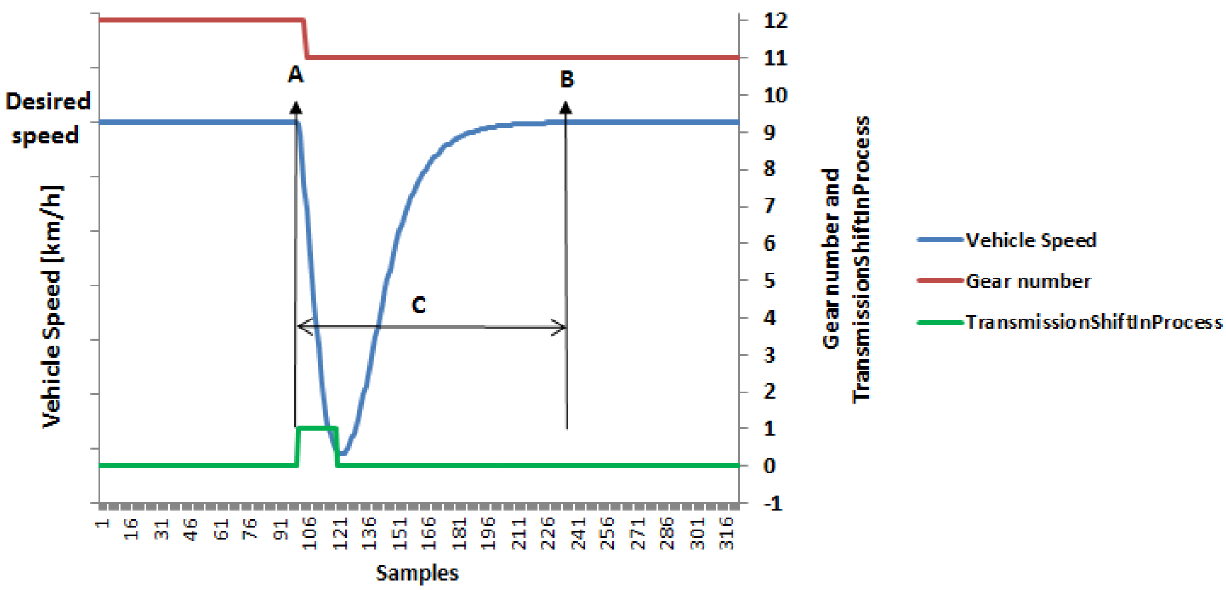


Figure 3.7: Variation of vehicle speed during gear shift event

The figure 3.7 depicts the scenario of a vehicle travelling on a constant road of 1% inclination, with a cruise control set speed which is called the desired speed. Till point A, *'steady state'* conditions were maintained. At point A, a gearshift from from gear 12 to gear 11 is triggered. Point A is the instant where the signal TransmissionShiftInProcess starts to take the value of 1 at point where the gearshift is triggered. According to the definition of *'steady state'* and *'gear shift event'*, this is the point where the gearshift event starts.

The vehicle speed starts to drop after this point as shown in the figure 3.7. When the vehicle speed recovers and reaches the desired set speed again at point B, the gearshift event is said to have ended when the vehicle is back to *'steady state'* conditions.

So, the duration *'C'* in the figure 3.7 is the ***'gearshift'*** event.

Hence, to define and identify the *'gearshift event'*, vehicle speed is used as the reference. Other parameters like engine torque or torque demand were not used as a reference since during the *'gearshift event'*, the torque demand and the driver demand torque vary a lot as it is ramped down to 0 and then recovers before reaching a constant level as shown in the figure 3.8. Although the engine torque reaches a constant level on returning to steady state, it is difficult to determine the instant at which the desired level of engine torque is reached.

But, in case of vehicle speed, since the target speed is already known by the cruise control set speed, it is easy to determine the instant of time when it returns back to this set level to define the end of a *'gearshift event'*.

As the torque is the effect and the Vehicle speed is the result which is easy to monitor, vehicle speed is used as a reference.

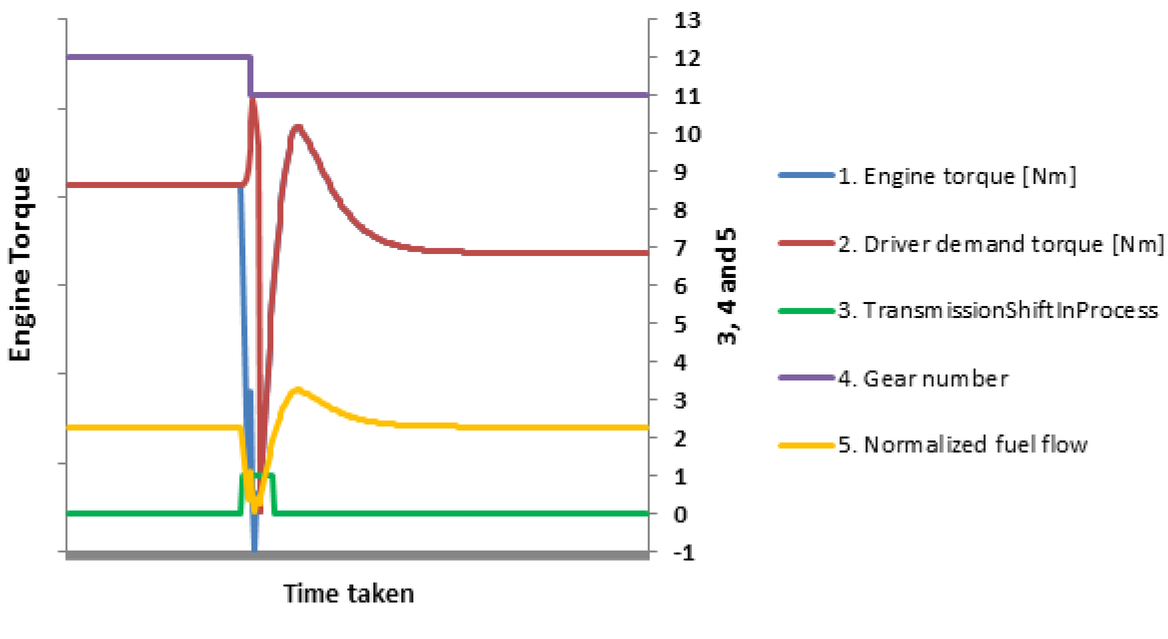


Figure 3.8: Variation of torque during gear shift event

- ***Time taken for gearshift event:***

  There are 2 ways of accounting the time taken for the gearshift event. They are:

  1. **Absolute time taken**:
     Absolute time taken is used to calculate the loss in time during a gearshift. Here, the time taken is recorded from point A till point B according to figure 3.7, which is till the Vehicle speed recovers to the level of cruise control set speed. It is indicated by **'A'** in figure 3.9.

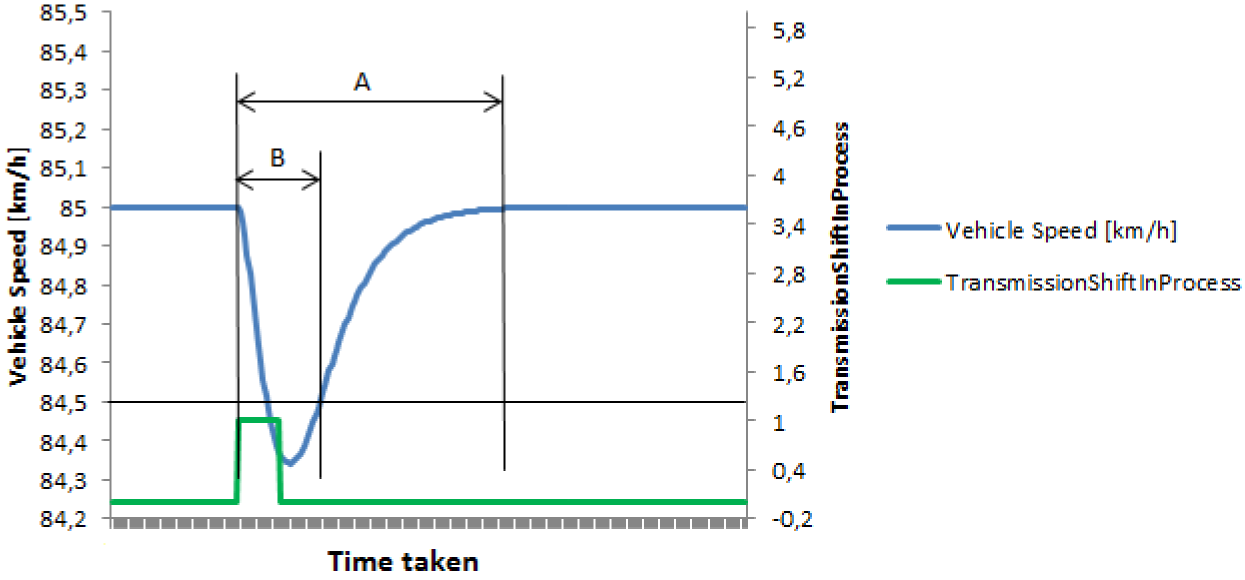


Figure 3.9: Variation of vehicle speed during gear shift event

2. **Driver feel time**:

   The on-board display in the truck gives an indication to the driver of what speed the truck is travelling in. Since this display only displays whole numbers, if the speed of the truck is 85 km/h, then it can be anywhere between 84.6 km/h till 85.4 km/h and the driver only feels the speed has dropped from 85 km/h if the vehicle speed falls below 84.5 km/h.

   So, driver feel time is the time duration that the driver feels when the vehicle is not travelling in the cruise controller set speed. It is indicated by **'B'** in figure 3.9.

   To quantify driver feel time, a vehicle speed band of 84.5 to 85.5 km/h (when the cc set speed is 85 km/h) is chosen because the driver can only see 84 or 85 (no decimals since it is rounded to whole numbers in the display). So, it is the time from when the Vehicle speed after the gear shift event has stared, goes out of this band till it recovers back.

- ***Static fuel consumed:***

  When travelling from one point to another, as in figure 3.7 from A to B, if the gear is maintained constant without any gearshifts, then the total fuel consumed to travel between A and B is called is termed as ***Static fuel consumed***.

- ***Dynamic fuel consumed:***

  When travelling from one point to another, as in figure 3.7 from A to B, if there are gearshifts involved, then the total fuel consumed also includes the losses due to the gearshift and this is termed as ***Dynamic fuel consumed***. It is the sum of ***Static fuel consumed*** between the same points and losses due to the gearshift as stated in equation 3.7.

**Simulation procedure to determine fuel and time loss during gearshifts:**

Once these terms as mentioned in the previous section are defined, the method followed for fuel and time loss calculation during gearshift can now be described. A total of 2 simulations have to be run one after the other for each experiment in order to calculate the losses. This process consisting of Simulation-1 and Simulation-2 is described in a step-by-step procedure:

- Simulation-1: Simulation with gearshift

  1. The required values of variables as mentioned in the section 3.2.2 are used to initialize the simulation. The total distance for which the vehicle was simulated in this case was 20 km.
  2. After the simulation has been initialized and started to run, shortly (around 100 m) before triggering a gearshift, the gear selection mode is switched from automatic to manual as indicated by point M in figure 3.10.
  3. Now that the gear selection mode is in manual mode, the required gear shift (in this case from gear 11 to gear 12) is triggered using *driver GUI* as mentioned in section 3.2.1 at a particular distance as seen in figure 3.10 around a distance of 250 m.
  4. After the gear shift has been triggered, there will be a deviation from the steady state conditions (section 3.2.3) and the simulation is continued till the steady state condition is recovered.
  5. Since the gear selection mode is in manual after the gear shift was triggered, there will not be any other gear shifts which are unintended and that can disturb the vehicle to return to steady state after the gearshift.
  6. The results from the simulation in terms of signals from various control units as mentioned in the section 3.2.1 are taken as output.

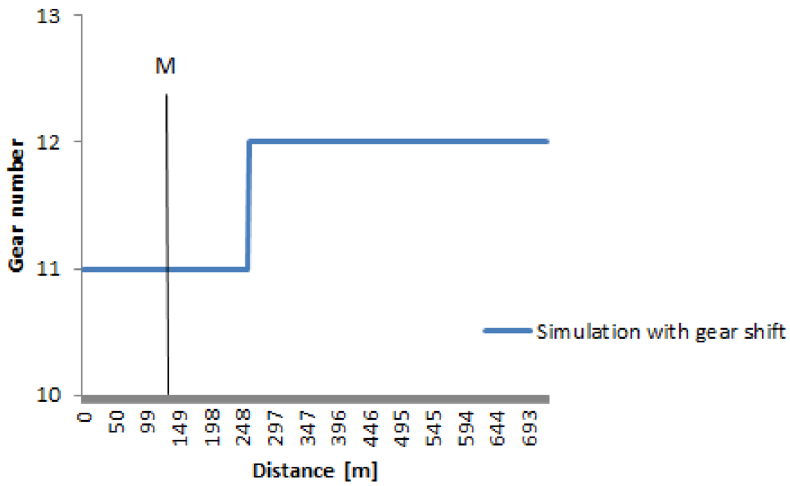


Figure 3.10: Simulation with gearshift triggered

- Simulation-2: Simulation without gearshift

  1. Simulation-2 is initialized with the with same set of initial conditions as simulation-1.
  2. As in simulation-1, the gear selection mode is switched to manual mode at the same distance as in step 2 of simulation-1 as indicated by point 'M' in figure 3.11.
  3. But in this run, the goal is to run on gear 12 (which is the upcoming gear after gearshift in simulation-1) in the stretch where the gearshift was triggered in step-3 in simulation-1. This means, no gearshift is triggered in simulation-2 at the point where gearshift was triggered in simulation-1 as shown in figure 3.11.
  4. For instance, the gearshift from gear 11 to gear 12 was triggered at a distance of 250 m in simulation-1. So, in simulation-2, the goal is to run on the gear 12 (which is the upcoming gear) starting from a distance of 250 m (or before) and stay in gear 12 till the simulation ends.
  5. The results from the simulation in terms of signals from various control units as mentioned in the section 3.2.1 are taken as output.

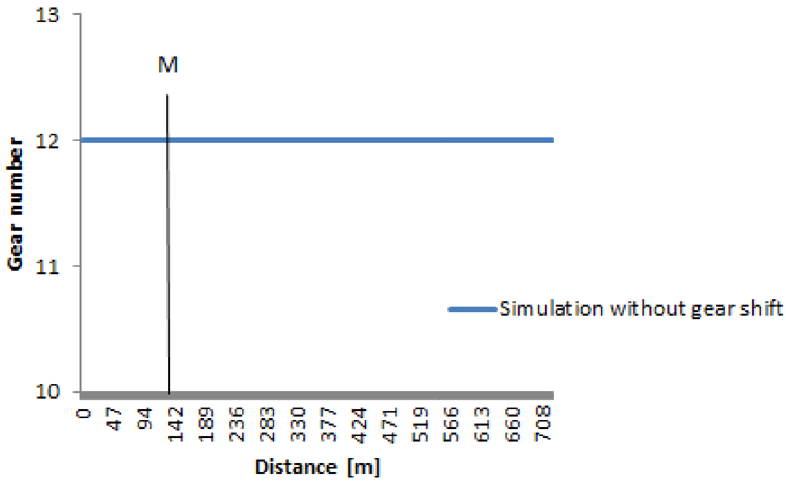


Figure 3.11: Simulation without gearshift

After obtaining results from both Simulation-1 and Simulation-2, the total fuel consumed in Simulation-1 from the instant at which the signal TransmissionShiftInProcess takes the value of 1 (indicating a gearshift) till the steady state conditions are regained as indicated by duration C in figure 3.7 is determined. Also, other details such as total distance travelled in the duration C is determined.

Consider the signal TransmissionShiftInProcess takes the value of 1 at a distance of 10.2 km indicating that the shift starts from this distance as indicated by point A in the figure 3.7.

The vehicle speed starts to drop from this point deviating from steady state conditions. Now, the point at which the steady state condition is recovered (vehicle speed is recovered) is found as indicated by point B in the figure 3.7. Let the distance at this point be 10.6 km.

Further, the total distance travelled, total time taken and total fuel consumed between these points A and B is determined. For the ease of understanding, assume these quantities to be 400m, 19.7s and 200g respectively. (These values are not realistic, they are only for the sake of intuitive understanding)

Now, from the results of simulation-2, for the same stretch of road between the two points A and B, that is starting from a distance of 10.2 km till 10.6 km, the total fuel consumed and the total time taken in the upcoming gear is determined. Let these be 197.5g and 19.65s respectively. But in this case, since there is no gearshift involved, the fuel consumed will be static.

From these calculations, fuel loss can now be determined as:

$$\textbf{Fuel\_loss} = 200 - 197.5 = 2.5g. \tag{3.5}$$

$$\textbf{Time\_loss} = 19.7 - 19.65 = 0.05s. \tag{3.6}$$

This procedure is carried out for every experiment case to determine losses.

After obtaining the fuel and time losses, the engine speed and engine torque at which the gearshift was triggered is also noted down. For this purpose, the engine speed and engine torque just before the TransmissionShiftInProcess takes the value of 1 is used. These values indicate the condition of the engine at which particular losses in fuel and time take place.

The Driver feel time as mentioned in the section 2 is also determined.

**Using upcoming gear as reference for comparison:**

In simulation-2, the vehicle is simulated on same road conditions as simulation-1, but now travels the entire distance (or a part of it during the distance with gearshift in simulation-1) in the upcoming gear as explained in the section 3.2.3. This is done due to the fact that:

- When a gearshift is triggered (from gear 11 to gear 12) as in figure 3.10, there is deviation from steady state conditions due to which fuel and time losses occur.

- But, the entire fuel consumed during this duration of dynamic state (as indicated by 'C' in figure 3.7 cannot be called as *'fuel loss'*.

- This is for the reason that in the duration 'C' in figure 3.7, although the fuel which is consumed results in gaining the lost vehicle speed, some distance is also covered. So not all the fuel consumed can be termed as a loss.

- To find out the fuel loss due to gearshift, the quantity of fuel which is spent in excess to the quantity of fuel spent if there was no gearshift needs to be found. This means, some quantity of fuel has to be subtracted from the total fuel consumed in the duration 'C' in in figure 3.7. This amount of fuel which needs to be subtracted is the amount of fuel needed to travel the distance in duration 'C' in in figure 3.7 without drop in vehicle speed, which means without any gearshift.

- This results in two ways of selecting the quantity of fuel to subtract. One is the quantity of fuel consumed in gear 11 and another is the quantity of fuel consumed in gear 12.

- The way of selecting is described in the figure 3.12.

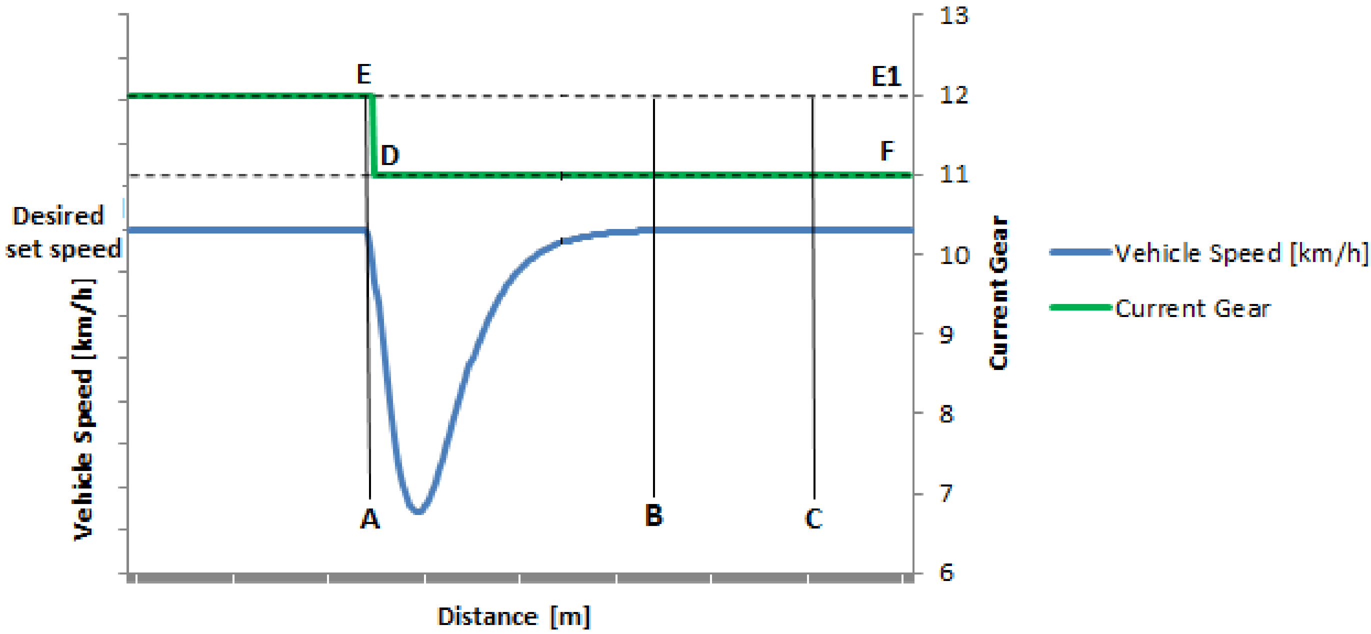


Figure 3.12: Various points of reference during a gearshift event

In the figure 3.12, various points and paths of reference are defined as follows:

Point A - gearshift takes place (deviation from steady state)

Point B - effect of gearshift ends (back to steady state)

Point C - random point for fuel and time loss evaluation

Path E-E1 - path followed while travelling from point A to C running static on gear 12

Path D-F - path followed while travelling from point A to C running static on gear 11

Path E-D-F - path followed while travelling from point A to C with gearshift from gear 12 to gear 11 at point A

**Fuel_AC_12** is the fuel consumed to travel from A to C on static conditions in gear 12 following path E-E1.

**Fuel_AC_11** is the fuel consumed to travel from A to C on static conditions in gear 11 following path D-F.

**Fuel_AC_12to11** is the dynamic fuel consumed (static fuel + fuel losses due to gearshift) from A to C when a gearshift is triggered at A.

**Fuel_AB_12to11** is the fuel consumed to travel from A to B when a gearshift from gear 12 to gear 11 is triggered at A. This is the amount of fuel which is consumed when there is deviation from steady state conditions (from point A) due to gearshift and till the steady state is recovered at point B.

**Fuel_AB_11** is the fuel consumed to travel from A to B on static conditions in gear 11.

**Fuel_AC_12** and **Fuel_AC_11** are easy to calculate on-board in the software available in transmission ECU.

But, the question is to determine the dynamic quantity of fuel, **Fuel_AC_12to11** on-board, which is the amount of fuel that will be consumed from A to C when a gearshift from gear 12 to gear 11 is triggered at point A following the path E-D-F.
This is difficult since there are no static conditions anymore since there is a gearshift involved which involves losses. This can be calculated by:

$$Dynamic\_fuel\_consumed = Static\_fuel\_consumed + Losses \tag{3.7}$$

$$\mathbf{Fuel\_AC\_12to11 = Fuel\_AC\_11 + Loss\_12to11} \tag{3.8}$$

Since the quantity **Fuel_AC_11** is easy to estimate on-board, the quantity **Loss_12to11**, which is the loss due to the gearshift can be calculated by:

$$\mathbf{Loss\_12to11 = Fuel\_AB\_12to11 \text{ - } Fuel\_AB\_11} \tag{3.9}$$

So, it is quite evident from equation's 3.7, 3.8 and 3.9 that, for a gearshift from gear 12 to gear 11, to determine the dynamic fuel consumed, **Fuel_AC_12to11**, **Loss_12to11** is required and to determine **Loss_12to11**, **Fuel_AB_11** is required, which is the static fuel consumed in the upcoming gear.
Since for a gearshift from gear 12 to gear 11, gear 11 is the upcoming gear.

So, to make the calculation of the dynamic fuel consumption (static fuel + losses due to gearshift) easier, fuel consumed in the upcoming gear is used as a reference.

**Invalid cases for fuel loss and time loss calculation:**

As stated in the section 1.4, at steady state conditions, only those cases are considered for the calculation of fuel and time loss during a gearshift in which:

- The cruise control set speed shall be maintained at steady state conditions before the gearshift is triggered and after the gearshift is completed.
- For example, for the gearshift from gear 11 to gear 12, a vehicle with 64T travelling on a 5% constant road at a cruise control set speed of 85 km/h should be able to reach and maintain the vehicle speed of 85 km/h in gear 11 before the shift is triggered from gear 11 to gear 12. And also, the vehicle speed should be back to 85 km/h on gear 12 after the gearshift is completed.
- If these conditions are not satisfied, that particular case is invalid and not considered for the calculation of fuel loss and time loss.

## 3.3 Calculation of fuel and time loss based on truck testing

### 3.3.1 Verification of GSP simulation results with truck testing

However the results obtained by simulations based on constant road inclination roads helps to identify the exact end of a gearshift process that is when the vehicle speed is regained back, but these roads are unrealistic in order to get realistic results test were conducted in trucks on real roads were torque demand will be different depending upon the inclination after the shift. Since time was limited, tests could only be conducted for certain cases in the simulation matrix also very few trucks were available with the required specifications.

The specifications of the truck used for the study are listed in the table3.4. Since the truck was equipped with a rear axle ratio of 3.40 it was possible to conduct various test with different masses and different cruising speeds. All the necessary signals were monitored using tool called VISION which is discussed in the section 2.

