Institutionen för systemteknik
Department of Electrical Engineering

Master Thesis

Controller Design Enabling Automated and Fuel-Efficient Driving Strategies for Heavy Duty Vehicles in Urban Environments

Master Thesis performed in Vehicular Systems
at The Institute of Technology at Linköping University
by

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Titel
Title

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Sammanfattning
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Through extensive simulations with a vehicle model, developed at and provided by Scania CV AB, different driving strategies are evaluated and analysed. This determined how to achieve a low fuel consumption when driving heavy vehicle in an urban environment.

The simulations shows that the fuel consumption can be lowered by coasting the vehicle when deceleration and thus minimize the use of the brakes. One should also when possible, select a higher gear to lower the fuel consumption due to engine friction.

These strategies are used to develop a controller which lowers the fuel consumption without increasing the trip time for the vehicle. The controller is able to alter the velocity of the vehicle within a reference window which results in both a lower fuel consumption and a shorter trip time for the driving cycle used.

Nyckelord
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Through extensive simulations with a vehicle model, developed at and provided by Scania CV AB, different driving strategies are evaluated and analysed. This determined how to achieve a low fuel consumption when driving heavy vehicle in an urban environment.

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Södertälje, June 2015
Erik Eneroth

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Notation

Notation	Explanation	Unit
v	Velocity	m/s
a	Acceleration	m/s^2
h	Height	m
d	Distance	m
t	Time	s
g	Gravitational acceleration	m/s^2
F	Force	N
W	Work	J
P	Power	W

1

Introduction

Due to the increasing cost of fuel and a greater environmental awareness the demands on fuel-efficient solutions for vehicles are getting stricter. Naturally these solutions are more requested by manufactures and operators for heavy trucks as both legislation and economy aspects are essential for them. In Agency [2007] it is estimated that the energy demand will increase by more than 15 % between the years 2000–2020 due to the growth of road freight transport in Europe. This indicates that the demand for fuel-efficient solutions for heavy trucks will continue to be high for years to come.

As stated in Scania AB [2012] one third of the total costs for a typical European trucking company related to owning a vehicle are fuel expenses and a lower fuel usage would result in a substantial cost reduction for the owner. There are a few procedures to increase the overall fuel efficiency of a powertrain:

- Optimize the powertrain to minimize losses in key components such as combustion engine, drive shaft and transmission.

- Add extra components to optimize the powertrain, e.g. hybridize the vehicle so the overall efficiency is increased.

- Optimize the control of the powertrain to make sure the vehicle is working at the optimal operating point in a fuel efficient point of view.

The costs for altering the powertrains components are often more expensive and time consuming than e.g. finding a control algorithm where the fuel usage is minimized or implement other adjustments in the vehicle's software.

1.1 Background

The topic of reducing the fuel consumption is quite investigated when it comes to long haulage, one example of this is Fröberg et al. [2006], where it is shown how road slopes could be used to reduce fuel consumption. This is further investigated and refined in Fröberg and Nielsen [2008] where focus is laid on shifting strategies and how to execute them. By including look-ahead information and a preprocessing algorithm in Hellström et al. [2009] a reduction of 3.5 % in fuel consumption is achieved on a $120km$ route. In Schwarzkopf and Leipnik [1977] it is shown that for passenger cars and under quite general conditions the fuel consumption is minimized by operating the vehicle at constant speed. This is later revised by Chang and Morlok [2005] where this is shown for different types of routes, including a level road.

Hooker [1988] describes a study with eight different cars of varying brands to find the optimal speed profile for each of them. The results show high variation between the different commercial cars and although the acceleration profile varies. Common for all cars are to accelerate more rapidly in the beginning and as the cruise speed is approached, lower the acceleration gradually. In the experiments no speed limits are introduced, so in all results the optimal cruising speed is below those where drivers normally drive. It is also suggested that a vehicle with unlimited braking power should apply the brakes instantaneously when the desired distance has been reached, which would give a shorter travel time compared to just rolling to a stop in idling but as more fuel is needed propelling the vehicle the full distance, more fuel would be required. Vagg et al. [2013] revises the topic and although the report treats light commercial vehicles it suggests more stringent acceleration limits even for heavy duty vehicles as more power is needed to accelerate and thus the savings from limiting this would be larger. This theory is backed to some extent by Saerens and Van de Bulck [2013] where for manual passenger cars it is also suggested that gear shifting should be carried out rapidly on relatively low engine speeds and that disengaging the clutch in the beginning of deceleration may be beneficial. Even if there is no fuel injected during engine braking this is true as a greater deceleration is achieved with the engine engaged and therefore the vehicle has to cruise longer before starting decelerating. In summary, there exists a few solutions for fuel-efficient control of heavy duty vehicles used for long haulage. But for heavy vehicles operating in urban environments where most of the driving is done at lower speeds together with more starts and stops the topic seems to be more or less unexplored.