Note: The brake stalk position, tires and Eco levels are discussed in brief in section 2.

| Specification table | |
|---|---|
| Truck identification number | FH1866 |
| Engine | 16 liter Diesel |
| Transmission | AMT-OD<br>(Automatic mechanical transmission - Overdrive) |
| Max Power | 750 HP |
| Max torque | 3500 Nm |
| Approved Legislation | EURO-6 STEP D |
| Rear axle ratio | 3.40 |
| Configuration | 8x4 Rigid |
| Tires | 315/80-22.5 |
| Eco level used | Eco level 2 |
| Brake stalk position | Position 1 |
| Curb weight | 12000 kg |

Table 3.4: Specification of truck used for testing

### 3.3.2 Test road selection

The on-road test needs to be conducted on roads with a constant inclination in order to have the constant torque demand, the fuel consumption is mainly dependent on the engine torque and any variation in torque demand will change the fuel values. However, these kinds of roads were not available at Volvo test facility so a different strategy was needed to get closely matching road inclinations, the only solution was to find a suitable highway were tests can be conducted.

The data of commonly used test routes close to Gothenburg were filtered and it is not practical to get a perfectly constant road for a longer stretch, a tolerance margin has to be defined in order to proceed further, the assumption here was to consider the inclination data which has a variation of demand torque in the range of 200 Nm, the figure 3.13 shows the road inclination with a variation of 0.0 to 0.6 % had a torque difference less than 200 Nm and this can be considered as 0 % inclination road.

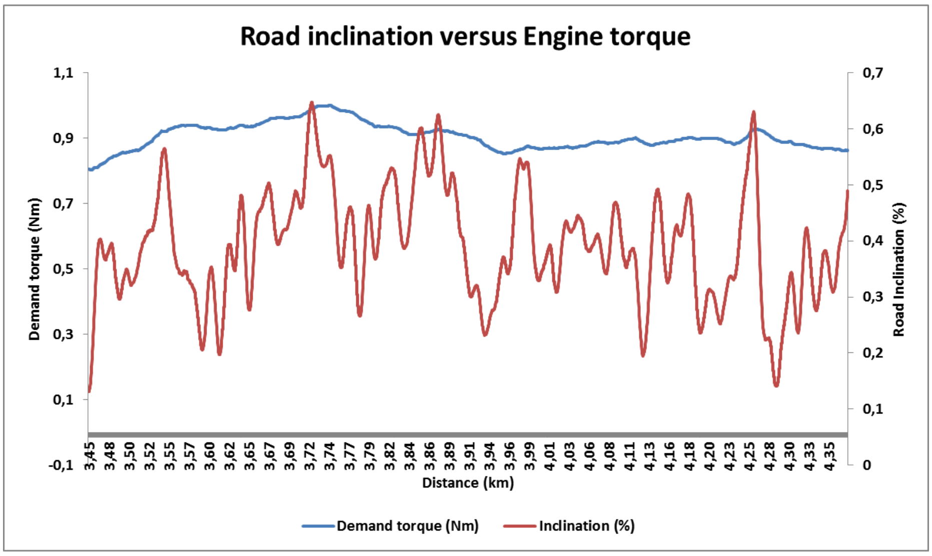


Figure 3.13: Variation of Engine torque with road inclination

By using a tool developed in Matlab with all the assumptions defined the filtering procedure is started for various roads, note that the minimum time for these inclination to remain constant in the required margin is set as 10 seconds which is the minimum time required to reach back to cruising speed after a gearshift. A list of constant inclination stretches are created using the tool developed which acts as the plan for conducting the test in a truck.

### 3.3.3 Data monitoring using VISION

For truck testing, ATI VISION tool is used to capture the data from various CAN buses arising from engine, transmission and various other sources. The different signals required for measurement are given in the table3.3.3, it has to be noted that all the signals measured in VISION are sampled at 10 ms (milliseconds).

| Sl no | Type of signal | VISION data |
|---|---|---|
| 1 | Road inclination (%) | 'PTCAN.TECU.VP244_X_T.inclinationHighRes_PT_X_T' |
| 2 | Vehicle distance (m) | 'TECU.veh_distance' |
| 3 | Fuel flow (mg/str) | 'EMS.em_FuelValue' |
| 4 | Altitude (m) | 'TECU.GPSDataAltitude' |
| 5 | Indicated torque (Nm) | 'EMS.tc_IndTrqValue' |
| 6 | Log revs | 'EMS.slot_Logrevs' |
| 7 | Vehicle speed (km/h) | 'BB1.EBS.EBC2_X_EBS.FrontAxleSpeed' |
| 8 | Engine speed (rpm) | 'BB1.EMS.EEC1_X_EMS.EngineSpeed' |
| 9 | Transmission shift in process | 'BB1.TECU.ETC1_X_TECU.TransmissionShiftInprocess" |
| 10 | Transmission current gear | 'BB1.TECU.ETC2_X_TranmissionCurrentGear' |

Table 3.5: Various signals monitored in VISION

The reason for choosing sampling time as 10 ms is because some of the signals could be obtained at this resolution, in the other hand signals which did not have this high resolution were generating repeated values at their highest possible resolution.

### 3.3.4 Testing in a real truck

Before starting the test run in a truck the things to be checked are,

- The rear axle ratio of the truck along with other specifications
- Weight of the truck is noted down

- Connect all the data plugs from Engine, transmission and chassis which will give access to all the sensor data

- Check whether the resolution of all the signals is set to 10 ms for better resolution

- Connect VISION and set up all the signals to be captured With VISION up and running start the engine and look at all the signals in VISION UI (user interface), when the time starts running it is a sign that the signals are being monitored

- Buckle up the seat belt for safety, it is a Volvo!

To begin the test a reference point had to be defined, after defining the start point the vehicle is driven on gear 11 over the entire cycle to capture the inclination and vehicle distance data. With the tool developed for sorting out the different inclination various stretches of different inclination are identified, this is the crucial step for truck testing as the data captured here will be used as a reference for the next runs.

Now the reference point is defined and stretches of different inclinations are known a test run is made to capture the data from gear 12 to 11 downshift by running the vehicle initially on 12th gear with the predefined cruising speed. As data is being captured in VISION a downshift is made to 11th gear when the vehicle approaches the stretch, which causes an interruption of power to the wheels and lowers the speed of the vehicle, the vehicle regains speed after a downshift is successful. The time and fuel signals are captured during the gearshift.

To calculate the loss in fuel and time, the data for gear 11 obtained in the initial run is utilized, by subtracting the time/fuel consumed during a downshift from gear 12 to 11 with that of time/fuel obtained by running on gear 11 the loss in time/fuel is obtained. To capture the effect of loss in time/fuel gearshifts are made for different inclinations, this entire procedure is repeated again to make sure there is no bias in the measurement data.

A similar procedure is adopted to calculate the loss in time/fuel for upshift from gear 11 to 12, where the vehicle is driven on 11 gear and upshift is triggered which is then compared with the time/fuel by running on 12 gear. This type of tests had to be carried out for various cases in the simulation matrix but time and availability of the trucks are limited the tests we conducted only to the following cases,

Case 1: **Gear shift from 12 to 11**

- Weight - 29860 kg

- Rear axle ratio - 3,40

- Cruising speed - 85 km/h

- Inclinations - 0,0.5,1,1.5,2,3,4 % inclination

Case 2: **Gear shift from 11 to 12**

- Weight - 29860 kg

- Rear axle ratio - 3,40

- Cruising speed - 85 km/h

- Inclinations - 0,0.5,1,1.5,2,3,4 % inclination

Tests are made for different inclination and the inclinations in which speed cannot be maintained is considered to be invalid as discussed earlier in the 3.1.1 section.

### 3.3.5 Fuel and time loss calculation

- **Signals captured in VISION**
  To capture very good data, the resolution for capturing the data from various sensors in VISION is set to 10 milliseconds, but some of the sensors do not generate output at this resolution instead repeats data values several times depending on their maximum resolution possible.

  The various signals which are critical for the loss calculations are,

  - Log revs
    It is the number of revolutions the crankshaft makes which are in the repetitive cycles of 0 to 1000, this signal can be obtained at a maximum resolution of 20 ms resolution which means the same value repeating twice. So in order to find the no of revolutions per time instance (10 ms) another variable is created by calculating the difference in the log revs for every alternative step.
  - Fuel flow
    The fuel signal measured in VISION is in the form of fuel consumed in milligrams per stroke captured at 20 ms resolution since this is a 6 cylinder diesel engine in which there are 3 power strokes taking place at any instance of time the total fuel amount will be thrice as this signal.
  - Transmission-shift-in-process
    This signal generates a value 1 when the gear shifting process begins which is the defined condition for calculating the fuel/time loss.

  Finally, to get the total fuel consumed from the point where the transmission-shift-in-process becomes 1 till the speed of the vehicle reaches back to set cruising speed, fuel signal in mg/stroke is multiplied with the difference in log revs and with the number of power strokes per revolution (i.e 3).

- **Loss calculation method**
  After obtaining the data for the entire cycle from VISION the gear shift sequences are identified by observing the transmission-shift-in-process signal turning 1. The gearshift sequence begins when the transmission-shift-in-process changes to 1 the gear shift process is initiated during this process the speed of the vehicle drops due to interruptions of power till the gearshift is completed, once the new gear is engaged the vehicle accelerates till the set cruising speed is reached.

  The total distance travelled during this gearshift is noted and this is used as a reference to find out the fuel and time consumption when running on upcoming gear. After the fuel and time signals are filtered out for both the cases the fuel and time loss are obtained by subtracting these values.

## 3.4 Loss calculation by re-creating real roads from VISION in GSP

As we have discussed the loss calculation methods in the sections 3.2.3 by simulating for constant inclination roads, in this method of loss calculation the demand torque will be constant which results in constant fuel flow values which is not practical as the inclination will be varying in the real roads. In order to verify the simulations, the tests are conducted on real roads which are discussed in section 3.3, now it is unreasonable to compare the results obtained in real roads (variable inclinations) with the simulation results (constant inclination) so to make a fair comparison simulations are carried out by re-creating the roads by the data obtained from VISION during truck testing.

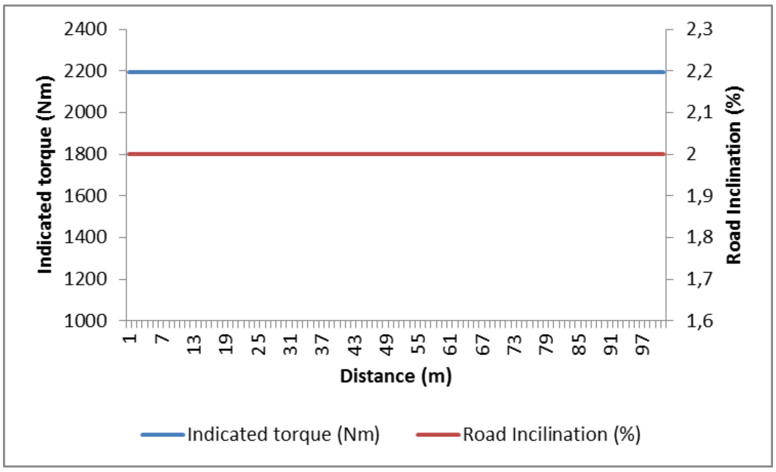


Figure 3.14: Indicated torque in constant inclination road

By looking at the figures 3.14 and 3.13 it is clear that the torque in the real roads will be varying to that of the constant inclination roads in GSP. By using the signals for inclination, distance and altitude obtained from vision as inputs a road can be created in GSP but altitude signal obtained from vision has a very low resolution of 1 second, since the gearshift happens in a couple of seconds it is not possible to create a road based on this low-resolution data. However, the high-resolution inclination data is used according to the equation3.10 to get altitude data with the same resolution. The figure3.15 shows road created by simulating VISION data, the loss in fuel ad time is calculated in the same way it was calculated for constant inclination roads which is discussed in detail in the section 3.2.3.

$$Altitude = \delta distance * \sin(\arctan(\frac{Roadinclination}{100})) \tag{3.10}$$

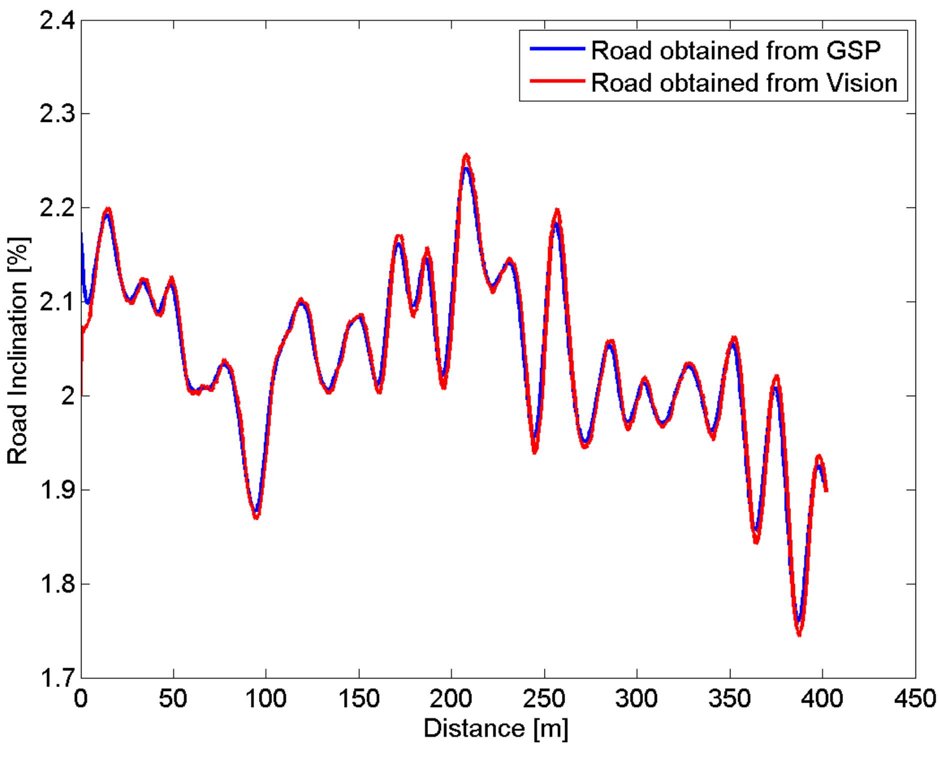


Figure 3.15: Road created using VISION data

# 4 Results and Discussion

The types of results which will be discussed in this section are as follows:

1. Constant road GSP simulation results
2. Thumb rules for fuel loss and time loss
3. Relative comparison study between fuel loss and time loss
4. Truck testing results
5. Comparison between truck testing results and GSP simulation results

## 4.1 Constant road GSP simulation results

The fuel loss and time loss were determined from GSP simulations using constant inclination roads as input. The trend of fuel loss and time loss will be shown based on various conditions of engine speed and engine torque.

The engine speed was varied by varying the rear axle ratio and vehicle speed. Although in the scope of this work, is is said that the engine torque was varied by varying the road inclination and vehicle mass, it is important to note that the rear axle ratio also affects the engine torque since that was varied as well.

In further sections that will follow, the nature of dependency of fuel and time loss on the engine torque will be discussed. Since the engine torque is varied due to the combination of vehicle mass and road inclination, it will be evaluated to see whether the way of reaching a particular engine torque, by different combinations of vehicle mass and road inclination will affect the fuel and time loss. For instance, if the engine torque is 1000 Nm, this torque can be demanded because of various combinations of vehicle mass and road inclination like 12t+5%, 32t+3%, etc.

So, it will be evaluated if the fuel and time losses at an engine torque of 1000 Nm vary because of different combinations of reaching the engine torque of 1000 Nm.

The results will be presented in the form of different kinds of figures for gearshifts from gear 11 to gear 12 and gear 12 to gear 11. The figures are divided into different categories from G1 to G4, each category representing different kind of results.

1. Category G1- Fuel loss based on engine torque - Engine torque is varied due to road inclination. Vehicle mass is constant.
2. Category G2- Time loss based on engine torque - Engine torque is varied due to road inclination. Vehicle mass is constant.
3. Category G3- Fuel loss based on engine torque - Engine torque is varied due to vehicle mass. Road inclination is constant.
4. Category G4- Time loss based on engine torque - Engine torque is varied due to vehicle mass. Road inclination is constant.

The categories G1 and G2 will be presented in this section. These figures are shown both for gearshift from 11 to 12 and 12 to 11.

The categories G3 and G4 are similar to G1 and G2 but the representation is with respect to different variables. So, G3 and G4 will be presented in the appendix. In all the categories from G1 to G4, the values of fuel and time loss are normalised, meaning that the absolute values of fuel and time loss are divided by their respective maximum values in each case. This is done in order to not disclose the absolute values as they are treated confidential by the company (Volvo Group Trucks Technology). However, the nature/trend of the graphs remain unchanged even after normalising.

Since the categories G1 and G2 show the variation of fuel and time loss against engine torque, the engine speed is kept constant in each particular case. But the engine speed is varied from one case to another as shown in the table 4.1 and table 4.2. The engine speed is varied by the combination of vehicle speed and rear axle ratio.

### 4.1.1 Gearshift from gear 11 to gear 12

In case of gearshift from gear 11 to gear 12, the following combinations of vehicle speed and rear axle ratio's were used to achieve different engine speeds. The different combinations are:

| Case number | Combination of vehicle speed [km/h] + Rear axle ratio |
|---|---|
| 1 | 85+2.85 |
| 2 | 85+3.09 |
| 3 | 85+3.4 |
| 4 | 80+2.85 |
| 5 | 80+3.09 |
| 6 | 80+3.4 |
| 7 | 75+2.85 |
| 8 | 75+3.09 |
| 9 | 75+3.4 |

Table 4.1: Combinations of vehicle speed and rear axle ratio for gearshift from gear 11 to gear 12.

Thus, in each of these cases, the engine speed is constant. The results are presented for various combinations of vehicle mass and road inclinations within each case.

For example, in Case 1, four different vehicle masses 12T, 32T, 54T, 64T and different road inclinations like 0%, 1%, 2%, 3% etc. are tested.

#### Plots for fuel loss and time loss

1. Category G1 - **Fuel loss based on engine torque - Engine torque is varied due to road inclination, vehicle mass is constant**

   For simplicity, the figures for Case 4, 5 and 6 as mentioned in the table 4.1 are shown here. For these cases, the vehicle speed is constant at 80 km/h and the rear axle ratio changes from case to case. The nature of the figures look similar in other cases too and some other cases are shown in section 1.

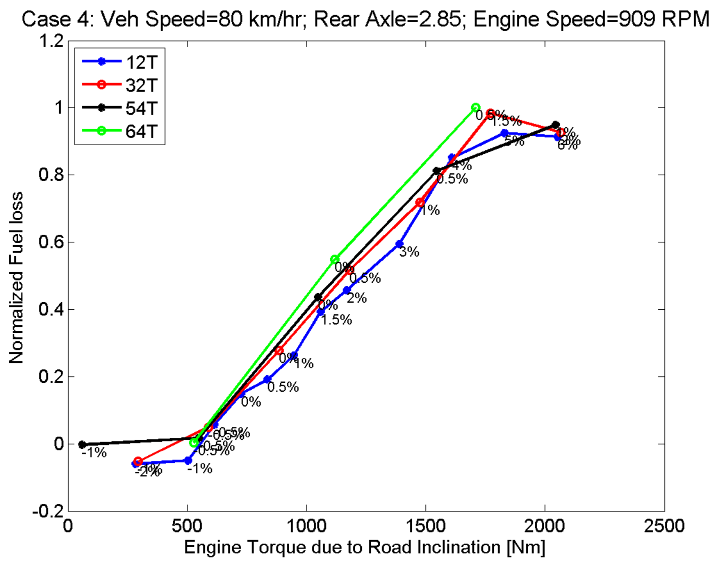


Figure 4.1: Variation of fuel loss against engine torque due to road inclination for Case 4

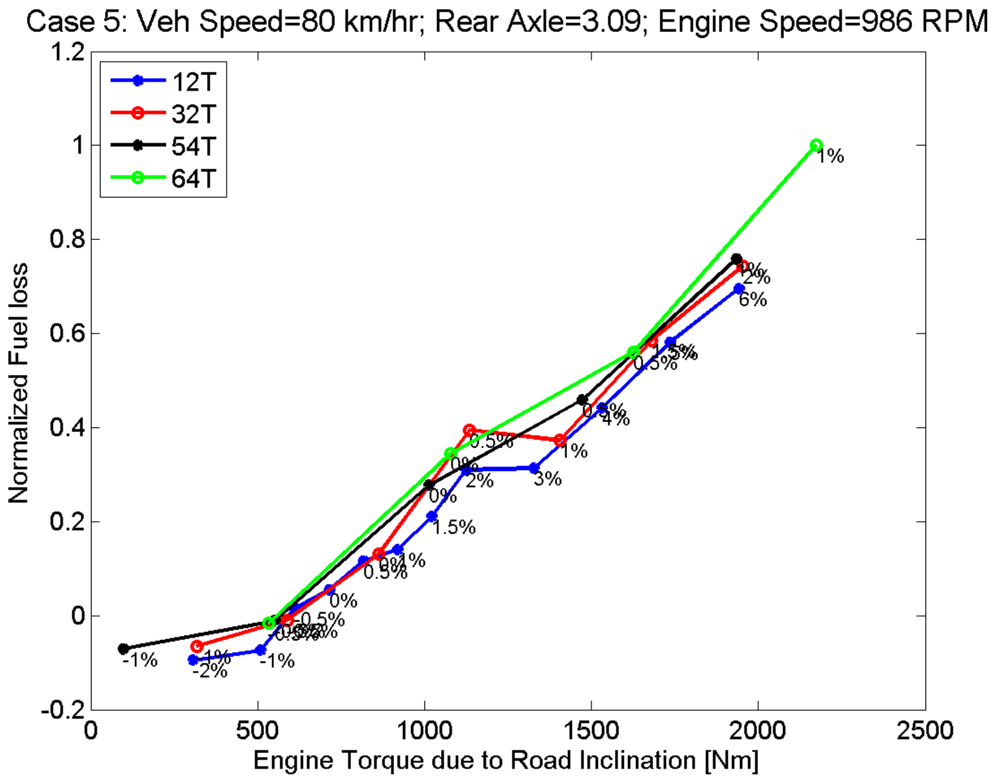


Figure 4.2: Variation of fuel loss against engine torque due to road inclination for Case 5

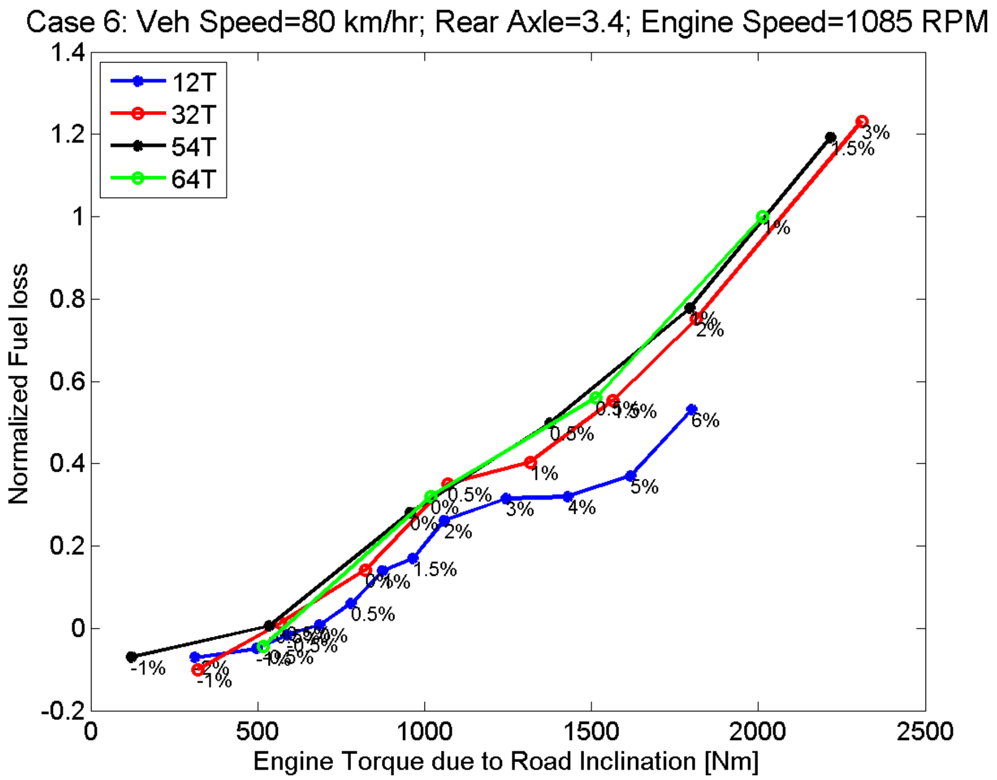


Figure 4.3: Variation of fuel loss against engine torque due to road inclination for Case 6

The trend of fuel loss against engine torque can be seen in the figures 4.1, 4.2 and 4.3. The fuel loss increases with engine torque at various road inclinations. Observing the figures for various vehicle masses from 12T to 64T as shown by different colored lines in 4.1, 4.2 and 4.3, the fuel loss does not vary too much when going from 12T to 64T at any particular torque level.

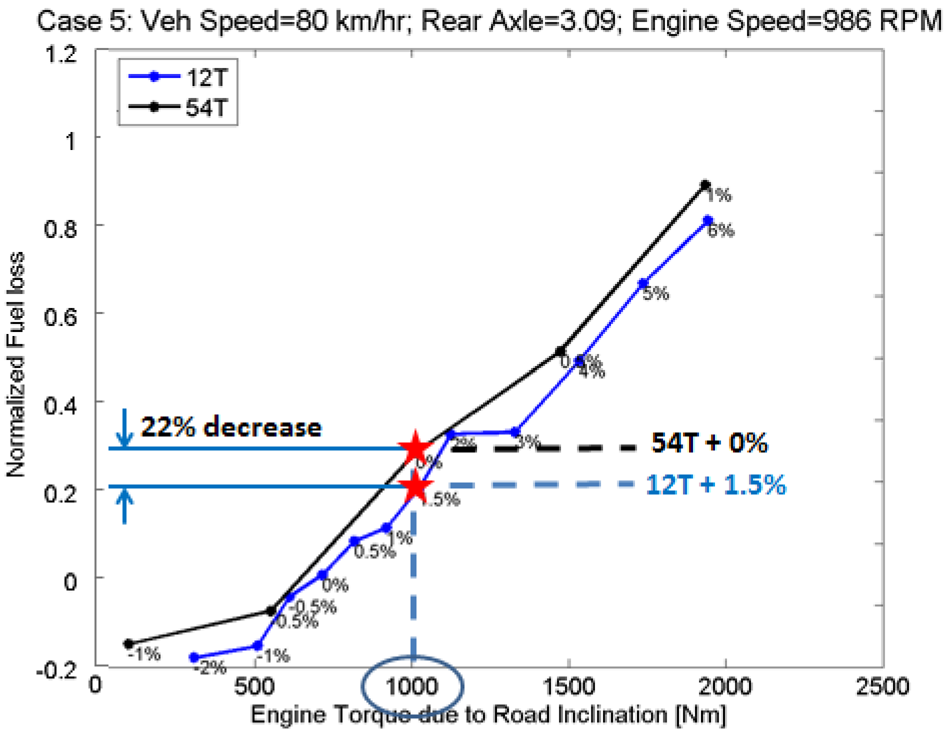


Figure 4.4: Variation of fuel loss when engine torque is reached due to different combinations of vehicle mass and road inclination

From the figure 4.4, it can be seen that an engine torque of 1000 Nm can be obtained due to more than 1 combination of vehicle mass and road inclination. But, the variation of fuel loss at 1000 Nm when this torque is reached due to different combinations, does not vary too much (around 22%) as compared to going from a vehicle mass of 12T to 54T.

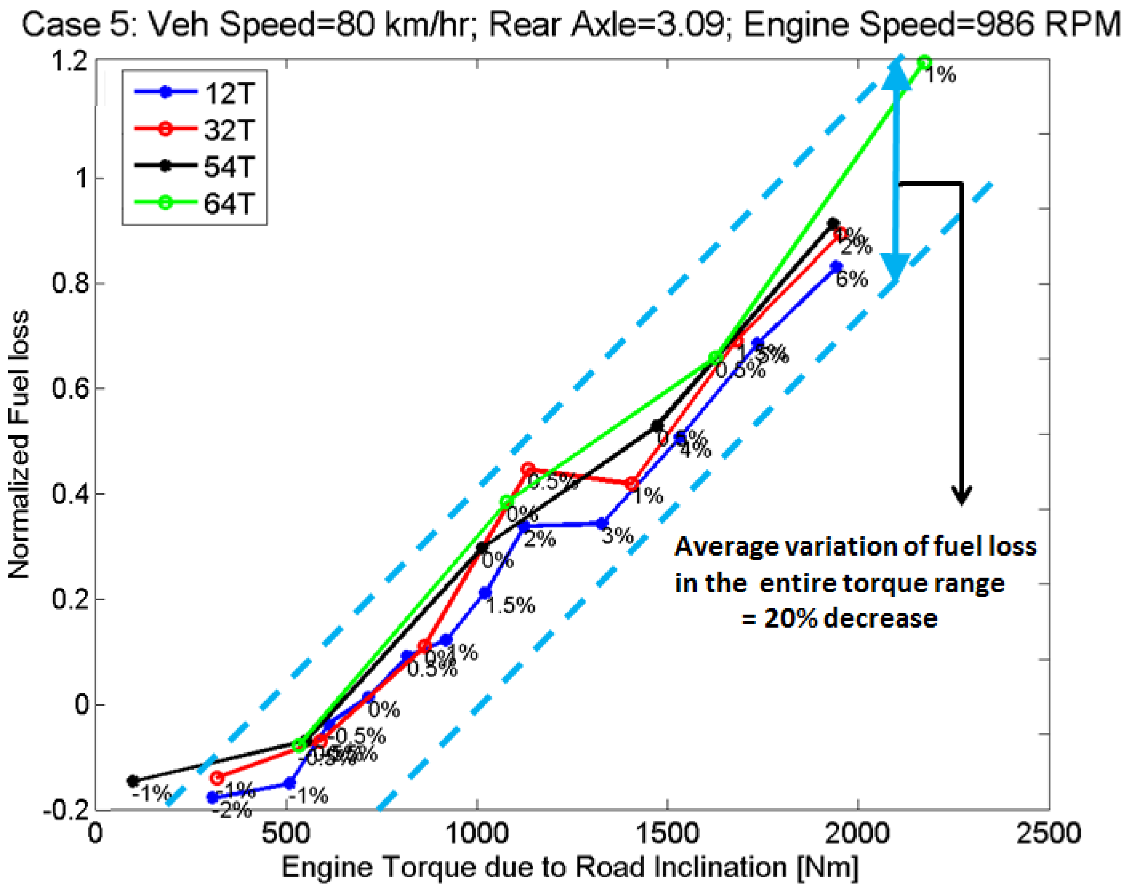


Figure 4.5: Variation of fuel loss over the entire range of engine torque

Further, from the figure 4.5, it can be seen that the average variation of fuel loss at different engine torques is around 20% when the engine torques are obtained due to different combinations of vehicle mass and road inclination. The % decrease in fuel loss at different engine torque levels due to different combinations of variables was determined similar to 4.4. Then, by taking the average of % decrease of fuel loss at many different engine torque levels, this number of 20% was obtained.

So, it can be concluded from these figures that the fuel loss at a particular engine torque level does not vary too much (around 20%), when a particular torque level is reached due to different combinations of vehicle mass and road inclination, which can be visualised from the fact that the figures for fuel loss for various vehicle masses ranging from 12T to 64T are very close to each other and lie in the band as indicated by the blue dotted line.

2. Category G2 - **Time loss based on engine torque - Engine torque is varied on the basis of road inclination, vehicle mass is constant**

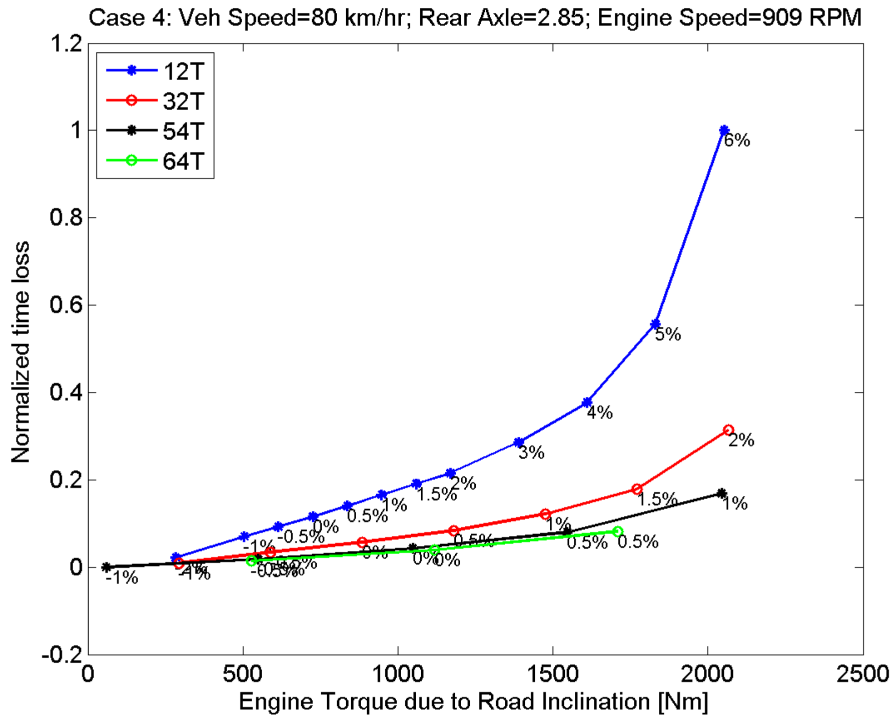


Figure 4.6: Variation of time loss against engine torque due to road inclination for Case 4

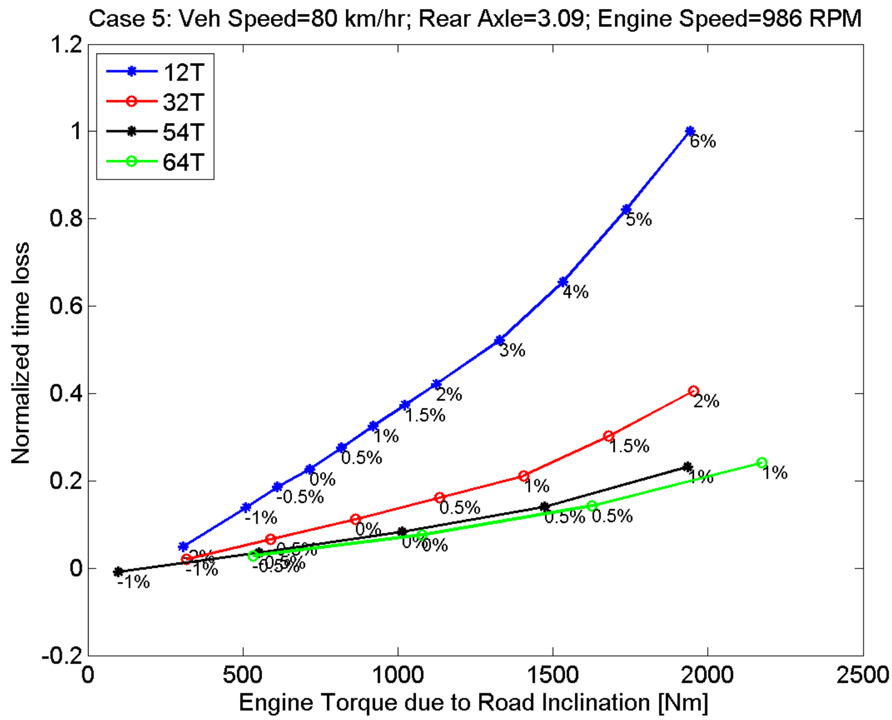


Figure 4.7: Variation of time loss against engine torque due to road inclination for Case 5

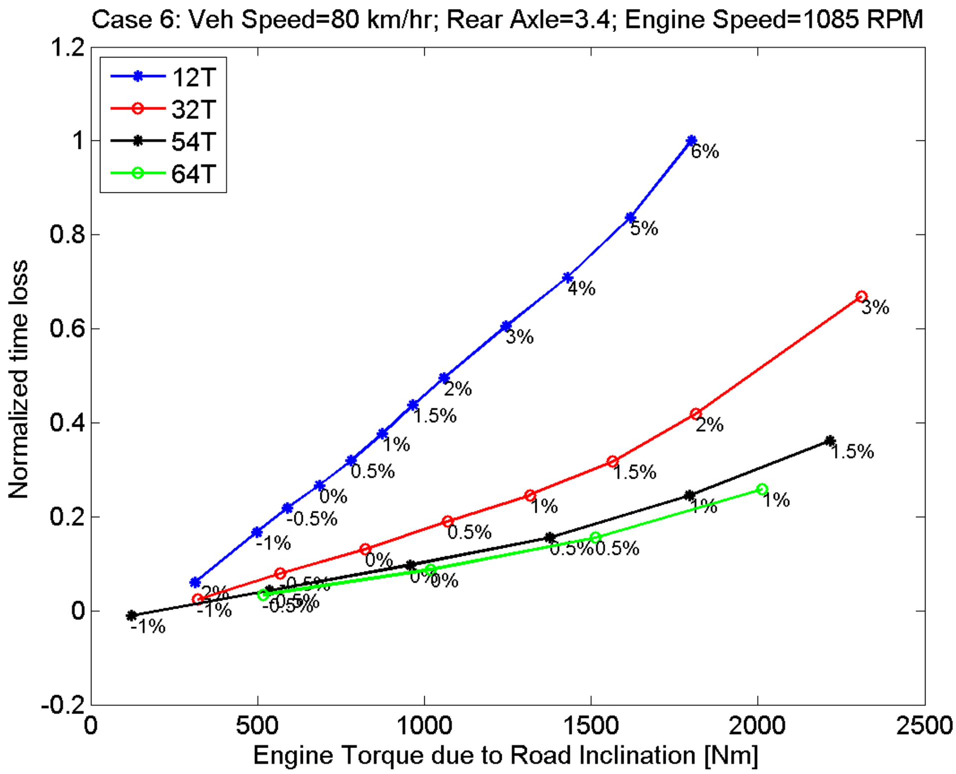


Figure 4.8: Variation of time loss against engine torque due to road inclination for Case 6

From figures 4.6, 4.7 and 4.8, the trend of time loss against engine torque can be seen. It can be clearly inferred that the time loss increases with engine torque at various inclinations. It can also be seen that as the vehicle mass increases from 12T to 64T, the time loss decreases, meaning that the heavier vehicles loose less time during a gearshift as compared to lighter vehicles. This is because of the higher inertia that the heavier vehicles possess, resulting in lesser loss of vehicle speed and consequently lesser time loss during a gearshift. And also, steeper inclination for lighter vehicles, which posses less inertia implies more speed loss.

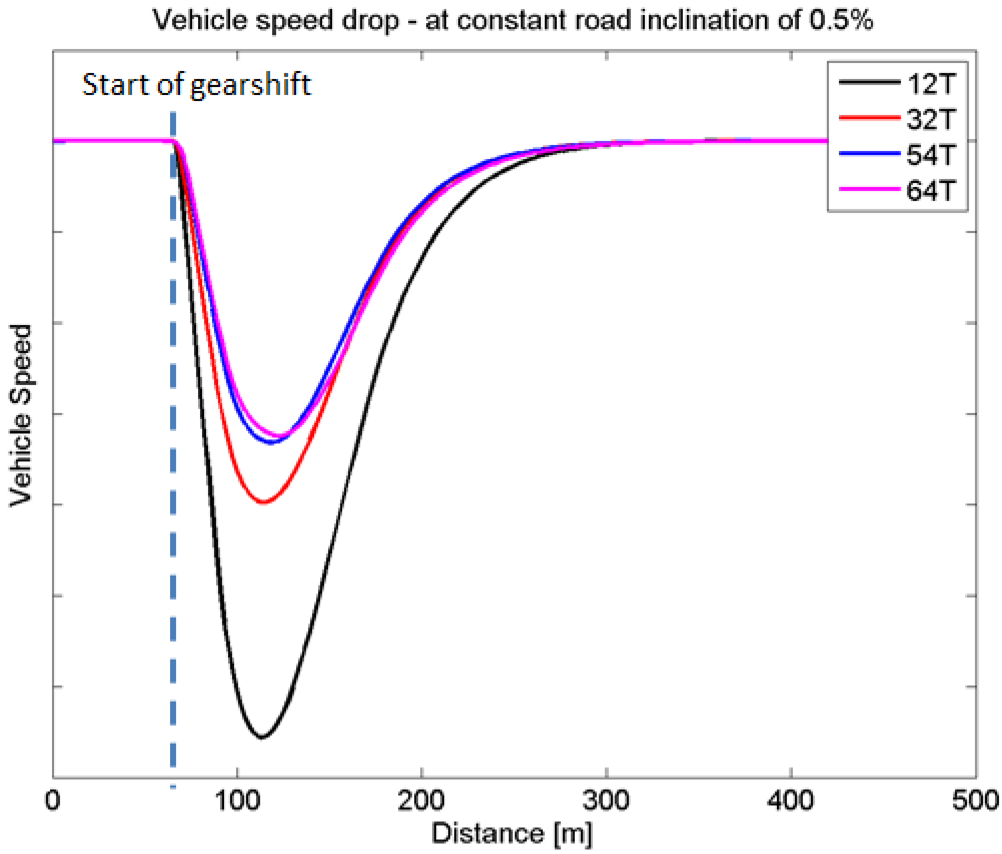


Figure 4.9: Variation of vehicle speed drop with vehicle mass

The figure 4.9 shows the variation of vehicle speed drop during a gearshift event for different vehicle masses at a constant road inclination of 0.5%, rear axle ratio of 3.09 and a particular vehicle set speed. As discussed in the previous section, it can be seen that as the vehicle mass increases, the drop in vehicle speed decreases during the gearshift event.

As can be seen in the figure 4.9, the time loss for a 12T vehicle is much more than the time loss for 32T, 54T and 64T vehicles. The difference in time loss between a 54T and 64T vehicle is small.

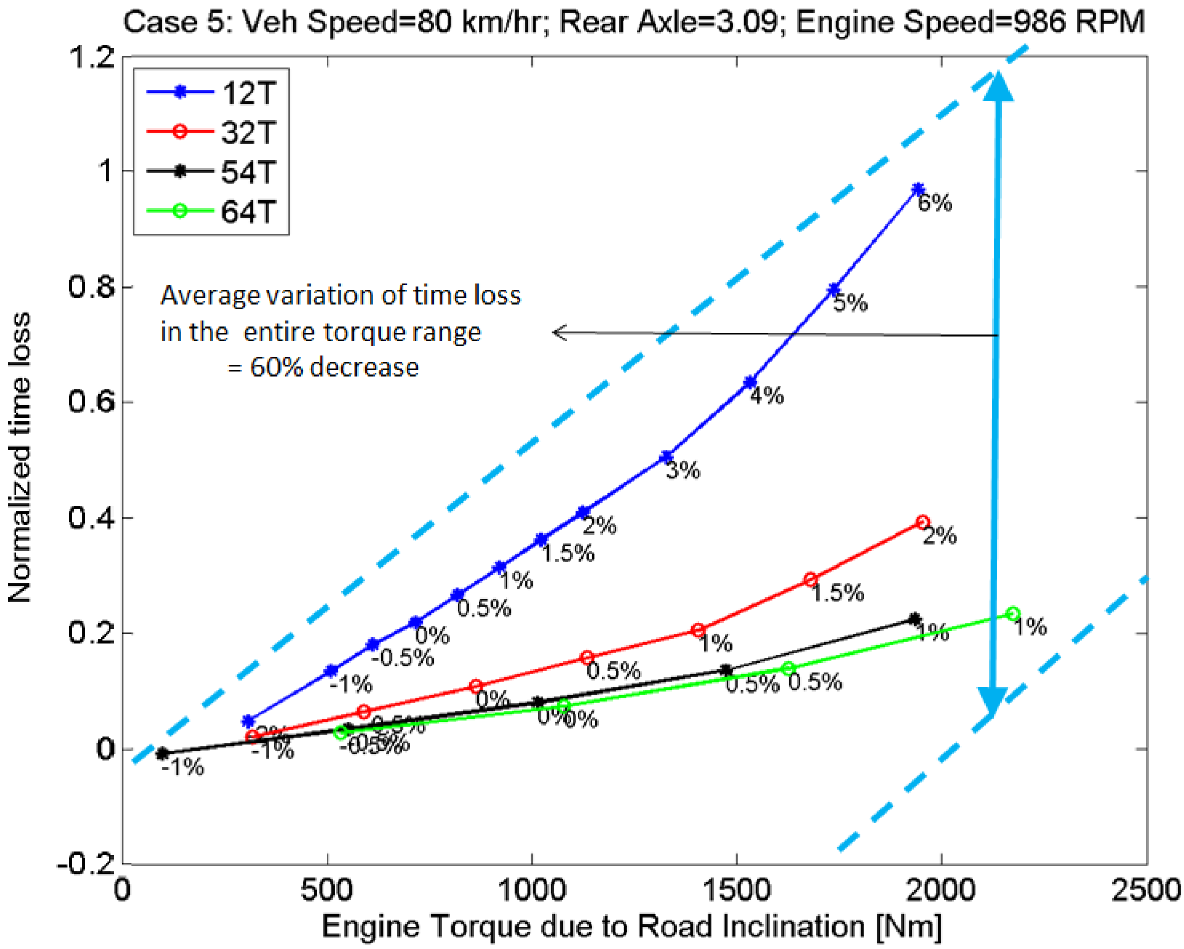


Figure 4.10: Variation of time loss in the entire torque range

From the figure 4.10, it can be observed that the time loss figures for different vehicle masses are not so close to each other as in the figure 4.5 for fuel loss and hence can be concluded that the average variation of time loss at a particular engine torque level, when this particular engine torque is reached due to different combinations of vehicle mass and road inclination is rather high (around 60%) and hence the time loss not only depends on engine torque but also on the combination of road inclination and vehicle mass which results in that particular engine torque.

For example, from the figure 4.10, an engine torque level of 1000 Nm can be reached due to various combinations such as, 12T+1.5% and 54T+0%. Although these combinations result in the same engine torque level, the variation in time loss due to these different combinations is around 80%, which is quite high.

### 4.1.2 Gearshift from gear 12 to gear 11

In case of gearshift from gear 12 to gear 11, the following combinations of vehicle speed and rear axle ratio's were used to achieve different engine speeds. The different combinations can be seen in the table 4.2.

| Case number | Combination of vehicle speed [km/h] + Rear axle ratio |
|---|---|
| 1 | 85+2.85 |
| 2 | 85+3.09 |
| 3 | 85+3.4 |
| 4 | 80+2.85 |
| 5 | 80+3.09 |
| 6 | 80+3.4 |
| 7 | 75+2.85 |
| 8 | 75+3.09 |
| 9 | 75+3.4 |

Table 4.2: Combinations of vehicle speed and rear axle ratio for gearshift from gear 12 to gear 11.

**Plots for fuel loss and time loss**

1. Category G1 - **Fuel loss based on engine torque - Engine torque is varied on the basis of road inclination, vehicle mass is constant**

   For simplicity, here, the figures for Case 4, 5 and 6 as mentioned in the table 4.2 are shown. For these cases, the vehicle speed is constant at 80 km/h and the rear axle ratio changes from case to case. The nature of the figures looks similar in other cases too.