As presented in Roos [2010] power losses increases with speed, especially the aerodynamic resistance. (1.1) shows one commonly used model for the those losses and (1.2) shows a model for the rolling resistance, where the vehicle mass has a great influence on the power losses. In low speeds engine losses accounts for the majority of the power losses, (1.3) describes a commonly used model for this.

$$P_{airRes} = \frac{1}{2} \cdot c_D \cdot A_{front} \cdot \rho_{air} \cdot v^3 \qquad (1.1)$$

Here, v is vehicle speed, ρ_{air} the density of ambient air and c_D the aerodynamic drag coefficient.

$$P_{rollRes} = c_R \cdot m_{veh} \cdot g \cdot cos(\alpha) \cdot v \qquad (1.2)$$

Here, m_{veh} is the vehicle mass, g the gravitational force, c_R the roll resistance coefficient and the term $cos(\alpha)$ the influence of non-horizontal road, [Guzzella and Sciaretta, 2007].

$$P_{engLoss} = T_{engLoss} \cdot \frac{i_{gb} \cdot i_{fd}}{r_{wheel}} \cdot v \qquad (1.3)$$

Where $T_{engLoss}$ is drag torque of the engine, igb gearbox ratio, i_{fs} final drive ratio and r_{wheel} the wheel radius, [Roos, 2010].

For every vehicle in motion there exists a specific velocity where the energy losses for that vehicle is at a minimum. In Figure 1.1 energy losses, converted to fuel consumption for a certain vehicle are plotted as a function of vehicle speed. As can be seen in the figure, there exists an interval in which a vehicle would consume the least fuel per distance. This interval differs from vehicle to vehicle, depending on specifications. The steps in fuel consumption over velocity is due to that the vehicle changes gear.
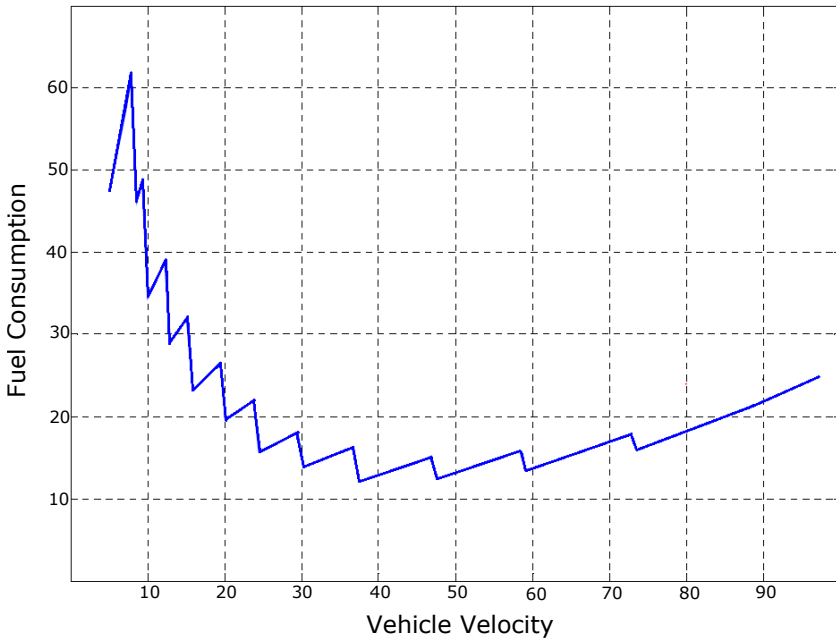
Figure 1.1: *Fuel consumption as a function of vehicle speed, the axis units and values are modified due to confidentiality.*

High speeds should be avoided to minimize fuel usage, although Roos [2010] points out the importance of comparing driving strategies with focus, not only on the fuel consumption itself, but also the trip time. Otherwise a strategy only decreasing the speed would save fuel regardless if the time increases, at least in high speeds. It is also concluded that lowering the usage of fuel by reducing one type of power loss is almost impossible without increasing another, with the exception of hybrid vehicles where braking energy can be stored in the battery to some extent.