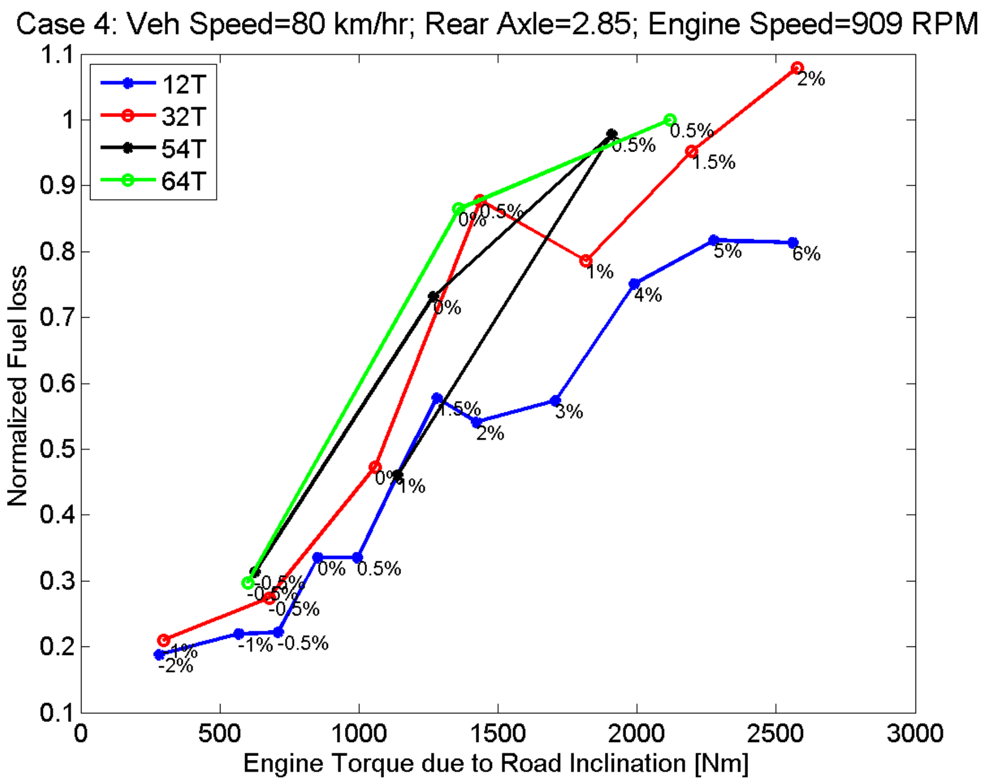


Figure 4.11: Variation of fuel loss against engine torque due to road inclination for Case 4

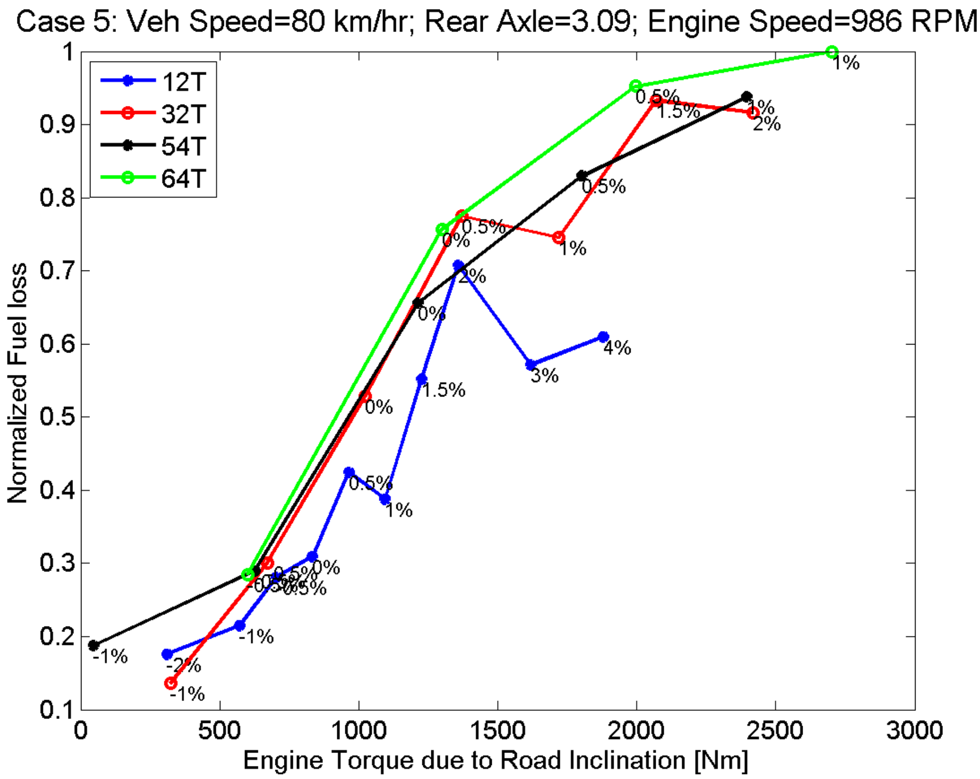


Figure 4.12: Variation of fuel loss against engine torque due to road inclination for Case 5

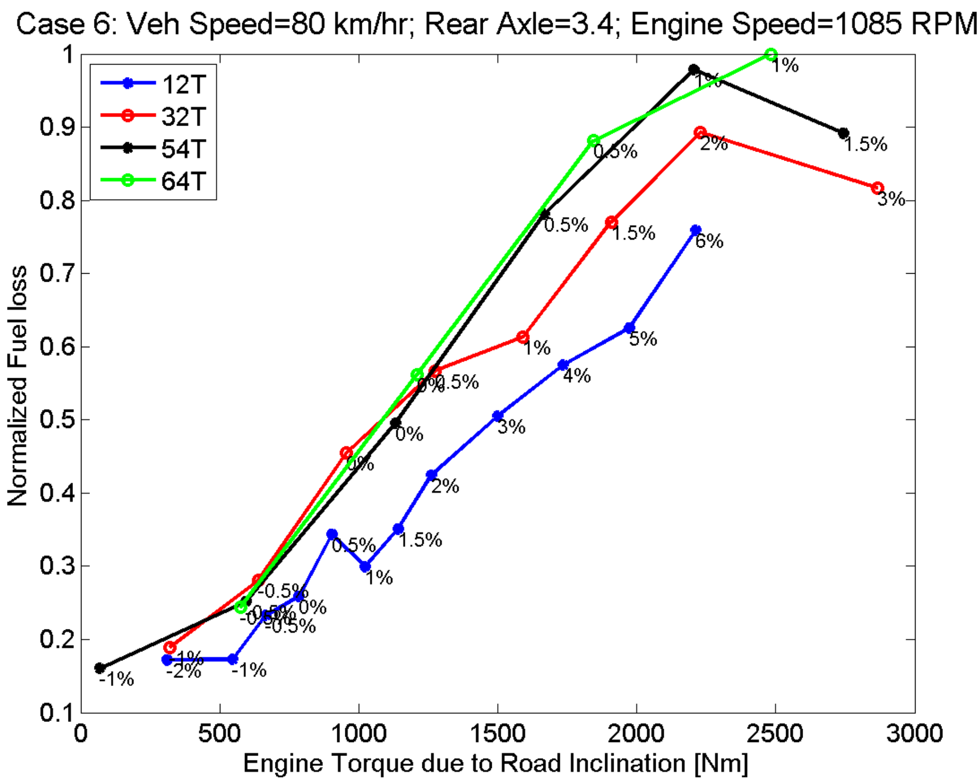


Figure 4.13: Variation of fuel loss against engine torque due to road inclination for Case 6

As can be seen from the figures 4.11, 4.12 and 4.13, the general trend of fuel loss is that it increases with the engine torque at various inclinations. In these figures, when the vehicle mass is varied from 12t to 64t, the fuel loss also increases with the vehicle mass, but the magnitude of variation of fuel loss varies at various constant inclinations. Similarly the magnitude of variation of fuel loss with road inclination depends on vehicle mass.

For example, with reference to the figure 4.13, the variation of fuel loss from a vehicle mass of 12t to 64t at different constant inclinations can be seen in the table 4.3. Similarly, the variation in fuel loss with inclination for various constant vehicle masses of 12t, 32t, 54t and 64t respectively can be seen in the table 4.4. In the table 4.4, the road inclination range differs at each vehicle mass since the vehicle speed of 80 km/h cannot be maintained out of this range.

| **Variation in vehicle mass** | **Road inclination [%]** | **Variation of fuel loss [%]** |
|---|---|---|
| 12t to 64t | 0 | 117 |
| 12t to 64t | 0.5 | 156 |
| 12t to 64t | 1 | 234 |

Table 4.3: Variation of fuel loss for vehicle mass ranging from 12t to 64t at various constant road inclinations, rear axle ratio 3.4, engine speed 1085 RPM and vehicle speed of 80 km/h.

| **Variation in Road inclination** | **Vehicle Mass [t]** | **Variation of fuel loss [%]** |
|---|---|---|
| 0% to 6% | 12 | 193 |
| 0% to 3% | 32 | 80 |
| 0% to 1.5% | 54 | 80 |
| 0% to 1% | 64 | 78 |

Table 4.4: Variation of fuel loss with road inclination at various constant vehicle masses, rear axle ratio 3.4, engine speed 1085 RPM and vehicle speed of 80 km/h.

Also in these figures, the trend for 32T, 54T and 64T vehicles are very close to each other and the figure for 12T is a bit off. The gap between different colored lines in these figures gets wider around an engine torque of 1500 Nm. And also, it can be seen particularly in figure for 12T in figures 4.11, 4.12 and 4.13 that the linear nature is disturbed at some point (for example at 0.5% in figure 4.13) with a slight dip before the linear nature starts again. This can be something to do with the behaviour of the cruise controller.

Comparing the trend of fuel loss in gearshift 11 to 12 in the figures 4.1, 4.2, 4.3 and gearshift 12 to 11 in the figures 4.11, 4.12, 4.13, the figures for fuel loss in the gearshift from 12 to 11 case are less closely spaced.

For example, from figure 4.13, an engine torque of 1300 Nm (approximately) can be reached due to a combination of 12T+2% (vehicle mass+road inclination) or due to 64T+0%. The magnitude of variation in fuel loss is around 45%. The average variation in the entire torque range is around 30% when going from a vehicle mass of 12T to 64T.

2. Category G2 - **Time loss based on engine torque - Engine torque is varied on the basis of road inclination, vehicle mass is constant**

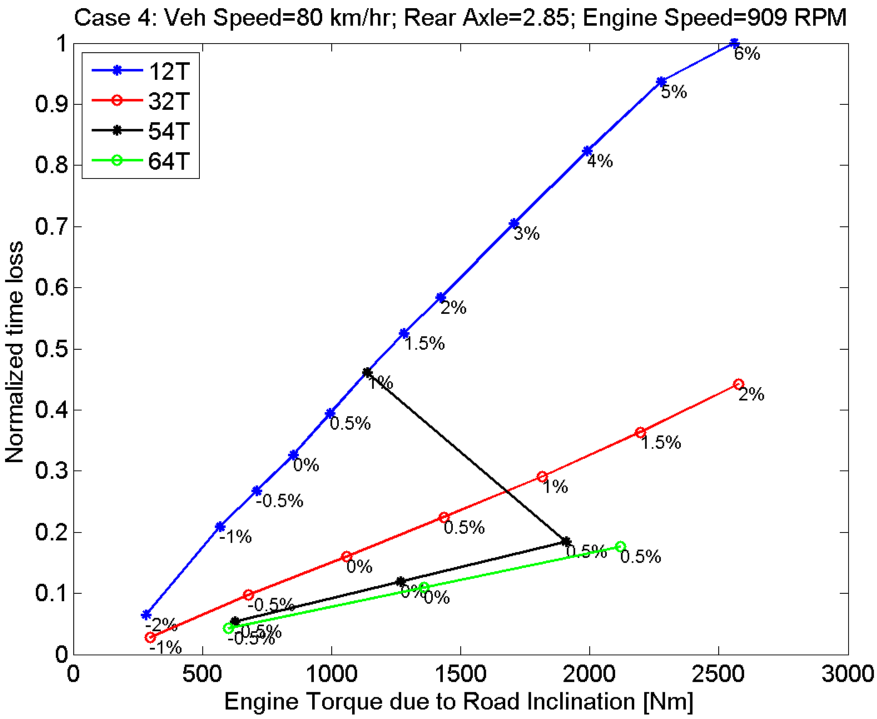


Figure 4.14: Variation of time loss against engine torque due to road inclination for Case 4

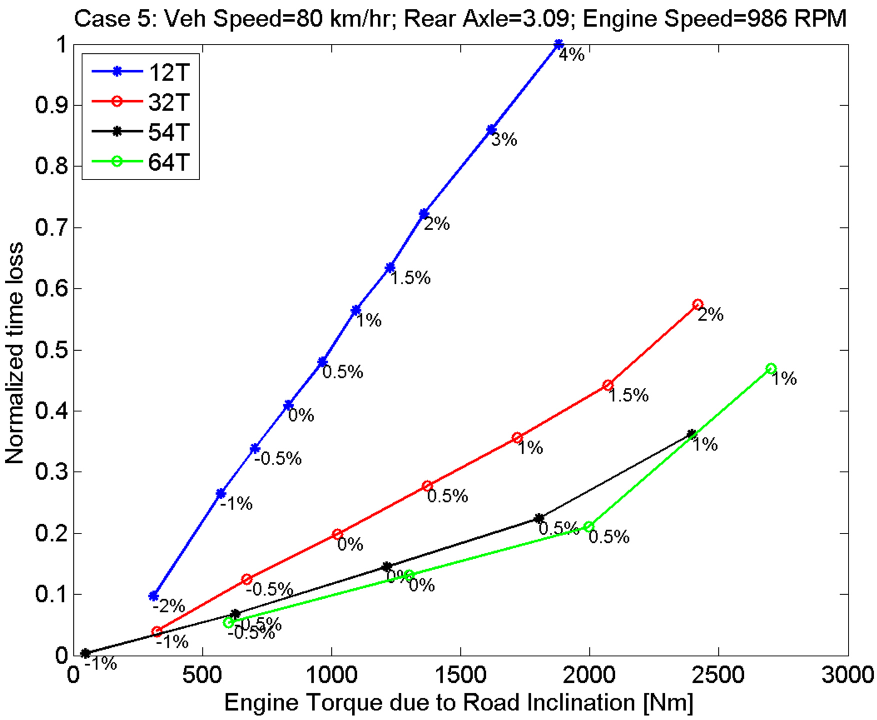


Figure 4.15: Variation of time loss against engine torque due to road inclination for Case 5

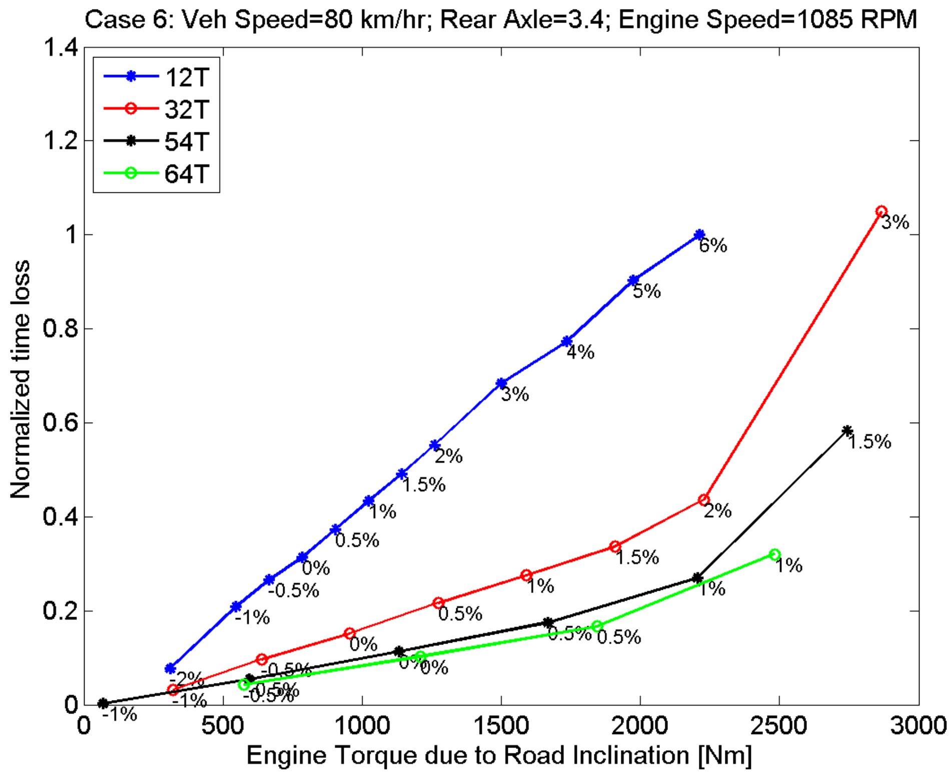


Figure 4.16: Variation of time loss against engine torque due to road inclination for Case 6

From figures 4.14, 4.15 and 4.16, it can be clearly seen that the time loss follows an increasing trend based on engine torque due to road inclination. But, for increase in vehicle mass from 12T to 64T, the time loss decreases for reasons explained in section 2.

Also, for instance, from figure 4.16, for an engine torque level of 1300 Nm, it matters on whether this particular engine torque is demanded due to the combinations of 32T+0.5% or 12T+2%, since for the same torque level, the variation in time loss is around 62% due to different combinations. Similarly, the variation in time loss over the entire torque range is around 60%, which is quite high. So, the conclusion is that, when it comes to time loss at a particular engine torque level, it depends on the combination of vehicle mass and inclination which results in reaching that particular torque level.

## 4.2 Thumb rules

Thumb rules are formulated for fuel loss and time loss during gearshift from gear 11 to 12 and from gear 12 to gear 11 with respect to various variables like engine torque, engine speed, road inclination, vehicle mass, rear axle ratio and vehicle speed.

### 4.2.1 Gearshift from gear 11 to gear 12

For gearshift from gear 11 to 12, as stated in the table 4.1, there are 9 different cases consisting of different combinations of rear axle ratio and vehicle speed resulting in 9 different engine speeds.

The thumb rules for fuel loss and time loss for one such case (Case 5) according to the table 4.1 are formulated according to the table 4.5. The values are not tabulated in the table 4.5 because of the confidentiality agreement. The values for different variables used while formulating these thumb rules are:

- Vehicle speed = 80 km/h
- Rear axle ratio = 3.09

| Road Inclination [%] | Vehicle Mass [T] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 12T | | 32T | | 54T | | 64T | |
| | Engine Torque [Nm] | Fuel loss [g] | Engine Torque [Nm] | Fuel loss [g] | Engine Torque [Nm] | Fuel loss [g] | Engine Torque [Nm] | Fuel loss [g] |
| -2 | | | | | | | | |
| -1 | | | | | | | | |
| -0,5 | | | | | | | | |
| 0 | | | | | | | | |
| 0,5 | | | | | | | | |
| 1 | | | | | | | | |
| 1,5 | | | | | | | | |
| 2 | | | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | |
| 6 | | | | | | | | |

Table 4.5: Thumb rules for fuel loss for gearshift from gear 11 to gear 12 for vehicle speed of 80 km/h, rear axle ratio 3.09

Similarly, thumb rules are also formulated for time loss based on the same set of variables.

### 4.2.2 Gearshift from gear 12 to gear 11

Similarly, the thumb rules for gearshift from gear 12 to gear 11 was also determined for all cases according to the table 4.2. They have been tabulated in the table 4.6. The values are not tabulated in the table 4.6 because of the confidentiality agreement.

| Road Inclination [%] | Vehicle Mass [T] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 12T | | 32T | | 54T | | 64T | |
| | Engine Torque [Nm] | Fuel loss [g] | Engine Torque [Nm] | Fuel loss [g] | Engine Torque [Nm] | Fuel loss [g] | Engine Torque [Nm] | Fuel loss [g] |
| -2 | | | | | | | | |
| -1 | | | | | | | | |
| -0,5 | | | | | | | | |
| 0 | | | | | | | | |
| 0,5 | | | | | | | | |
| 1 | | | | | | | | |
| 1,5 | | | | | | | | |
| 2 | | | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | |
| 6 | | | | | | | | |

Table 4.6: Thumb rules for fuel loss for gearshift from gear 12 to gear 11 for vehicle speed of 80 km/h, rear axle ratio 3.09

## 4.3 Relative loss comparison study

From the previous section, the thumb rules or the losses in fuel and time are calculated. But, till now the fuel and time loss are equally weighted and to have a better understanding a comparison study is made.

This study is made by running simulations for Borås-Landvetter-Borås (BLB) drive cycle to find the total fuel and total time consumed for the journey. The relative fuel/time loss is then calculated by dividing the total fuel/time loss for gearshift from gear 11 to 12 and back from gear 12 to 11 which is obtained from thumb rules by the total fuel/time taken for BLB drive cycle.

$$Relative\ Fuel\ loss = \frac{Fuel\ loss\ for\ 11\ to\ 12\ gearshift + Fuel\ loss\ for\ 12\ to\ 11\ gearshift}{Total\ fuel\ consumed\ for\ BLB\ cycle} \tag{4.1}$$

$$Relative\ Time\ loss = \frac{Time\ loss\ for\ 11\ to\ 12\ gearshift + Time\ loss\ for\ 12\ to\ 11\ gearshift}{Total\ Time\ taken\ for\ BLB\ cycle} \tag{4.2}$$

The relative fuel loss for different cases of vehicle mass, rear axle ratio and road inclination for a vehicle speed of 80 km/h are shown in the table 4.7, however the results for all cases can be found in appendix. Similarly, the relative time loss is listed in the table 4.8.

| Road inclination (%) | Relative fuel loss for vehicle speed of 80 km/h | | | | | |
|---|---|---|---|---|---|---|
| | Rear axle ratio - 2.85 | | Rear axle ratio - 3.09 | | Rear axle ratio - 3.4 | |
| | 12 Ton | 54 Ton | 12 Ton | 54 Ton | 12 Ton | 54 Ton |
| | Fuel loss (%) | Fuel loss (%) | Fuel loss (%) | Fuel loss (%) | Fuel loss (%) | Fuel loss (%) |
| -2 | 0.0010 | 0.0000 | 0.0000 | 0.0002 | 0.0000 | 0.0000 |
| -1 | 0.0020 | 0.0000 | 0.0000 | 0.0009 | 0.0030 | 0.0012 |
| -0.5 | 0.0050 | 0.0028 | 0.0030 | 0.0028 | 0.0050 | 0.0032 |
| 0 | 0.0080 | 0.0114 | 0.0110 | 0.0106 | 0.0060 | 0.0096 |
| 0.5 | 0.0090 | 0.0182 | 0.0180 | 0.0150 | 0.0090 | 0.0157 |
| 1 | 0.0130 | 0.0156 | 0.0210 | 0.0203 | 0.0100 | 0.0216 |
| 1.5 | 0.0180 | 0.0000 | 0.0000 | 0.0000 | 0.0120 | 0.0255 |
| 2 | 0.0190 | 0.0000 | 0.0000 | 0.0000 | 0.0160 | 0.0000 |

Table 4.7: Relative fuel loss table

| Road inclination (%) | Relative time loss for vehicle speed of 80 kmph | | | | | |
|---|---|---|---|---|---|---|
| | Rear axle ratio - 2.85 | | Rear axle ratio - 3.09 | | Rear axle ratio - 3.4 | |
| | 12 Ton | 54 Ton | 12 Ton | 54 Ton | 12 Ton | 54 Ton |
| | Relative loss (%) | Relative loss (%) | Relative loss (%) | Relative loss (%) | Relative loss (%) | Relative loss (%) |
| -2 | 0.0010 | 0.0000 | 0.0010 | 0.0000 | 0.0010 | 0.0000 |
| -1 | 0.0020 | 0.0000 | 0.0020 | 0.0000 | 0.0002 | 0.0000 |
| -0.5 | 0.0020 | 0.0004 | 0.0020 | 0.0000 | 0.0020 | 0.0000 |
| 0 | 0.0030 | 0.0010 | 0.0030 | 0.0010 | 0.0030 | 0.0010 |
| 0.5 | 0.0040 | 0.0030 | 0.0040 | 0.0030 | 0.0040 | 0.0020 |
| 1 | 0.0040 | 0.0030 | 0.0040 | 0.0030 | 0.0040 | 0.0020 |
| 1.5 | 0.0040 | 0.0000 | 0.0050 | 0.0000 | 0.0050 | 0.0040 |
| 2 | 0.0050 | 0.0000 | 0.0050 | 0.0000 | 0.0050 | 0.0000 |

Table 4.8: Relative time loss table

In order to understand the effect of the fuel and time loss, the results for the case of vehicle mass 12 ton, rear axle ratio 2.85 and vehicle speed of 80 km/h is plotted. The figure 4.17 shows the variation of relative fuel and time losses for different road inclinations. Now, figure 4.18 shows the relative time and fuel loss for vehicle mass of 54 ton, rear axle ratio of 2.85 and vehicle speed of 80 km/h where it is clear that the time loss in most of the cases is less than 15% of the fuel loss. However, the effect of time loss varies for different cases in the table but it is always minimal compared to fuel loss. So, it is evident from this study that effect of time losses for the case of 12 ton is relatively more important to be considered as compared to that of the case of 54 ton where time losses are very minimal when compared to fuel losses. But, since the time losses are relatively less (around 10 to 15% of fuel loss) in most of the cases (vehicle mass > 30T, which are majority) when compared to fuel losses, it can be given less importance in further calculations and study.

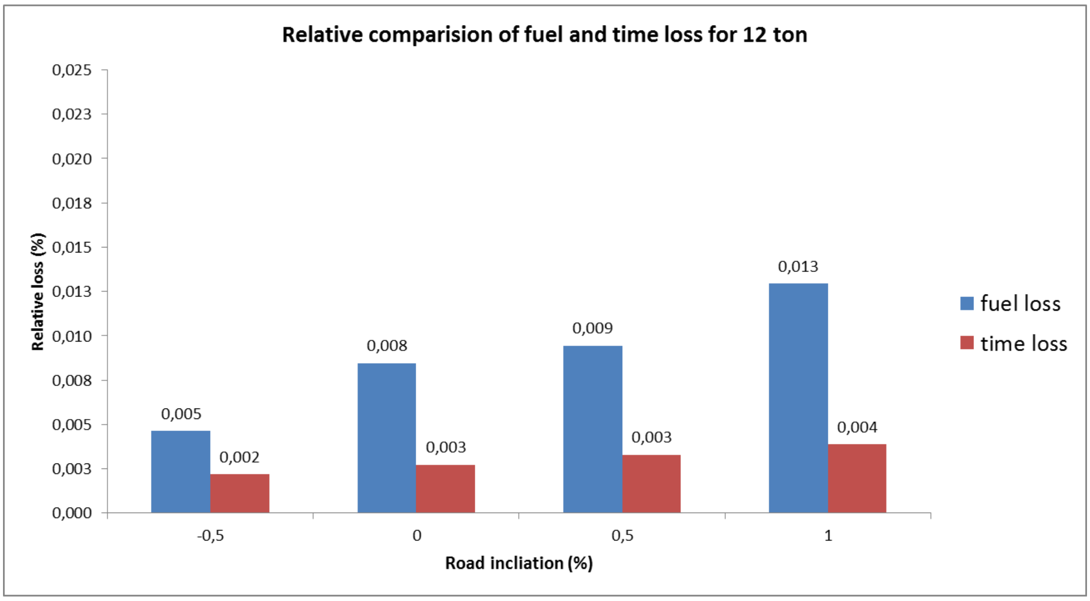


Figure 4.17: Relative fuel and time loss comparison for 12 ton, rear axle ratio of 2.85 and vehicle speed of 80 km/h

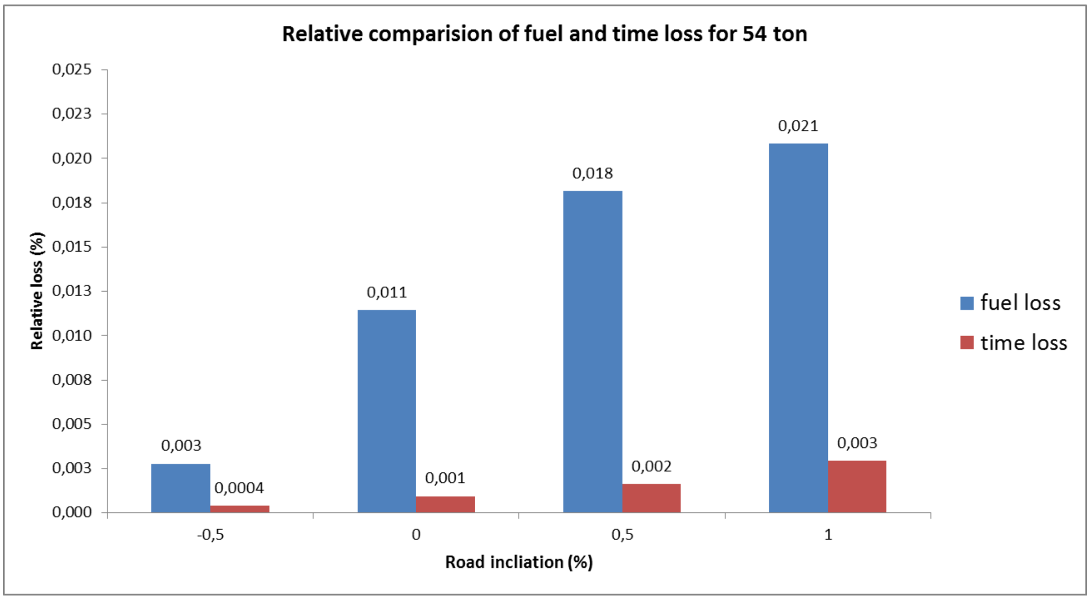


Figure 4.18: Relative fuel and time loss comparison for 54 ton, rear axle ratio of 2.85 and vehicle speed of 80 km/h

### 4.3.1 Holistic study

From the previous section, it is clear that the effect of time loss is minimal when compared to fuel loss. In order to quantify magnitude of fuel loss during gearshifts holistically and understand the importance of it, a holistic study of cost of gearshifts is made. The study is made with the BLB drive cycle and the other parameter values which are used are detailed as follows:

- Vehicle mass = 64 ton
- Rear axle ratio = 3.4
- Vehicle speed = 80 km/h

By simulating with these specifications, the total fuel consumed and the total number of gearshifts between gears 11 and 12 for BLB cycle is calculated.

The average fuel loss per shift is found using the thumb rules. Since the total number of gearshifts between gear 11 and 12 is also found, the total fuel loss due to all shifts between gear 11 and 12 is calculated. So, the fuel lost due to gearshifts between gear 11 and 12 during the whole journey on BLB is determined as a percentage of the total fuel consumed for the entire journey on BLB,

$$Fuel\ lost = \frac{Total\ fuel\ loss\ due\ to\ all\ gearshifts\ between\ gear\ 11\ and\ 12\ on\ BLB}{Total\ fuel\ consumed\ for\ the\ whole\ journey\ on\ BLB} \tag{4.3}$$

The obtained magnitude of the fuel lost is an interesting quantity in this holistic study. Analysis can be made if this quantity is low or high and appropriate measures can be taken if the loss is high.

## 4.4 Results from truck testing

As mentioned in section 3.3.4, measurements during truck testing were made to estimate the fuel loss and time loss during a gearshift. The measurements were made in the sequence mentioned as follows:

- Firstly, a stretch of road was chosen to carry out the measurements. The BLB cycle was chosen in this case.
- Within the BLB cycle, various segments of roads with near constant inclination were chosen, where the measurements are made.

In order to check the repeat-ability and consistency of the measurements, the following types of measurements were made:

### 4.4.1 Measurements in same run

In this type of measurements, multiple measurements were carried out at similar constant inclination stretches at different distances during the same run. Here, '1 run' stands for running on BLB cycle once.

| **Vehicle distance [km]** | **Road inclination [%]** |
|---|---|
| 2 | 0 |
| 3.5 | 1 |
| 5 | 1.5 |
| 8.3 | 0 |
| 10.8 | 2.5 |
| 14.3 | 0.5 |
| 18.6 | 1 |
| 20.3 | 0.5 |
| 25.8 | 1.5 |
| 30.4 | 1 |

Table 4.9: Measurement during truck testing in the same run

As can be seen in the table 4.9, measurements were made at different distances and respective inclinations during the same run. Then, to check the consistency and repeat-ability of the results, comparison is made between the results obtained at different distances at same inclination during the same run. For example, from table 4.9, comparison is made between the results obtained at distances of 2km and 8.3km, distances where the inclination is same (0%).

### 4.4.2 Measurements in same run - Gearshift from gear 11 to gear 12

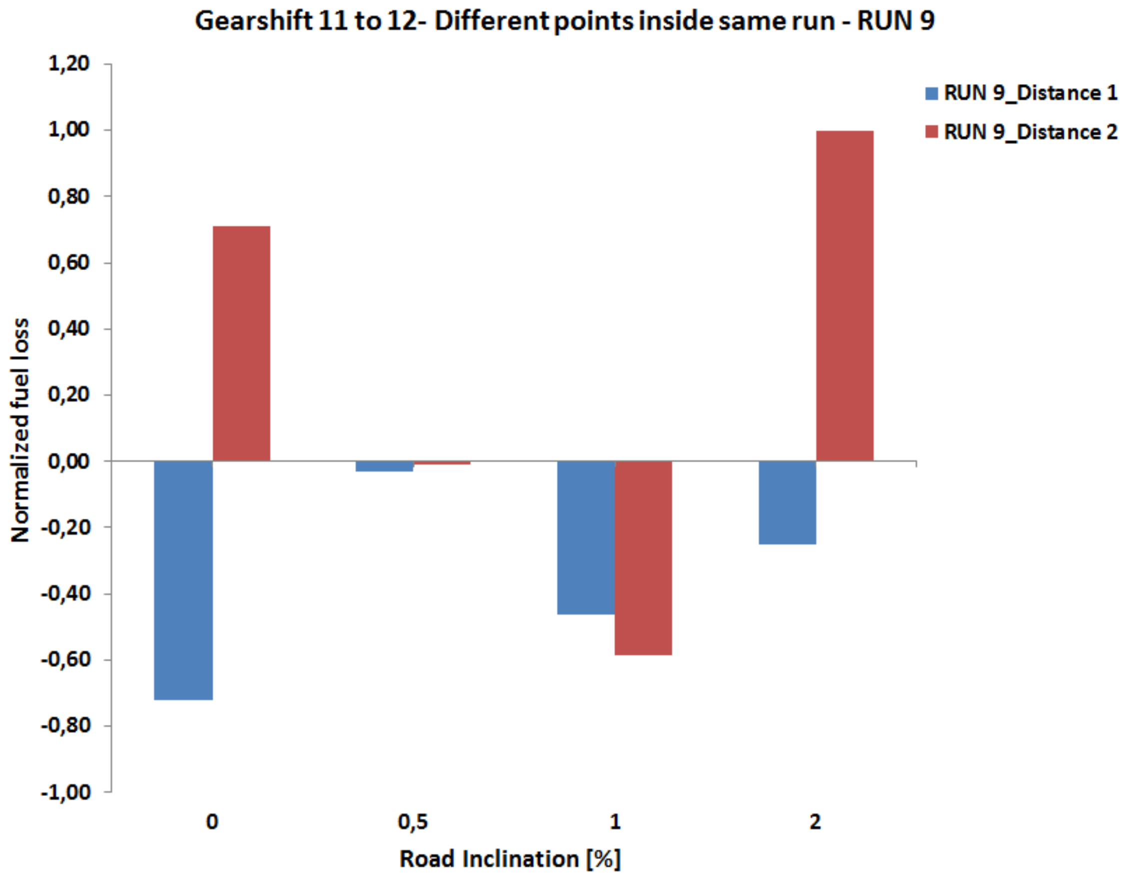


Figure 4.19: Comparison of fuel loss for gearshift 11 to 12 obtained from measurements in same run-RUN 9

The figure 4.19 shows the comparison of fuel loss for gearshift 11 to 12, measured at different distances during the same run. The blue and red bars indicate the magnitude of fuel loss at a particular inclination, but at two different distances. For instance, in the figure 4.19, the fuel loss at 2% road inclination, measured at distance 1 is -0.4 and at distance 2 is 1.

The average variation between the fuel loss values measured at distance 1 and distance 2 at various inclinations in figure 4.19 was more than 100%, which is quite high. The reference value for determining the % of average variation in fuel loss here is the fuel loss values at distance 1.

### 4.4.3 Measurements in same run - Gearshift from gear 12 to gear 11

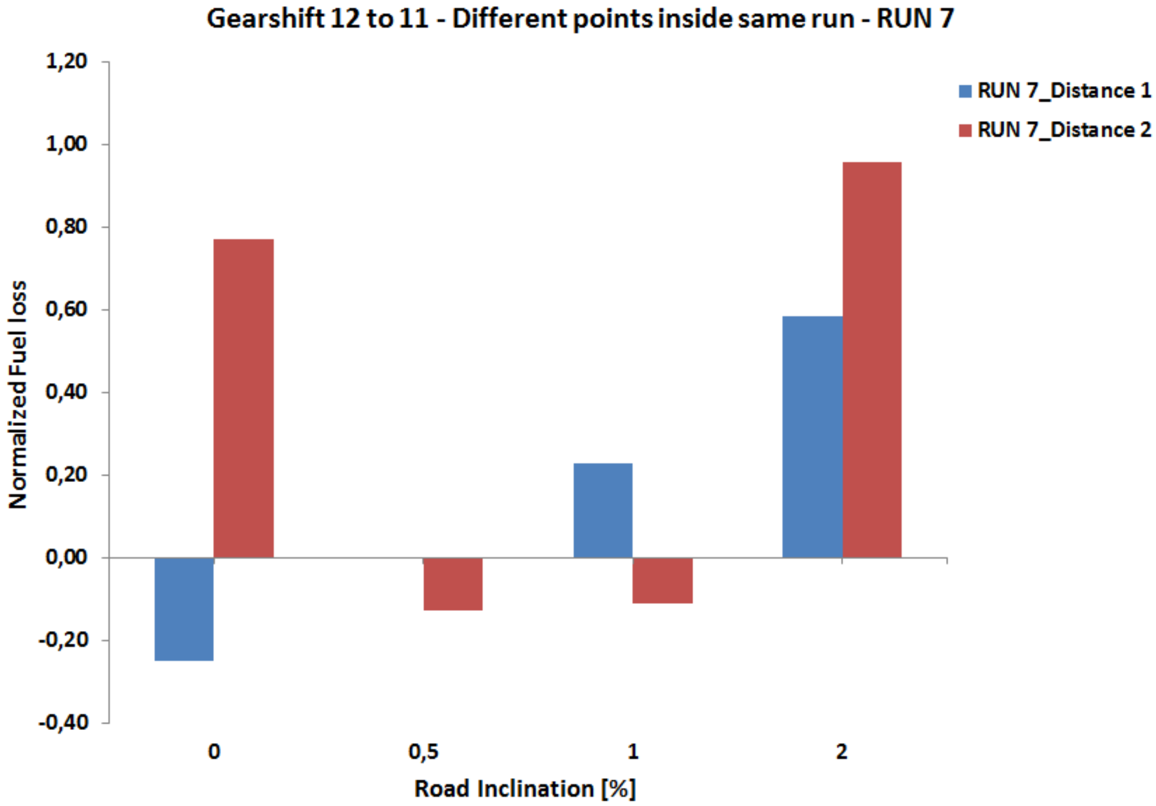


Figure 4.20: Comparison of fuel loss for gearshift from 12 to 11 obtained from measurements in same run-RUN 7

The figure 4.20 shows the comparison of fuel loss for gearshift 12 to 11, measured at different distances during same run. The blue and red bars indicate the magnitude of fuel loss at a particular inclination, but at two different distances. For instance, in the figure 4.20, the fuel loss at 2% road inclination, measured at distance 1 is 0.6 and at distance 2 is 0.9.

The average variation between the fuel loss values measured at distance 1 and distance 2 at various inclinations in figures 4.19 and 4.20 are more than 100%, which is quite high. The reference value for determining this % variation is the fuel loss values at distance 1.

In the figures 4.19 and 4.20, it has to be noted that the fuel loss values at some inclinations are negative. When the fuel losses are determined from measurements, measured values from two different runs (that is one run with shift and one run in the upcoming gear) are used. Fuel loss is then determined by taking the difference between fuel consumed in the run with shift and fuel consumed in the upcoming gear, which is used as a reference as indicated by equation 4.4.

$$\text{Fuel loss during gearshift from point A to B} = 1 - 2$$

1 = Fuel consumed in run with gearshift from point A to B
2 = Fuel consumed without shift from point A to B by running on upcoming gear
(4.4)

So, when the fuel loss is negative, it usually does not mean that the quantity 2 is more than quantity 1 in the equation 4.4 although mathematically it may not seem so, because the quantity 1 is usually greater than quantity 2.

As quantity 1 and quantity 2 are measured in different runs to determine the fuel loss, the negative fuel loss could be because of incorrect measurement data.

From the magnitude of variation in fuel loss results at different distances during the same run, it can be concluded that the fuel loss results are not consistent/repeatable. Some of the reasons this could have happened is that:

- At different distances in each run, although the comparison is made between the points at which inclinations are same, the band for a particular inclination was slightly different at different distances.

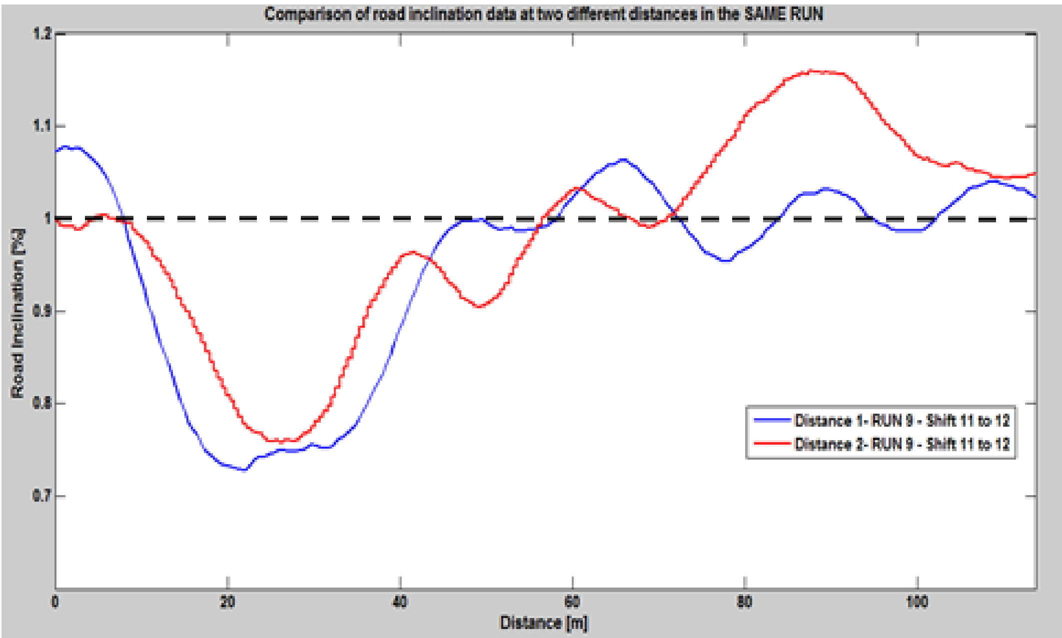


Figure 4.21: Comparison of inclination band for the same inclination at different distances in the same run

  For instance, with reference to figure 4.21, in RUN 9, for a constant inclination of 1% at distance 1, the inclination band chosen was 0.8% to 1.2%. Whereas in the same RUN 9, for a near constant inclination of 1% at distance 2, the inclination band chosen was 0.9% to 1.3%. This minor variation results in minor variation of the torque demand and consequently minor variation in fuel consumption values.

- The way in which the history looks like with respect to inclination and torque demand before the gearshift is triggered could be different at different distances. Due to this, the engine torque and speed before the shift could be slightly different and hence the fuel and time losses measured could be slightly different.

- During testing on road and recording data, before triggering a gearshift, steady state conditions could be ensured by waiting for long enough, if there is a stretch of road available for enough distance with constant inclination. But, in this case, since the constant inclination stretches were chosen from within the segments from BLB, it may not be always that the steady state conditions are reached due to availability of the constant inclination stretch for a limited distance.

### 4.4.4 Measurements in different runs - Gearshift from gear 11 to gear 12

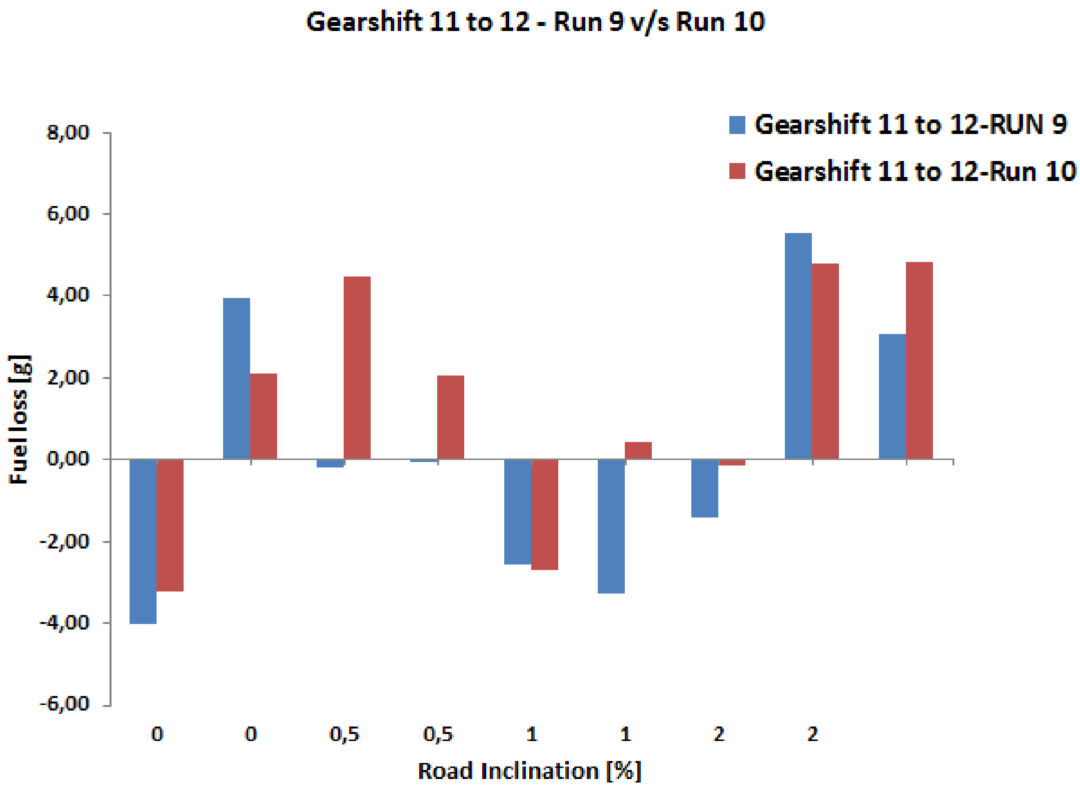


Figure 4.22: Comparison of fuel loss for gearshift from gear 11 to gear 12 obtained from measurements in different runs

Figure 4.22 shows the comparison between fuel loss during gearshift 11 to 12, obtained from two different runs at particular road inclinations. Here, measurements were made at the same distances (of similar road inclinations), but in two different runs to check the repeat-ability and consistency between the results.

For instance, in the figure 4.22, at 0% road inclination, the fuel loss obtained from run 9 is 4g, whereas that obtained from run 10 is 2g. So, the variation of fuel loss is a 100% increase. Although the trend of fuel loss at various inclinations looks similar, the magnitude differs. The average variation of fuel loss measured at same distances, but from different runs at all inclinations is more than 100%, which is quite high. This number was obtained by taking simple average of % variation (increase) of fuel losses at each inclination as shown in figure 4.22.

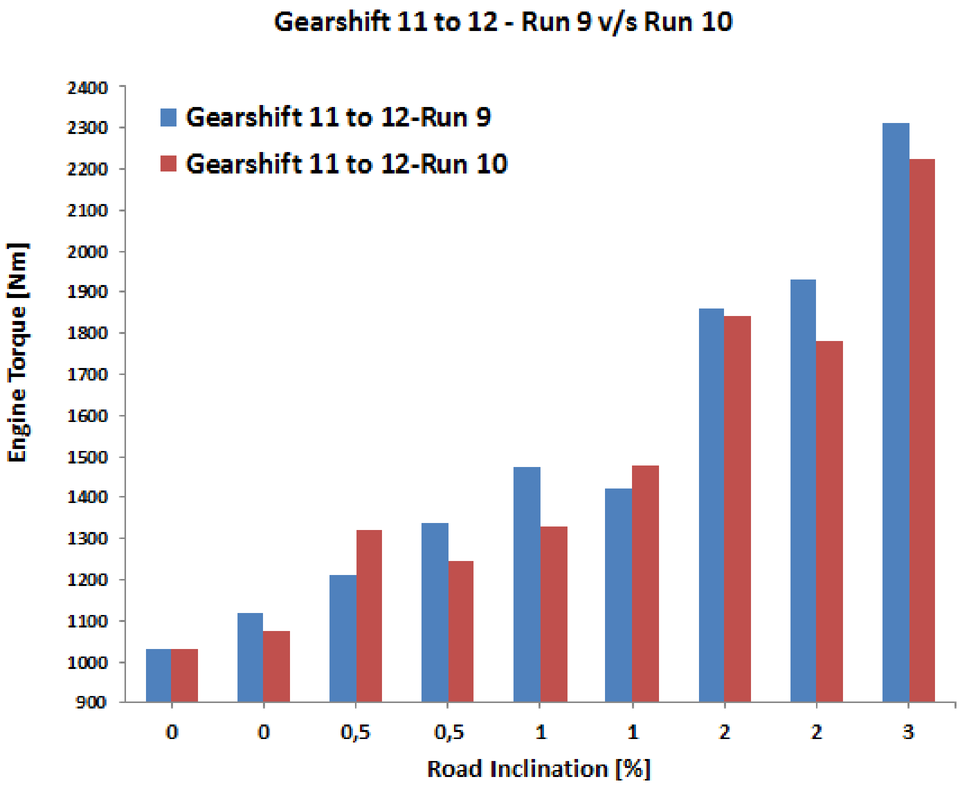


Figure 4.23: Comparison of engine torque on gear 11 before gearshift 11 to 12 obtained from measurements in different runs

Figure 4.23 shows the comparison between engine torque on gear 11, just before shifting from gear 11 to 12, obtained from two different runs at particular road inclinations. Here, the measurements were made at same distances (of similar road inclinations), but in two different runs to check the repeat-ability and consistency between the results.

For instance, in the figure 4.23, the average variation of engine torque measured at same distances, but from different runs at all inclinations is around 5%, which is quite low. So, the measurement of engine torque was quite consistent across various inclinations. The consistency of engine torque measurement is important for determining the fuel loss since the fuel loss is quite sensitive to engine torque levels. From this result, it can be concluded that, since the engine torque measurements looks consistent, the error in fuel loss results are not due to the inconsistent measurement of engine torque data or the contribution of error in engine torque measurement to fuel loss results is very less.

The measurements made with gearshift 12 to 11 had similar results.

Some of the reasons for large variation of fuel loss measured from different runs could be:

- The precise distance at which the shift was made in different runs could have differed slightly as the shift was triggered on the basis of monitoring the distance travelled manually and minor errors could have occurred in not triggering the shift at exactly the same points in different runs.
- Since fuel loss is the thing which is of concern, it is a few grams of fuel which we are speaking about and it is difficult to achieve the level of measurement accuracy and repeat-ability from different sensors to account such a small fuel quantity during testing on a truck.

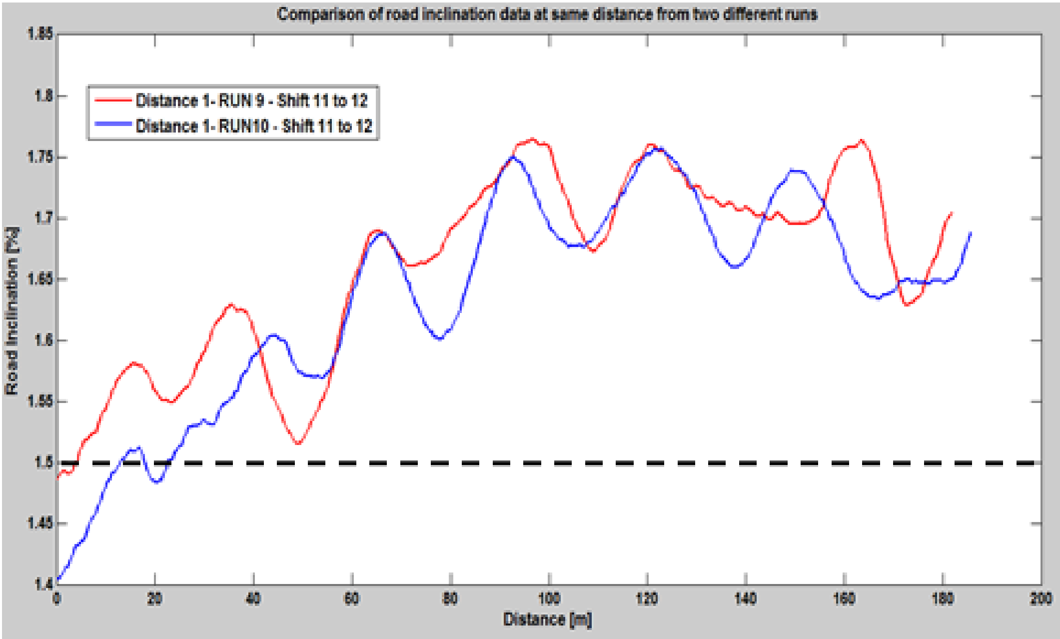


Figure 4.24: Comparison of inclination band for the same inclination at same distance in the different runs

As can be seen in the figure 4.24, for a constant inclination of 1.5%, even though the inclination band chosen is 1.4% to 1.75%, which is the same in different runs (RUN 9 and RUN 10), it can be seen that the road inclination data differs slightly when measured in different runs. In addition to what was discussed in figure 4.21 with respect to different inclination bands, it can now be concluded that even though the inclination band is same, the measurement data at different distances could differ slightly.