Finding the optimal speed profile from a fuel efficient point of view can be achieved in a number of ways. Dynamic Programming is one solution where discrete state-space models are used to find optimum, this is used in e.g. Llamas et al. [2013] where fast gear-shifts are proposed as well as keeping a constant cruise speed. Another way to solve it is with Pontrygagin's maximum principle where solutions are found by maximizing the Hamiltonian. This is used in Saerens and Van de Bulck [2013] where the minimum-fuel driving control is calculated for a point-mass vehicle.

One application developed and used by Scania is their so-called *Scania Active Prediction* which controls the vehicle's speed in a fuel-efficient way. The system uses GPS to determine the road topography ahead which is then used to develop a specific strategy based on the vehicle's specifications. Depending on the topography and compared to an ordinary cruise control up to 3 % fuel can be saved, [Scania AB, 2011].

1.2   Problem Formulation

Scania has developed solutions for saving fuel during long haulage driving, however for vehicles used in urban environments, the topic is more or less unexplored. The aim with this Master Thesis is therefore to investigate potential fuel savings to be done for vehicles operating in urban environments. By initially examine speed profiles with trapezoid shapes, interesting parameters and connections can be found. See Figure 1.2 for some simple examples of driving cycle where the travelled distances are the same in all examples. With these trapezoid shaped drive cycles a number of combinations can be produced to resemble some basic infrastructure, such as stop signs and speed limitations.
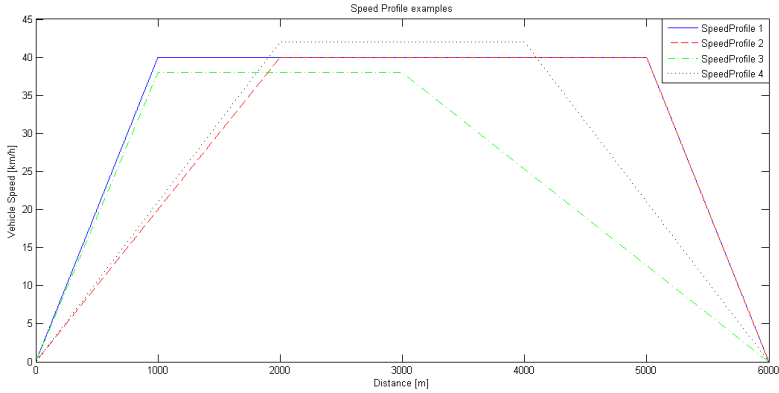
Figure 1.2: Examples of speed profiles where the cruise speed, acceleration and deceleration are varying over distance.

The main problem is to minimize the energy used for transferring a vehicle from point A to B, i.e. fuel usage. The problem is formulated in (1.4).

$$min \int_0^T \dot{m}_f \, dt \tag{1.4}$$

$$X(0) = A$$
$$X(T) = B$$

where $\dot{m}_f$ is the mass flow rate of the fuel.

The first step towards solving the problem presented is to get knowledge about different driving strategies, how to drive the vehicle to save as much fuel as possible. This is achieved through extensive simulation studies with a vehicle model provided by Scania CV AV. By selecting different settings for acceleration, cruise speed and deceleration, data will be collected to determine fuel efficient driving strategies. This information will later be used to develop a controller.

The input to the controller will be a reference velocity, this can for example be viewed as a requested velocity set by the driver in the cruise controller or environmental restraints, such as curves. A reference window around the reference velocity will be introduced, in which the controller is allowed to alter the velocity according to the fuel efficient strategies identified in the thesis. This will lead to a lower fuel consumption for the vehicle.

2

Overview of the System

This chapter will describe the structure of the system used in the thesis enabling investigation of how different driving strategies affect the fuel consumption. The system is defined as the vehicle model and the input drive cycles used.