## 4.5 Comparison between results from testing in truck and Simulation results from GSP

For the results in this section, various parameters are compared between the results obtained from testing in truck using ATI Vision and simulation results from GSP.
In order to make a fair comparison between the simulation data and testing data, for the simulation in GSP, the road input is mimicked from the road data obtained in Vision during testing in truck as shown in figure 3.15.

### 4.5.1 Gearshift from gear 12 to gear 11

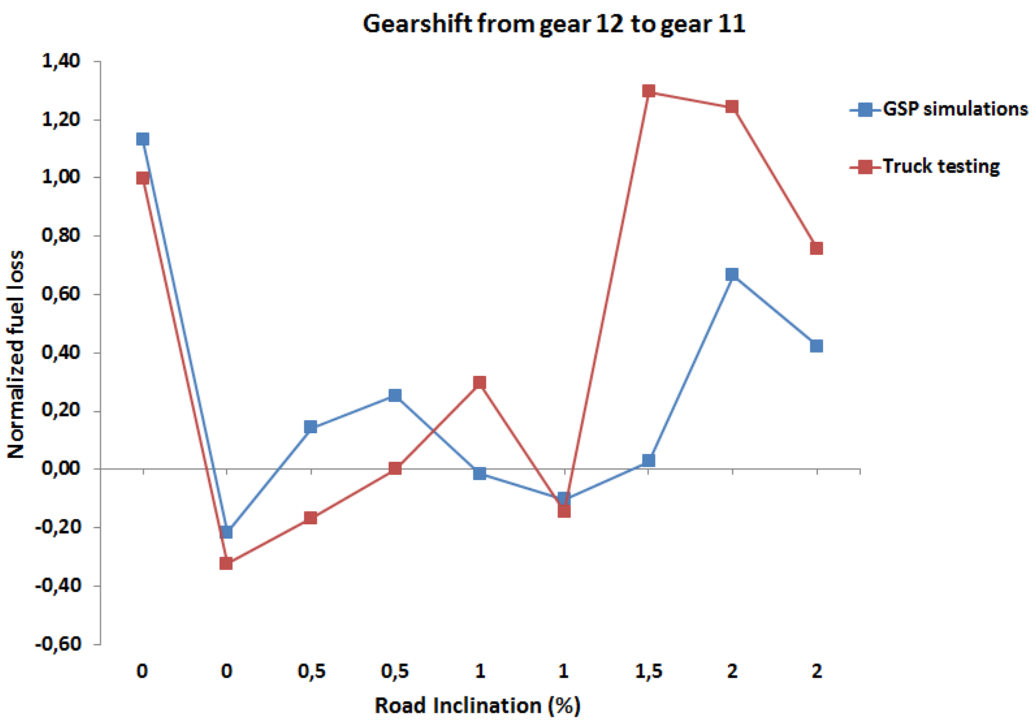


Figure 4.25: Comparison of fuel loss for gearshift from 12 to 11 obtained from testing in truck (in RUN 7) and simulation results from GSP

The figure 4.25 shows the comparison between fuel loss obtained from truck testing and GSP simulation. As can be seen from this figure, although the trend of fuel loss at various inclinations is similar, the magnitude differs. Here, the average variation in fuel loss at various inclinations is around 70%, which is quite high.

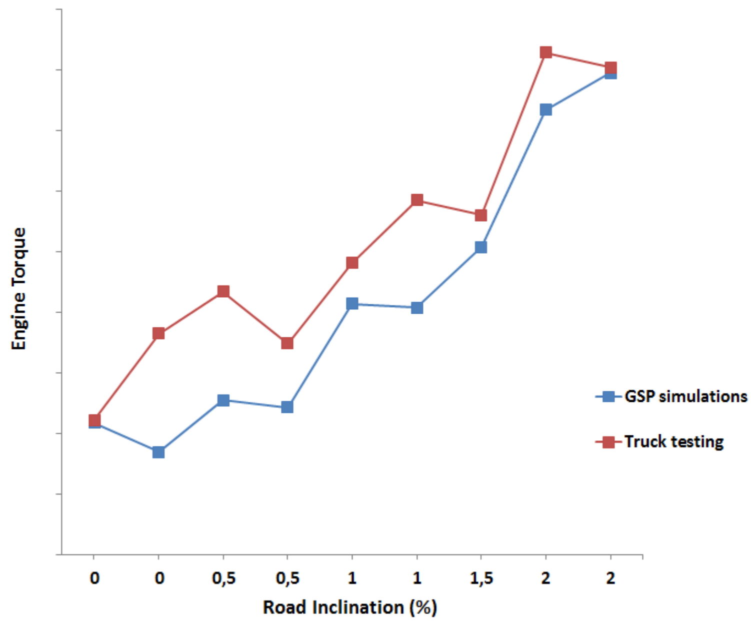


Figure 4.26: Comparison of engine torque for gearshift from 12 to 11 obtained from testing in truck and simulation results from GSP

The figure 4.26 shows the comparison between engine torque on gear 12, just before shifting from gear 12 to 11 obtained from truck testing and GSP simulation. As can be seen from this figure, although the trend of engine torque at various inclinations is similar, the magnitude differs slightly. Here, the average variation in engine torque at various inclinations is around 10%. Also, a clear trend can be observed where the engine torque in GSP Simulations are lesser than the engine torque obtained from truck testing. Possible reasons for this error could be the way of modelling various components and losses in GSP. Hence, it can be concluded that the engine torque results were quite similar between testing and simulations.

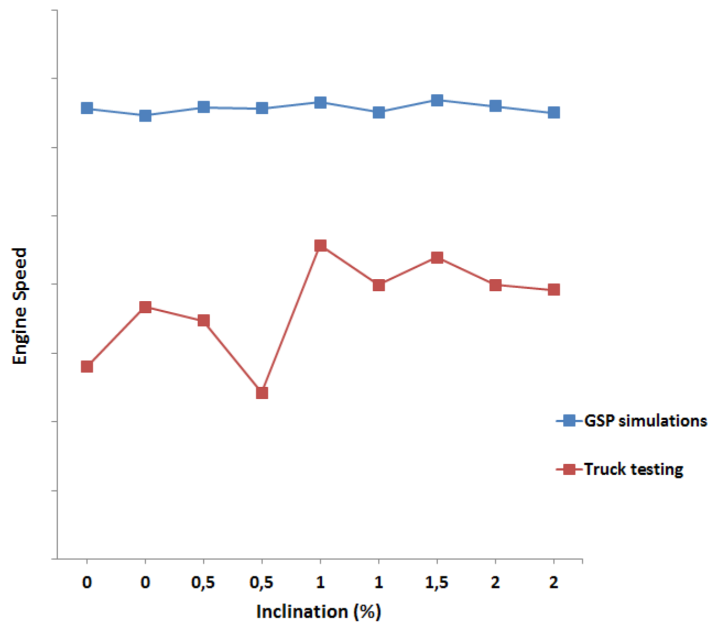


Figure 4.27: Comparison of engine torque for gearshift from gear 12 to gear 11 obtained from testing in truck and simulation results from GSP

The figure 4.27 shows the comparison between engine speed on gear 12, just before shifting from gear 12 to 11 obtained from truck testing and GSP simulation. As can be seen from this figure, although the trend of engine speed at various inclinations is quite similar, the magnitude differs slightly. Here, the average variation in engine speed at various inclinations is around 1%. Hence, it can be concluded that the engine speed results were quite similar between testing and simulations.

This minor difference in engine speed results could be attributed to some of the simulation settings which were slightly different from the ones used on the test truck such as the tyres used.

Since the variation in fuel loss results are quite high as observed in figure 4.25, it can be concluded that the fuel loss results from simulations could not be verified with the losses measured from the truck. Some of the reasons for the large variation of fuel loss results between GSP simulations and truck testing could be:

- The fuel consumption results in simulation and truck testing are a result of the estimation of fuel consumed in the models used in engine software. On a truck, advanced models are used to estimate the fuel consumed whereas in the simulation platform that was used in this work, simplified models were used. The use of different models could have contributed to some difference in fuel loss results.

- While calculating the fuel losses in simulation, steady-state conditions defining end of a gearshift can be defined easily resulting in precise calculation of the losses involved. Whereas, in the measurements obtained from truck testing, due to the nature of data captured, steady-state conditions cannot be easily defined to define the end of a gearshift. Since the fuel consumed values are very sensitive to the duration of a gearshift event, difficulty and inconsistency in defining the steady-state and hence the end of a gearshift event results in variation of fuel loss results from one case to another.

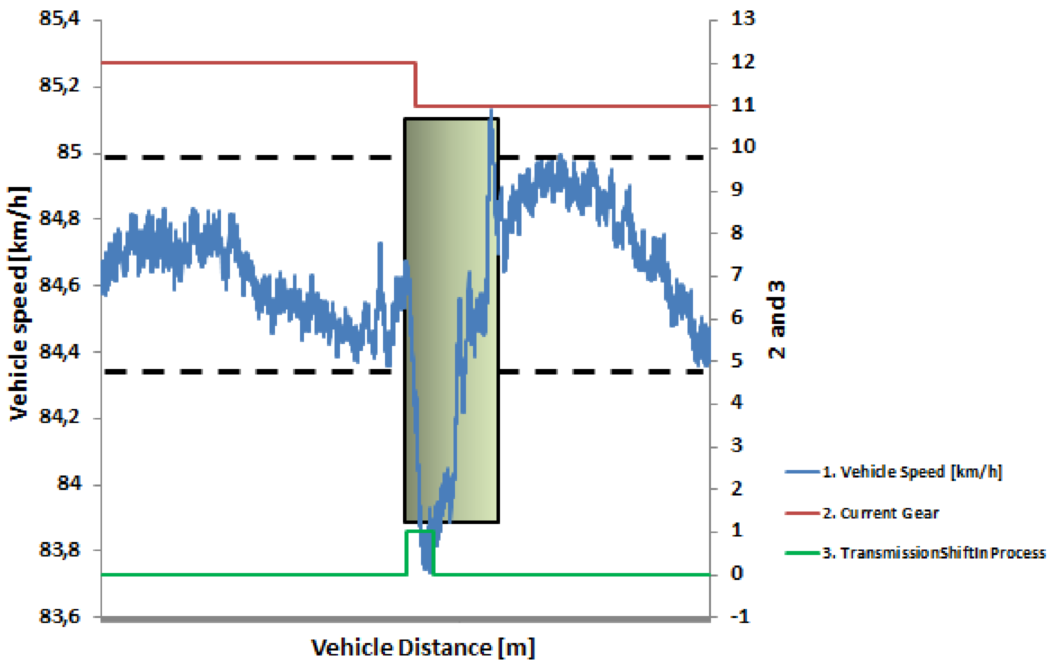


Figure 4.28: Consistent vehicle speed band before and after a gearshift-Simulation data

In the figure 4.28, the duration of the gearshift is indicated by the shaded portion. It can be seen from the figure that the vehicle speed band before and after the gearshift duration is the same. The start of the gearshift is easily defined by the start of the signal 'TransmissionShiftInProcess' as indicated by green line and since the vehicle speed band is constant, before (84.3 km/h-85.0 km/h) and after (84.3 km/h-85.0 km/h) the gearshift, the vehicle speed band throughout the distance can be defined easily and this is uniform for gearshifts in different scenarios (inclination, vehicle mass, etc.) and hence the end of the gearshift can also be defined easily by the first instance after the start of the gearshift at which the vehicle speed re-enters the defined vehicle speed band.

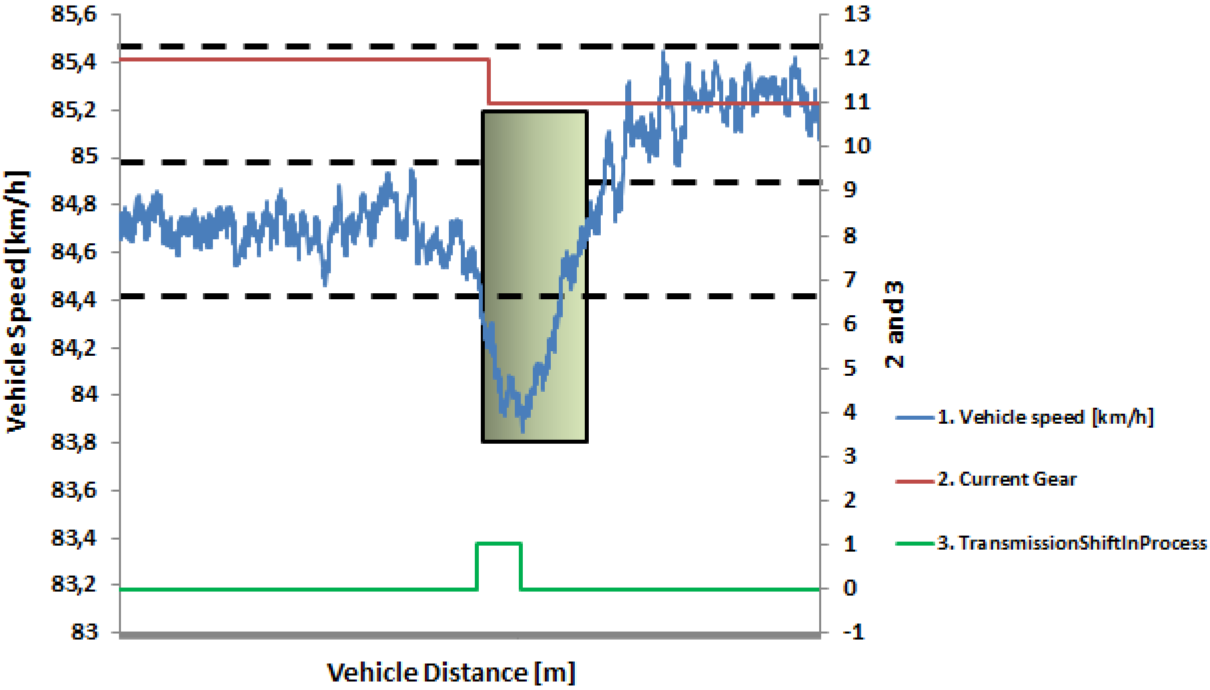


Figure 4.29: Inconsistent vehicle speed band before and after a gearshift-Truck testing data

In the figure 4.29, the duration of the gearshift is indicated by the shaded portion. It can be seen from the figure that the vehicle speed band before the gearshift is from 84.4 km/h-85.0 km/h and after the gearshift is from 85.0 km/h-85.5 km/h, which are slightly at different levels. Now, due to this inconsistency, in order to define a common speed band, a much wider band from 84.4 km/h-85.5 km/h has to be chosen. This inconsistency differs from case to case and a uniform speed band cannot be defined which is consistent for gearshifts in different scenarios (inclination, vehicle mass, etc.). Consequently, this makes it difficult to define the end of a gearshift.

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# A Appendix A

## A.1 Constant road GSP simulation results

### A.1.1 Gearshift from gear 11 to gear 12

1. Category G1 - **Fuel loss based on engine torque - Engine torque is varied on the basis of road inclination. Vehicle mass is constant**

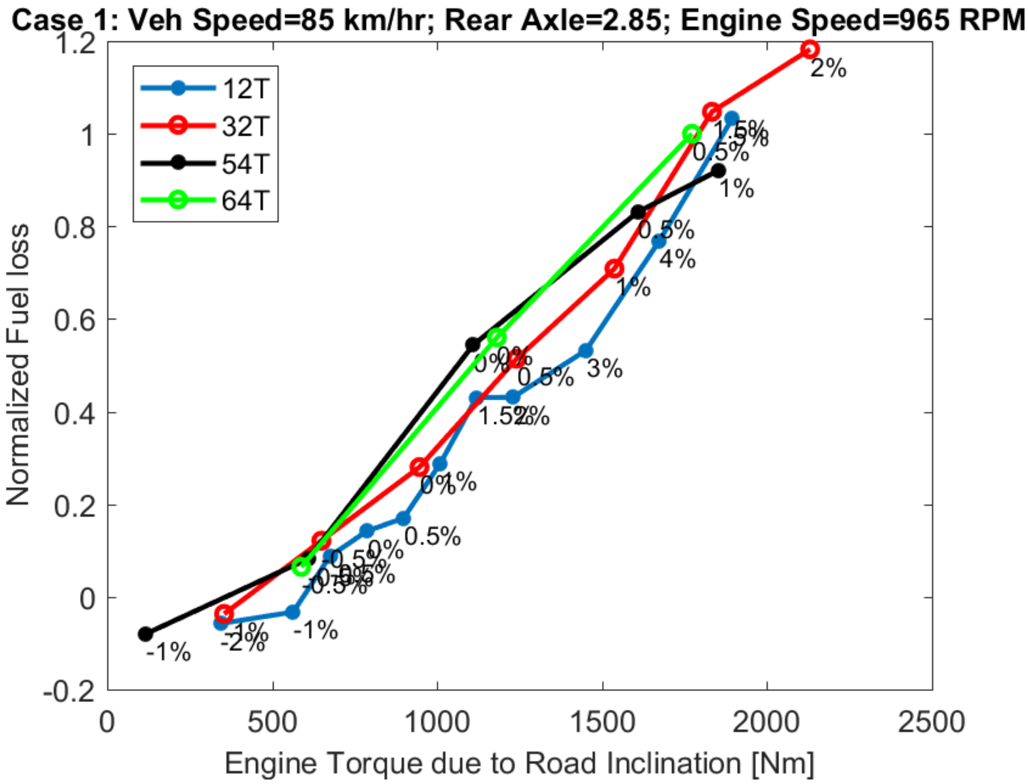


Figure A.1: Variation of fuel loss against engine torque due to road inclination for Case 1

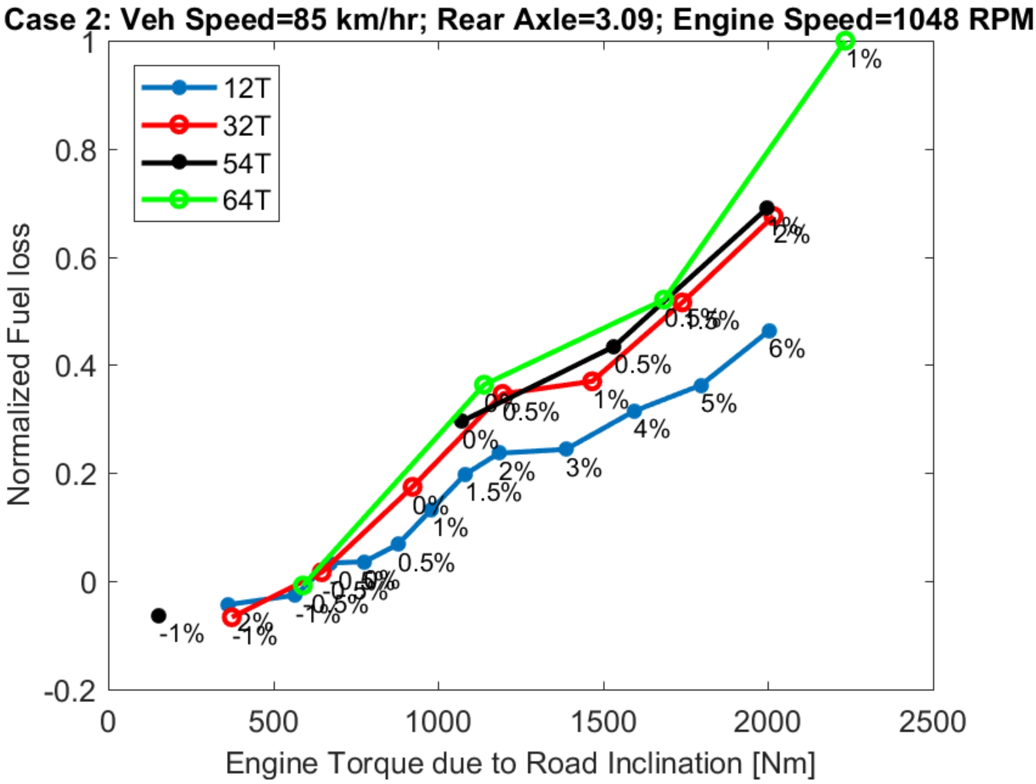


Figure A.2: Variation of fuel loss against engine torque due to road inclination for Case 2

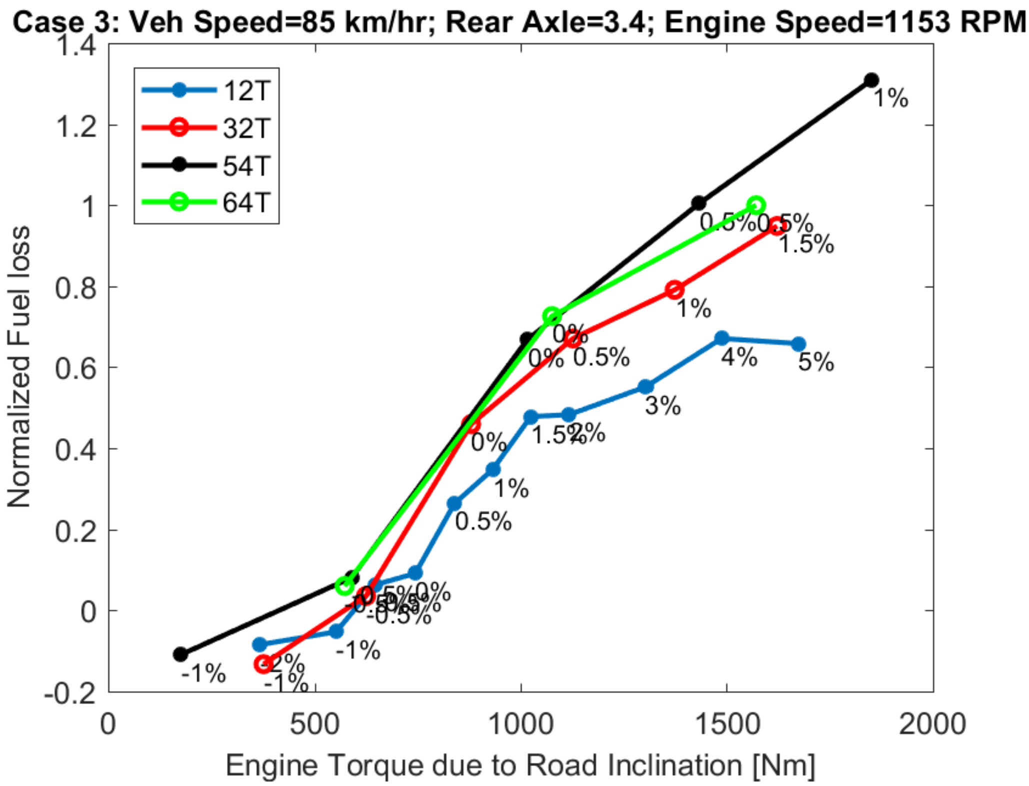


Figure A.3: Variation of fuel loss against engine torque due to road inclination for Case 3

2. Category G2 - **Time loss based on engine torque - Engine torque is varied on the basis of road inclination. Vehicle mass is constant**

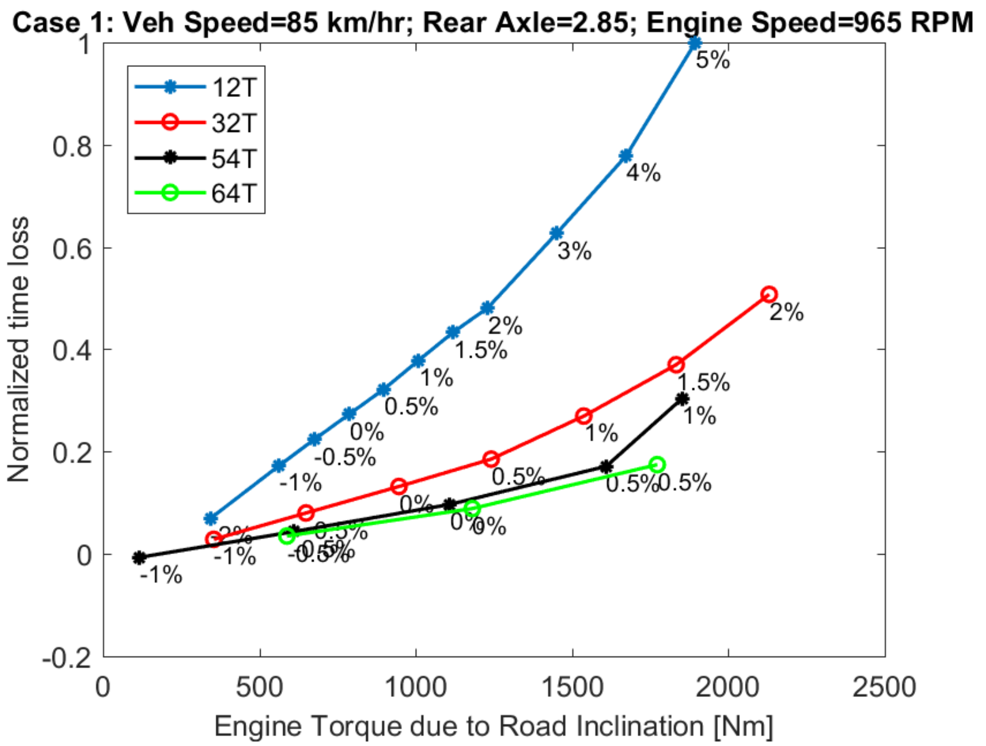


Figure A.4: Variation of time loss against engine torque due to road inclination for Case 1

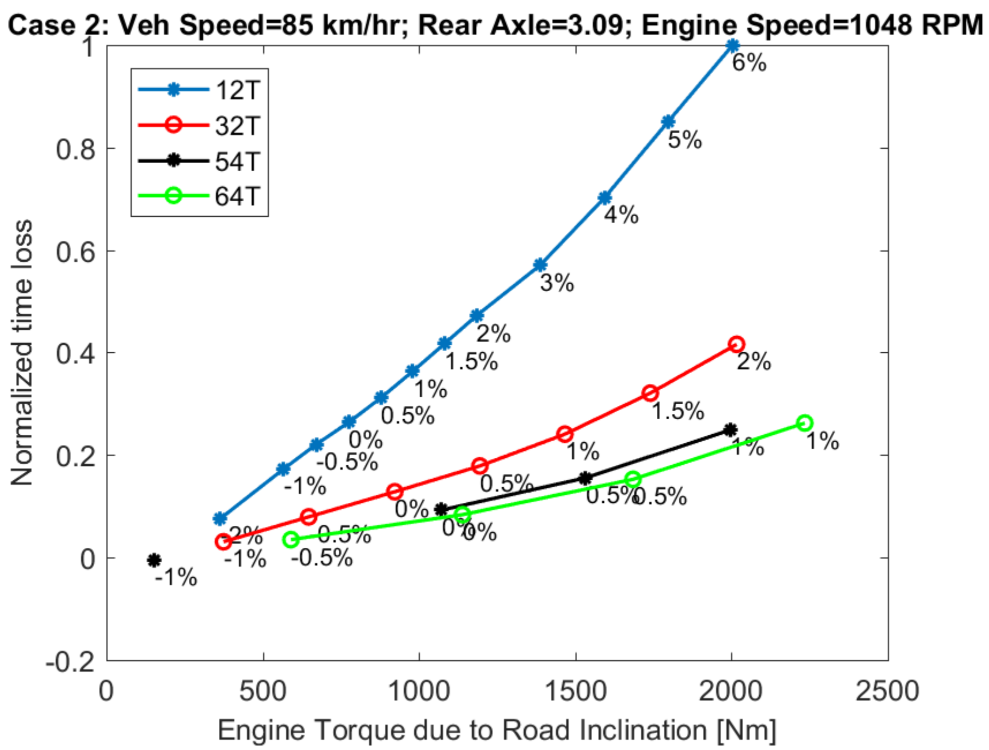


Figure A.5: Variation of time loss against engine torque due to road inclination for Case 2

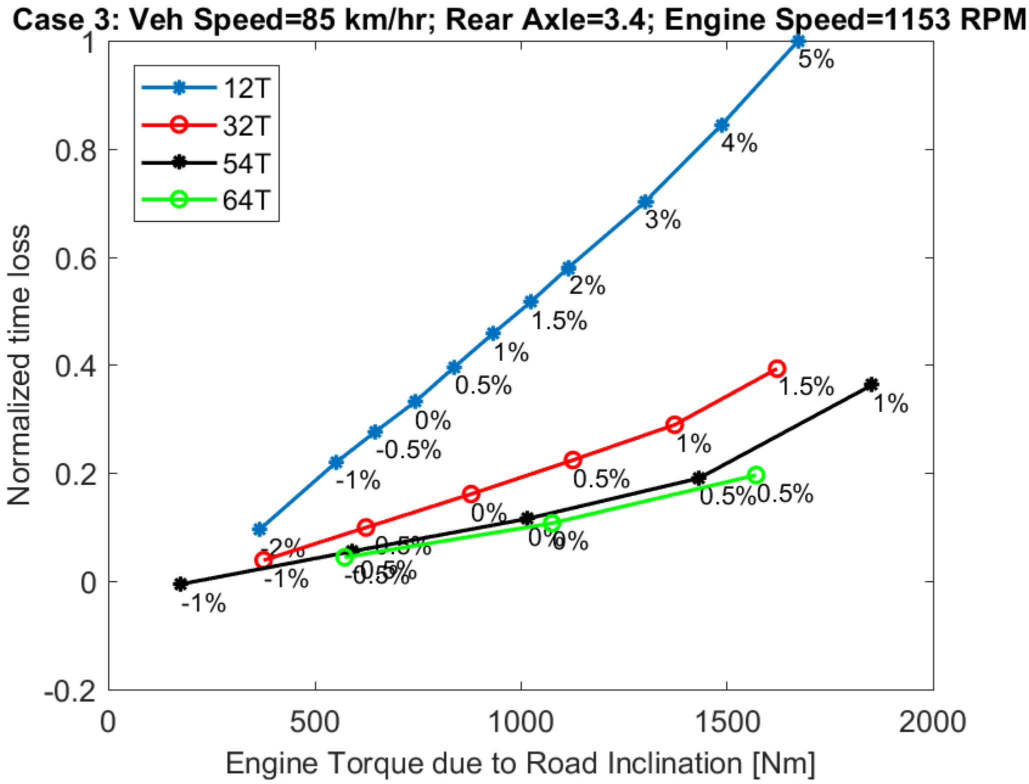


Figure A.6: Variation of time loss against engine torque due to road inclination for Case 3

3. Category G3 - **Fuel loss based on engine torque - Engine torque is varied on the basis of vehicle mass. Road inclination is constant**

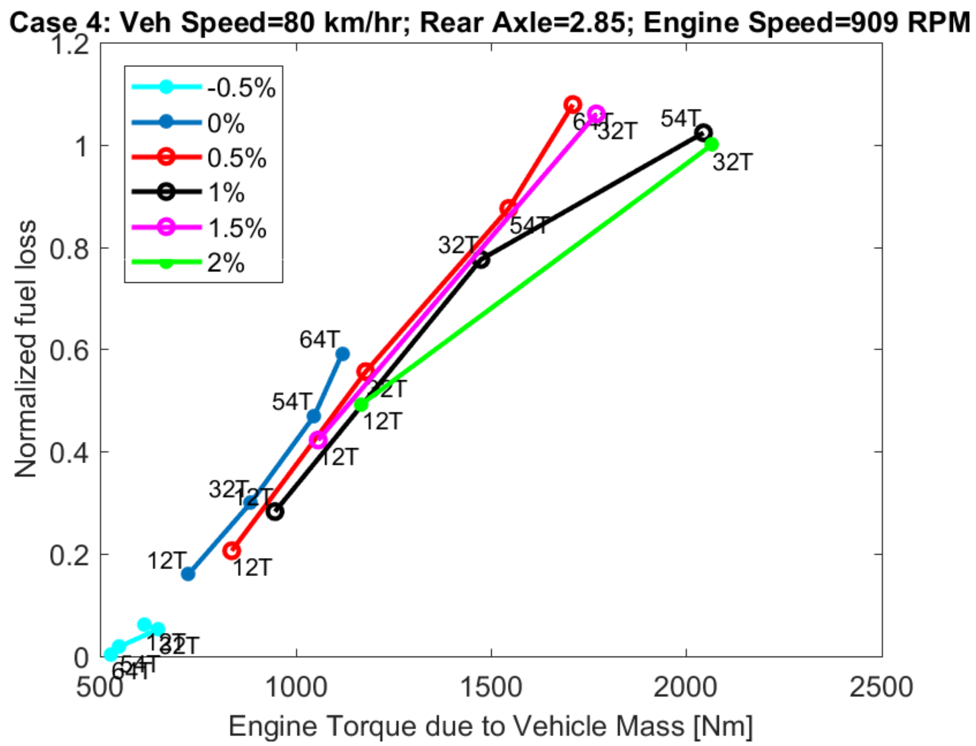


Figure A.7: Variation of fuel loss against engine torque due to vehicle mass for Case 4

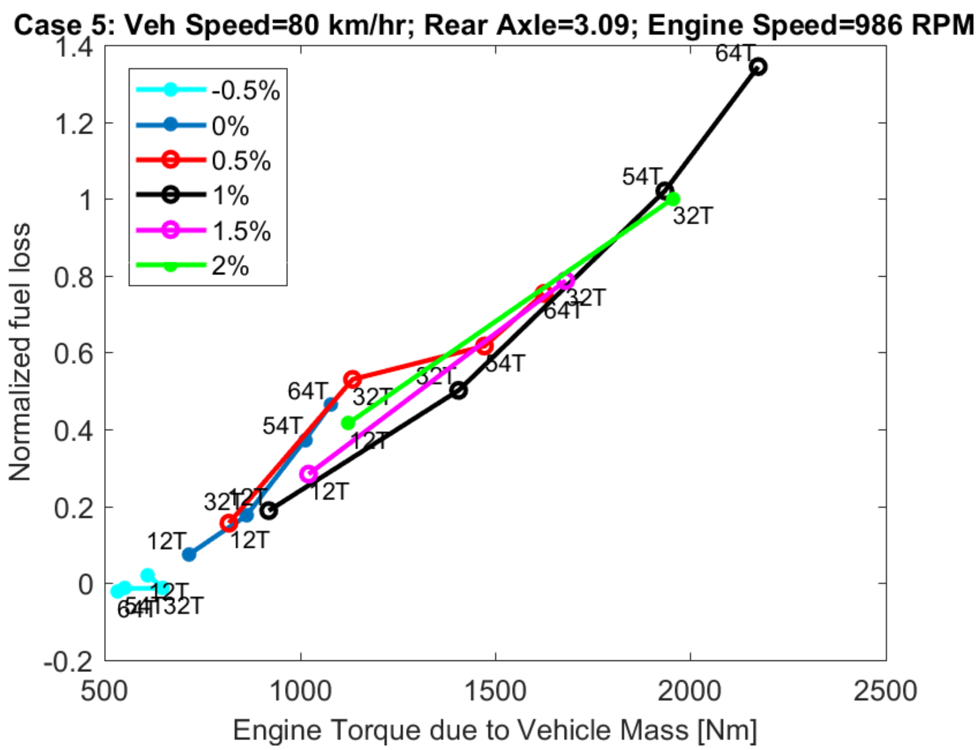


Figure A.8: Variation of fuel loss against engine torque due to vehicle mass for Case 5

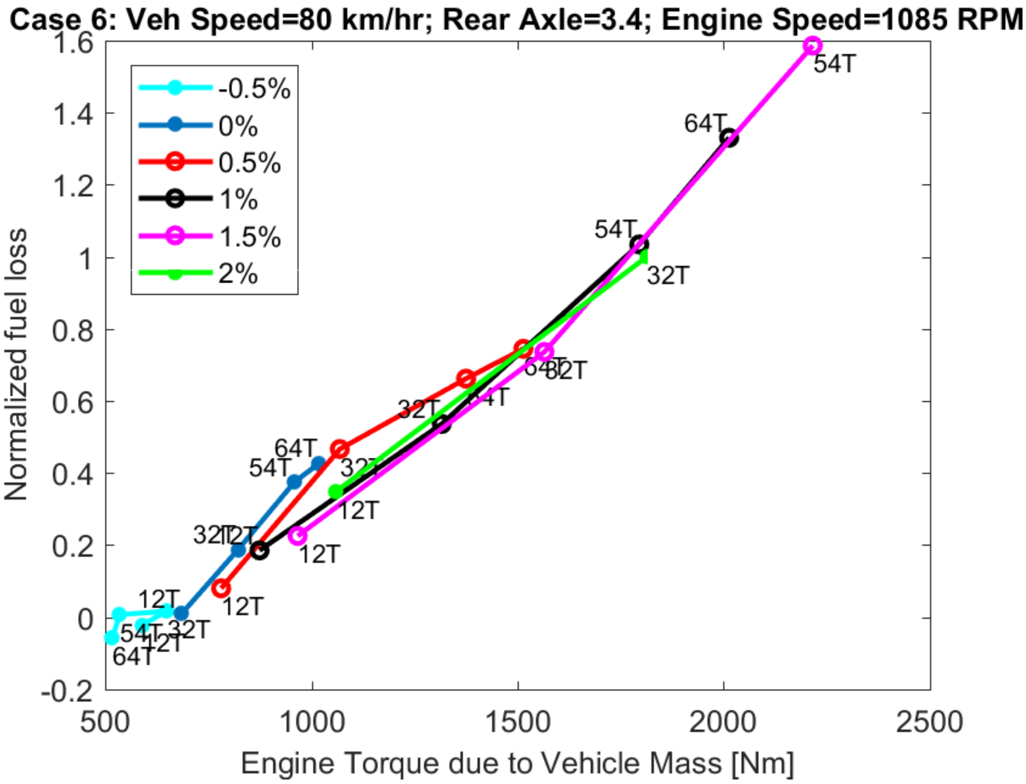


Figure A.9: Variation of fuel loss against engine torque due to vehicle mass for Case 6

4. Category G4 - **Time loss based on engine torque - Engine torque is varied on the basis of vehicle mass. Road inclination is constant**

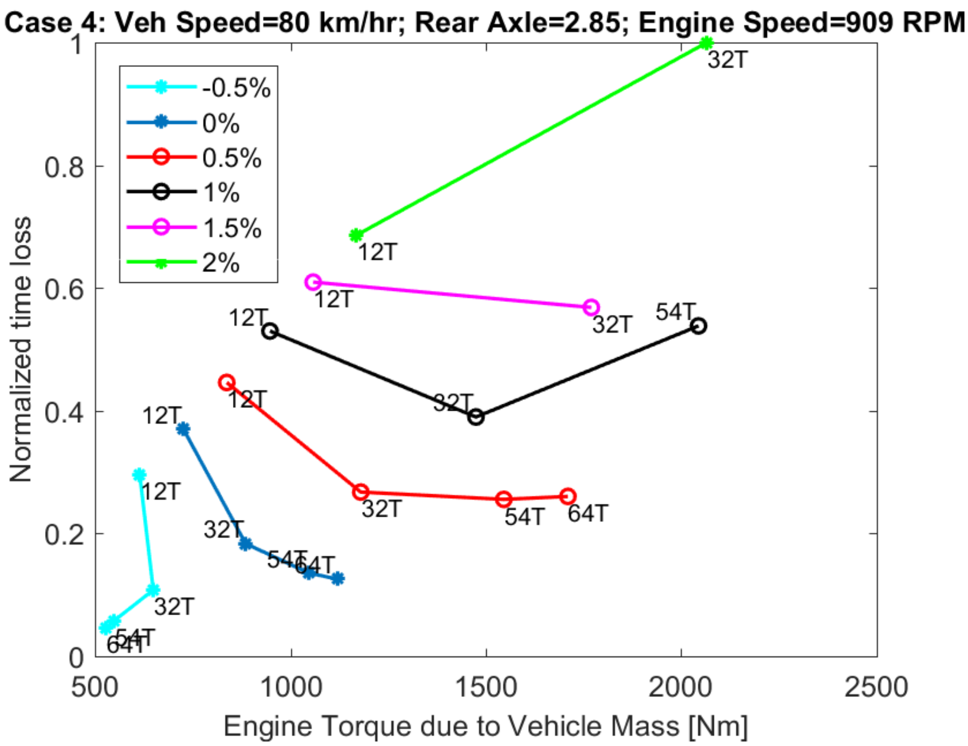


Figure A.10: Variation of time loss against engine torque due to vehicle mass for Case 4

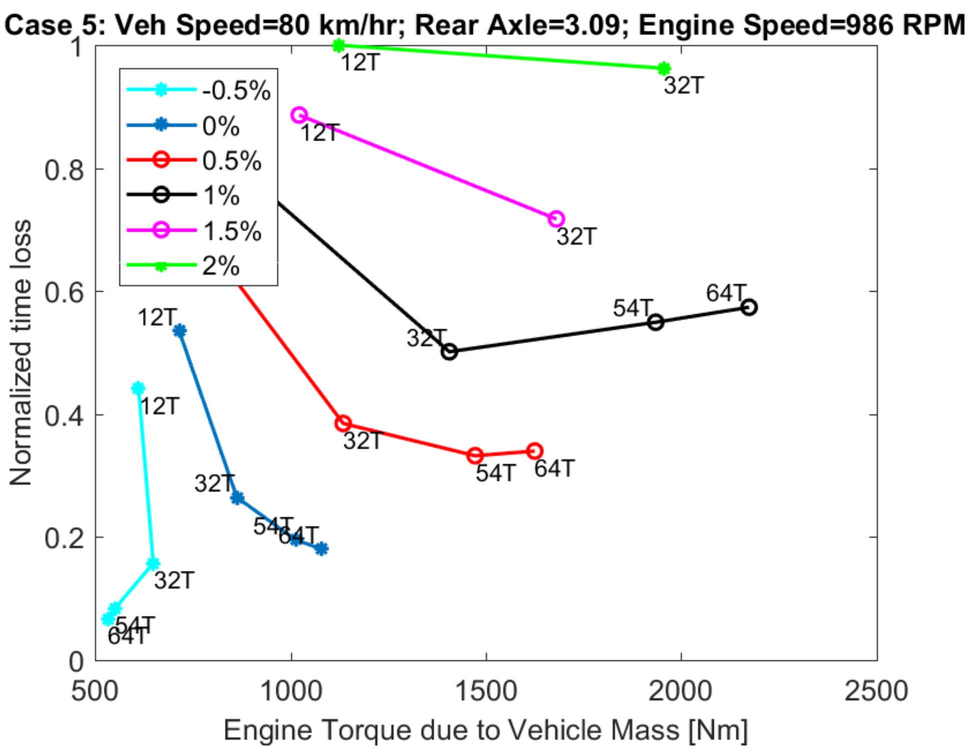


Figure A.11: Variation of time loss against engine torque due to vehicle mass for Case 5

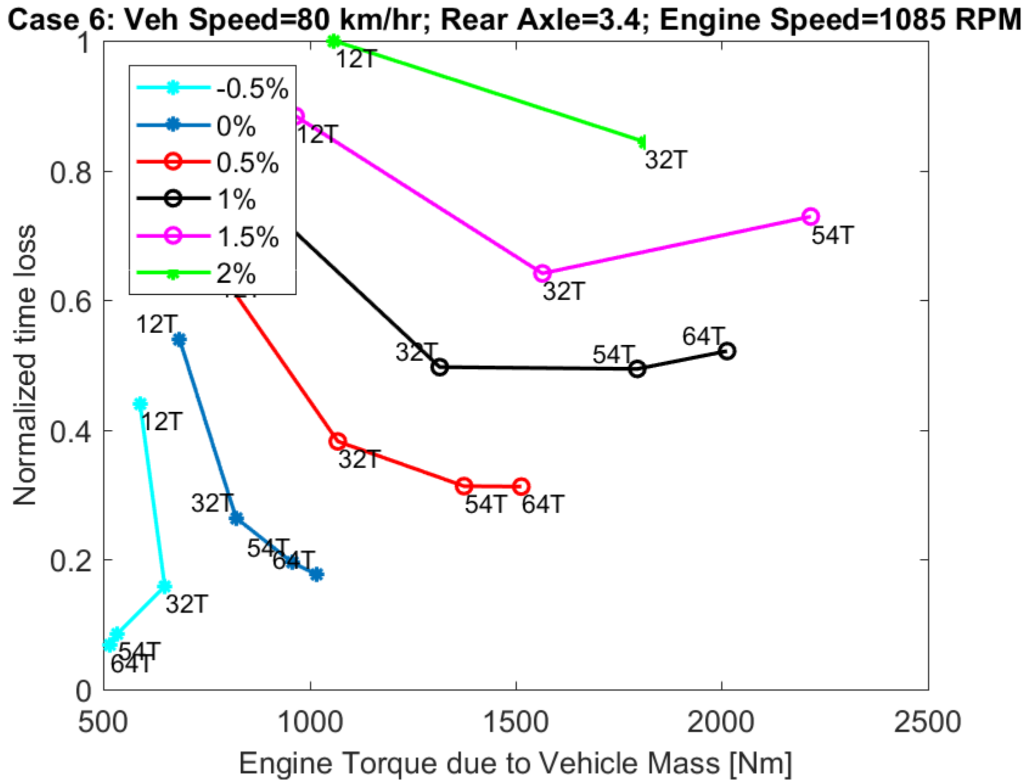


Figure A.12: Variation of time loss against engine torque due to vehicle mass for Case 6

### A.1.2 Gearshift from gear 12 to gear 11

1. Category G1 - **Fuel loss based on engine torque - Engine torque is varied on the basis of road inclination. Vehicle mass is constant**

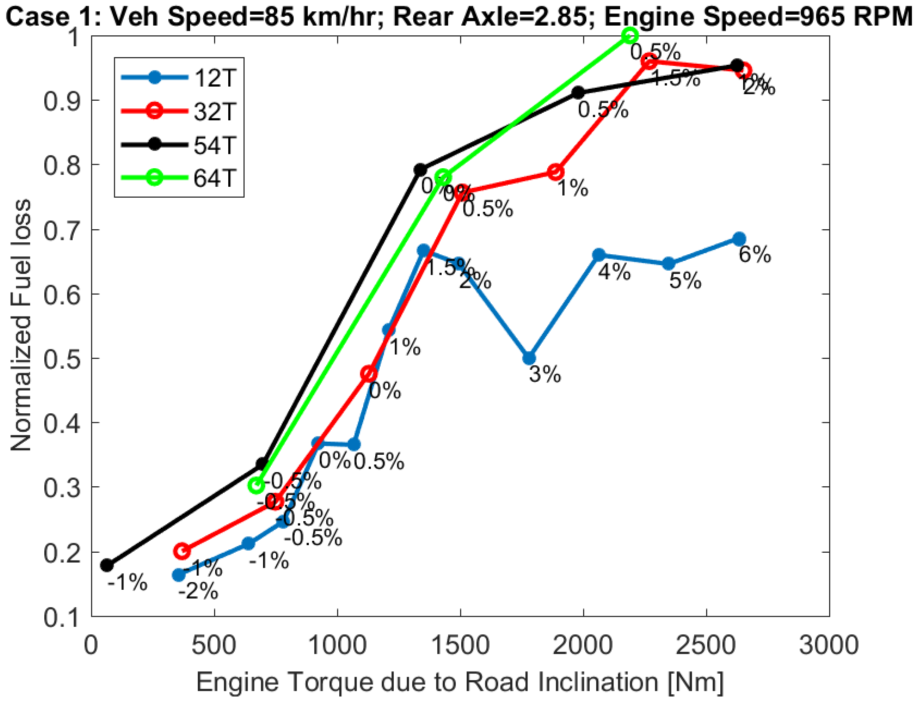


Figure A.13: Variation of fuel loss against engine torque due to road inclination for Case 1

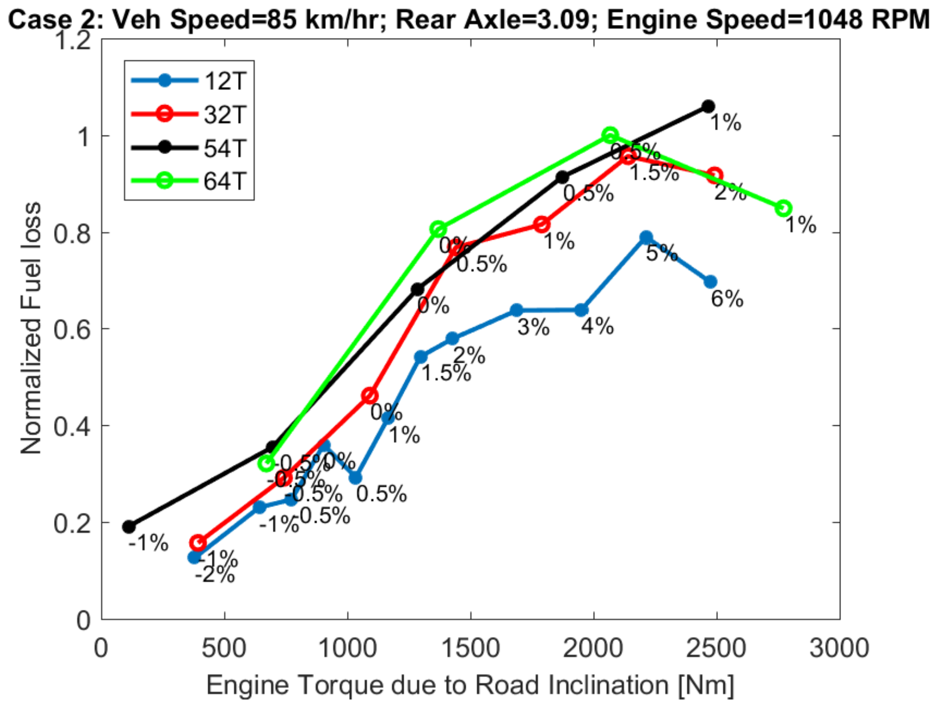


Figure A.14: Variation of fuel loss against engine torque due to road inclination for Case 2

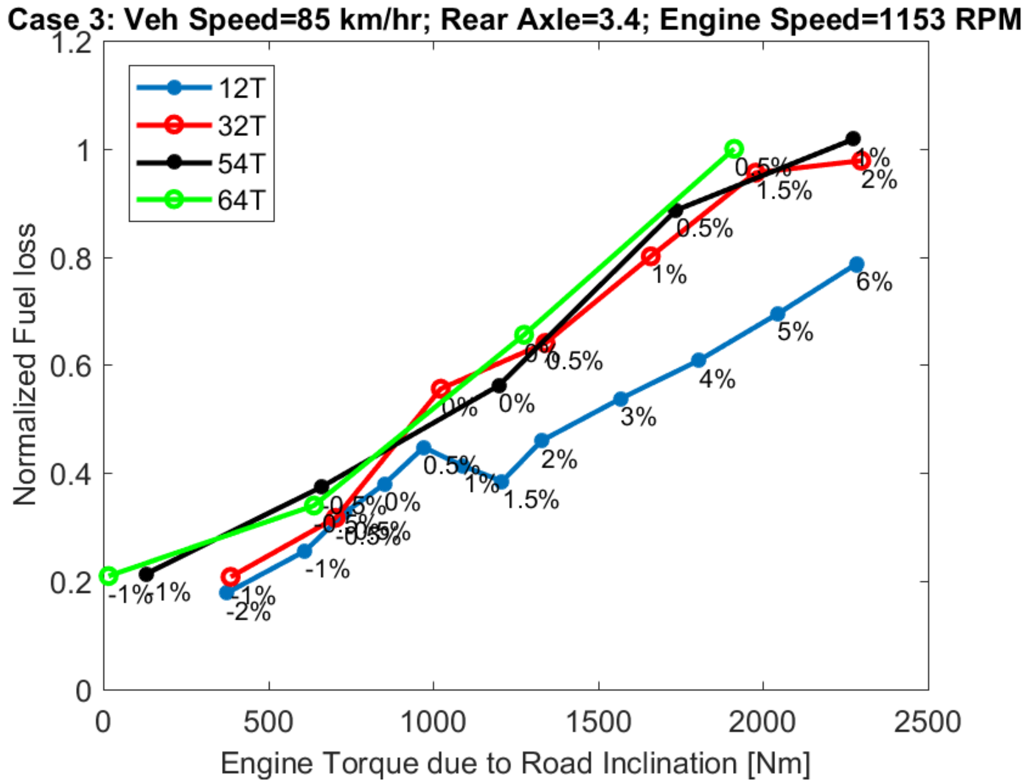


Figure A.15: Variation of fuel loss against engine torque due to road inclination for Case 3

2. Category G2 - **Time loss based on engine torque - Engine torque is varied on the basis of road inclination. Vehicle mass is constant**

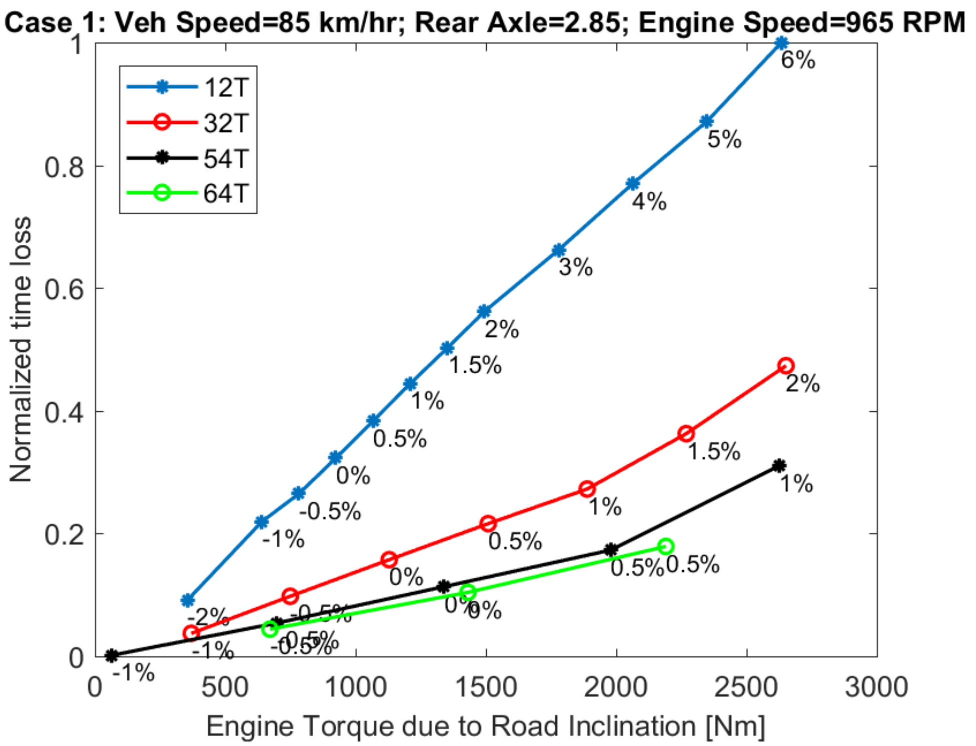


Figure A.16: Variation of time loss against engine torque due to road inclination for Case 1

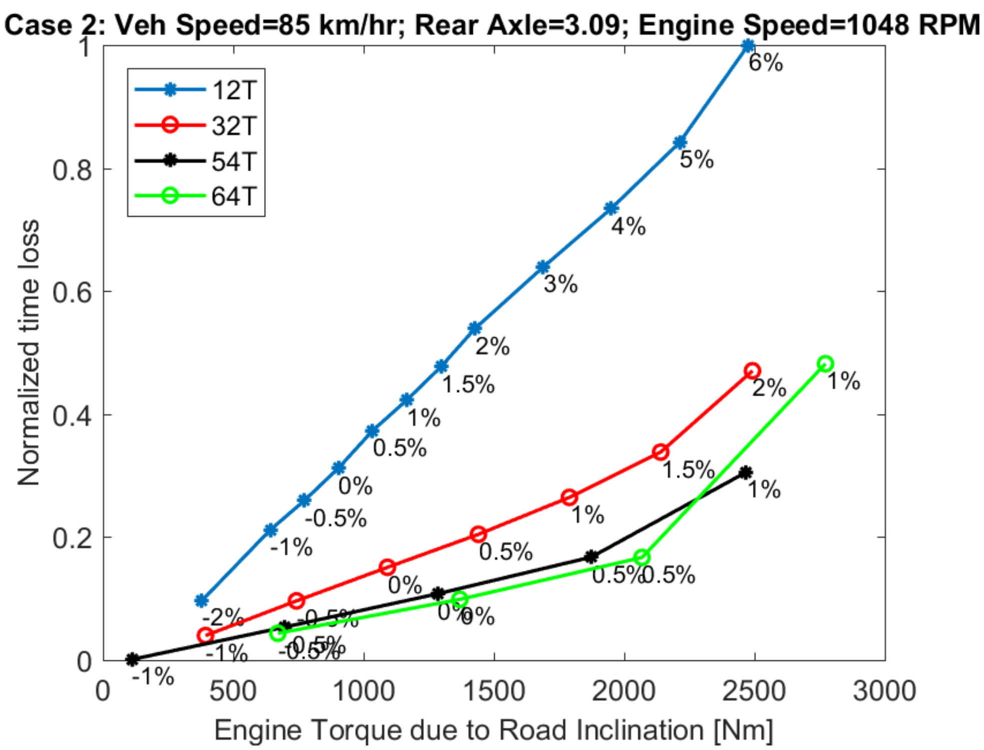


Figure A.17: Variation of time loss against engine torque due to road inclination for Case 2

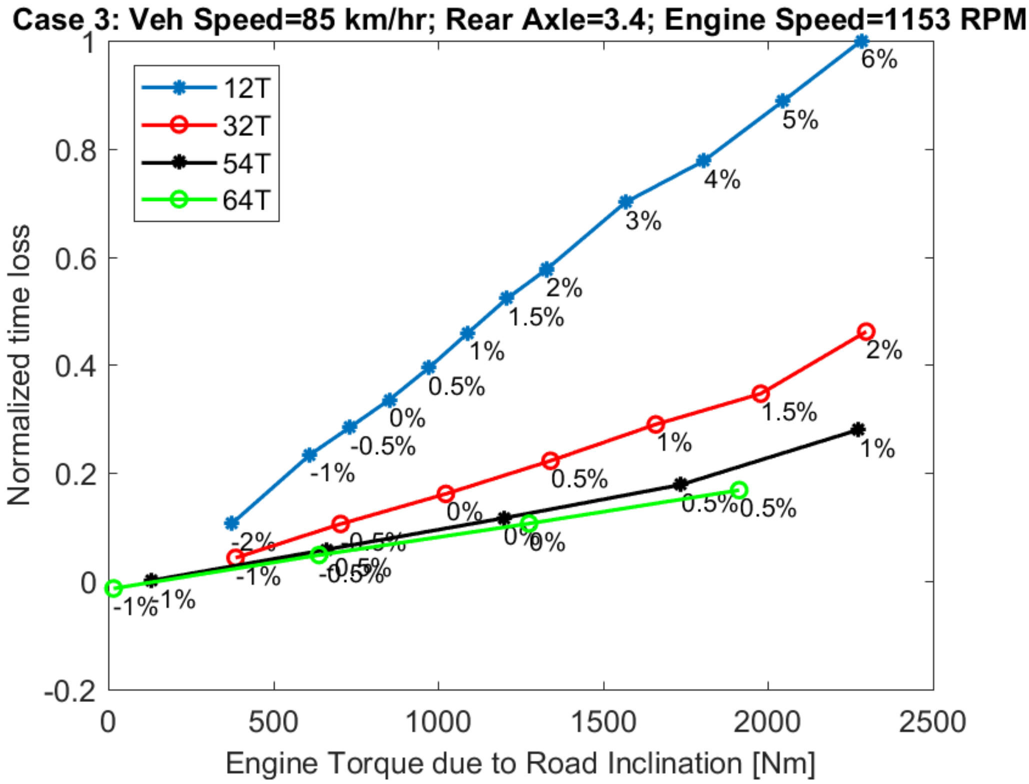


Figure A.18: Variation of time loss against engine torque due to road inclination for Case 3

3. Category G3 - **Fuel loss based on engine torque - Engine torque is varied on the basis of vehicle mass. Road inclination is constant**

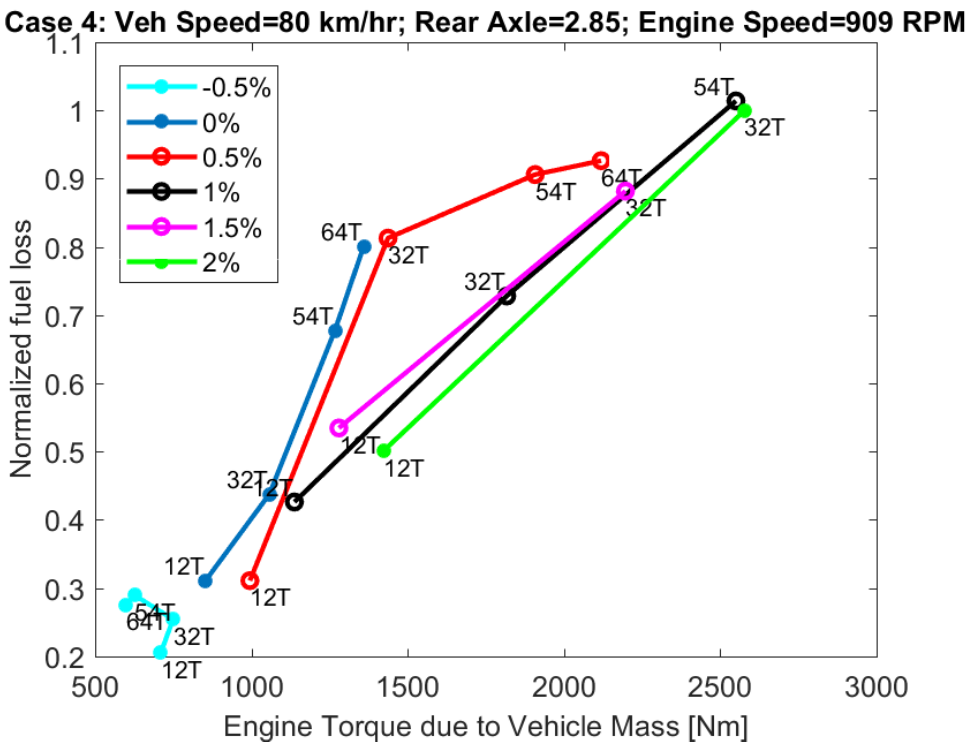


Figure A.19: Variation of fuel loss against engine torque due to vehicle mass for Case 4

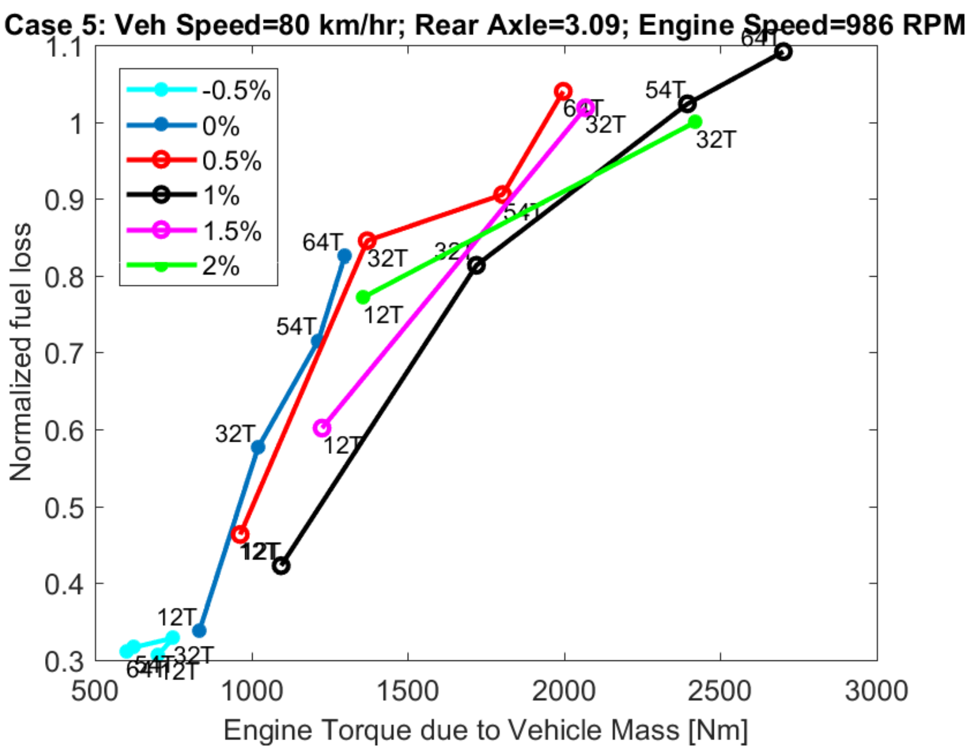


Figure A.20: Variation of fuel loss against engine torque due to vehicle mass for Case 5

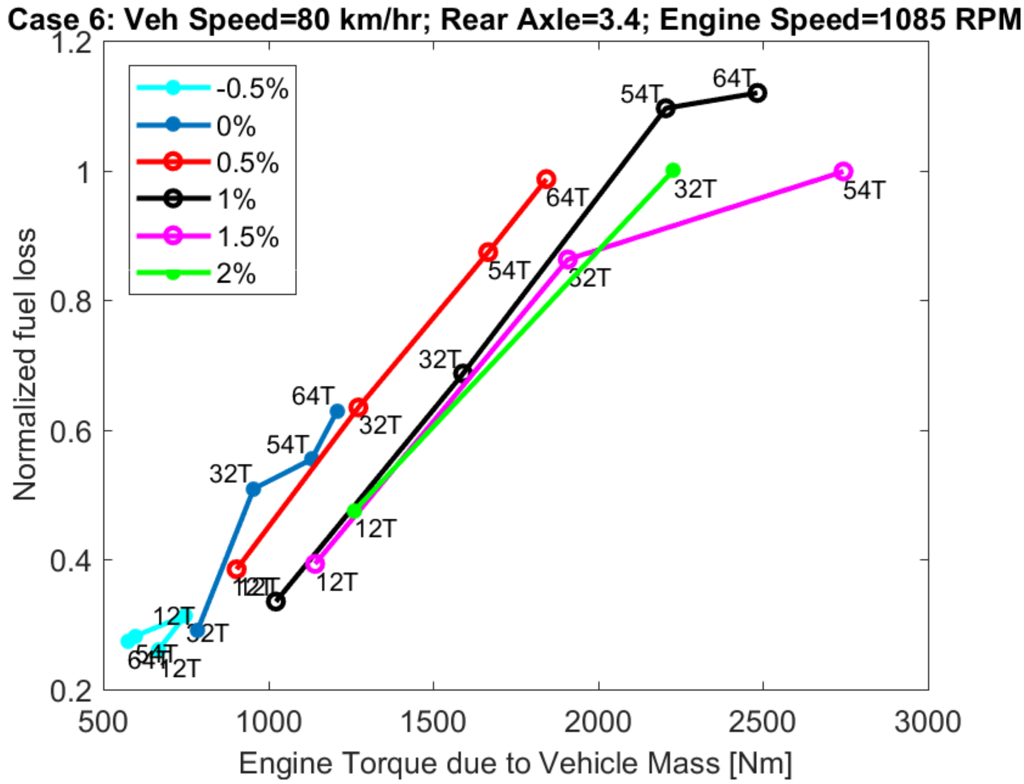


Figure A.21: Variation of fuel loss against engine torque due to vehicle mass for Case 6

4. Category G4 - **Time loss based on engine torque - Engine torque is varied on the basis of vehicle mass. Road inclination is constant**

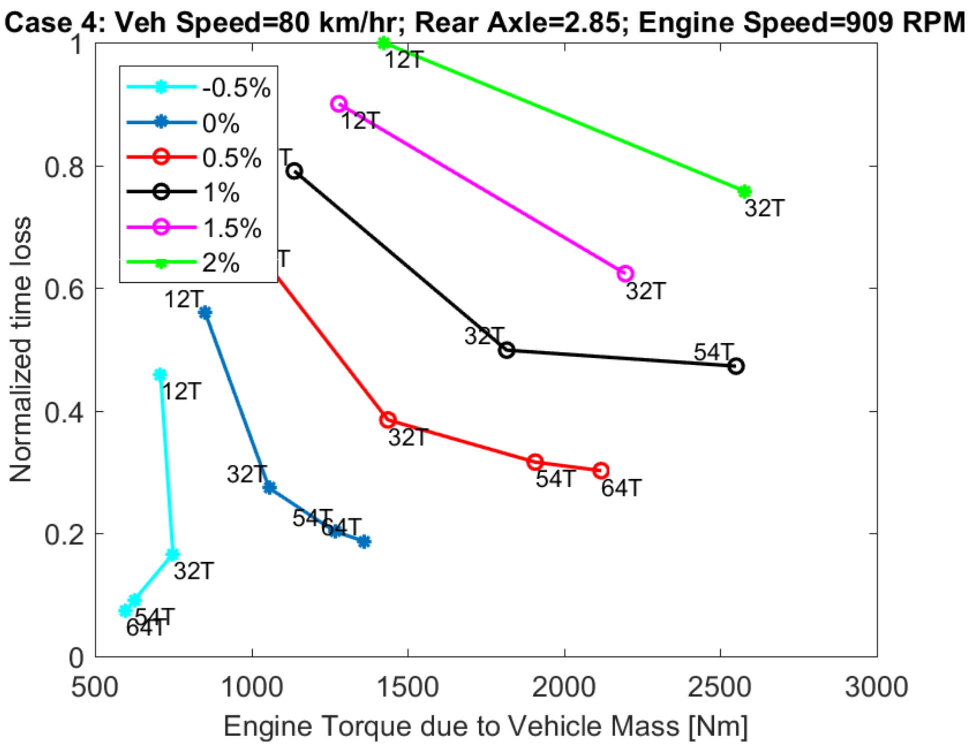


Figure A.22: Variation of time loss against engine torque due to vehicle mass for Case 4

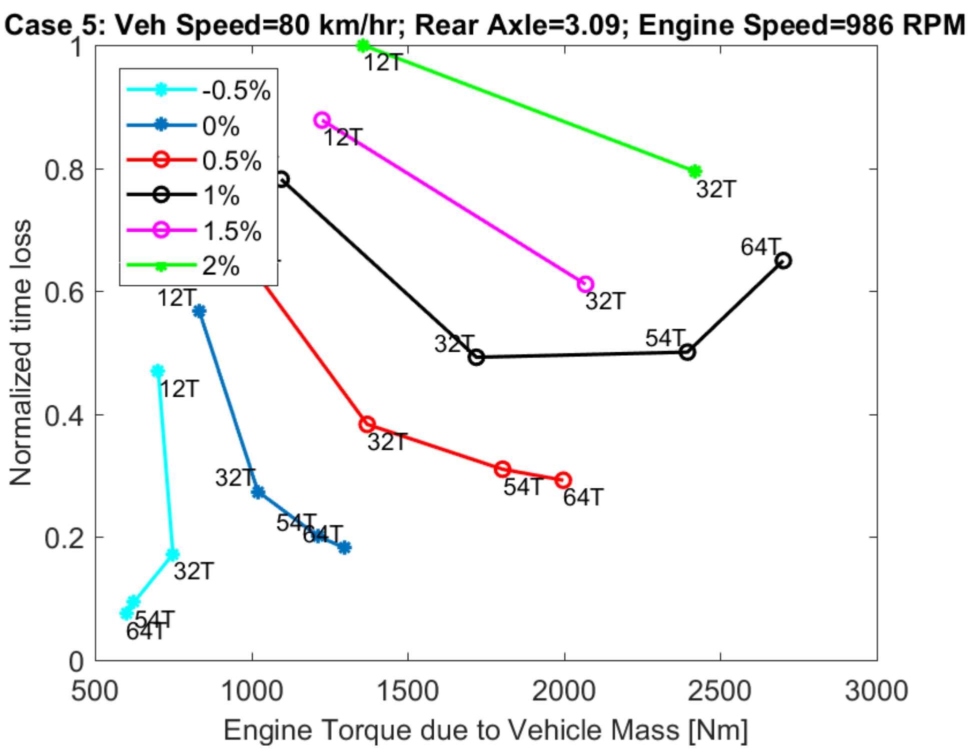


Figure A.23: Variation of time loss against engine torque due to vehicle mass for Case 5

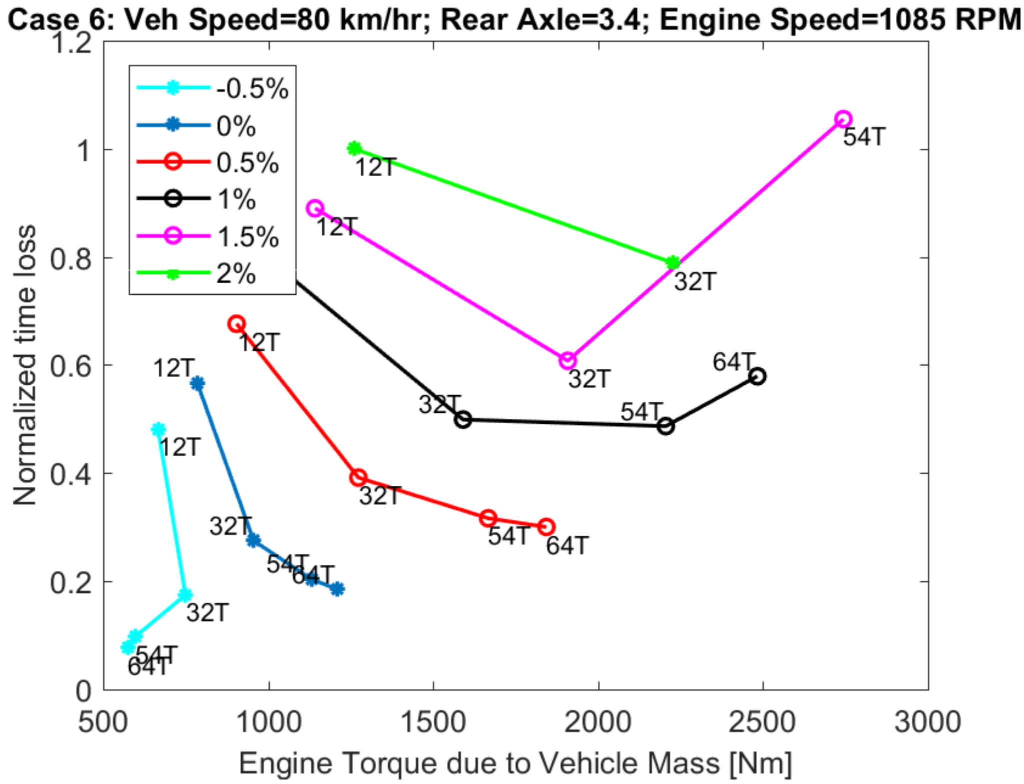


Figure A.24: Variation of time loss against engine torque due to vehicle mass for Case 6