2.1 Vehicle Model

The vehicle model used throughout the thesis is a discrete, parametrized and simplified vehicle model developed and used at Scania CV AB. Important characteristics for the thesis are the general functions of the vehicle model. This model is used as a tool enabling analysis and studies of various driving methods and the capability to alter physical parameters of the vehicle. Editable parameters that are of interest for the thesis are presented in Table 2.1.

Table 2.1: Parameters used by the vehicle model.

Parameter	Symbol	Unit
Vehicle Mass	m_{veh}	kg
Frontal Area	A_v	m^2
Wheel Radius	r_w	m
Air drag coeff.	C_d	–
Final drive	f_d	–

The vehicle model calculates energy losses, these are presented in Table 2.2.

Table 2.2: Losses computed for each simulation.

Losses	Unit	Losses	Unit
Rolling Resistance	*J*	Transmission Losses	*J*
Air Resistance	*J*	Brake Losses	*J*
Engine Friction	*J*		

How the losses are used and estimated is further discussed in Section 2.1.2.

2.1.1   Components & Functionality of the model

The vehicle model consists of various components enabling realistic simulations for a heavy duty truck, such as models for engine, gearbox and brakes. As mentioned earlier the development of these models are not the aim of the thesis as the model only is a tool for analysis and for the development of a controller.

The gear selection algorithm is engine speed dependent, gear selections are performed depending on which engine speed the vehicle is operating in together with deviations from reference velocity.

The model features a set of controllers enabling the vehicle to follow reference signals for cruise and brake speeds. By feeding the model with these signals the vehicle is controlled to drive accordingly. This enables, not only to follow any velocity but also to stop at any specific place This is shown in Figure 2.1, where the two reference signals are plotted for a vehicle driving a trapezoid cycle. If the speed is lower than the reference for velocity, the controller will increase the speed. Should the speed cross the brake reference, the model will decrease the speed by braking, i.e. the controllers will ensure that the output velocity of the model is between the two signals.
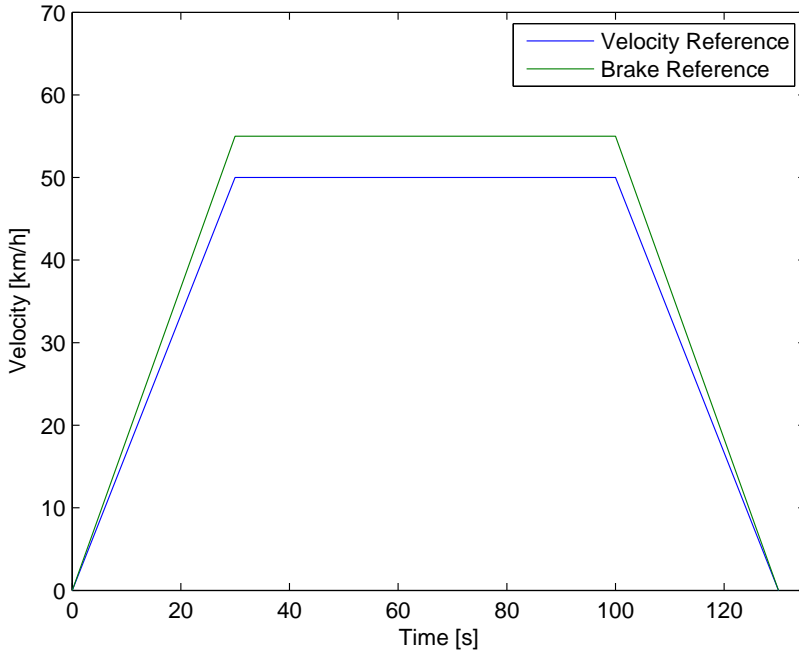
Figure 2.1: *Reference signals controlling the velocity and the brakes in the vehicle model.*

The vehicle model uses a set of signals, some of which are of interest in the thesis. These are viewed as sensor signals accessible in a real truck. The signals of interest are presented in Table 2.3.

Table 2.3: *Signals available in the vehicle model.*

Signal	Unit
Velocity	*km/h*
Altitude	*m*
Position along path	*m*
Engine Speed	*rad/s*
Engine Torque	*Nm*
Engine Motoring Torque	*Nm*

2.1.2 Energy Losses

The vehicle model uses relations derived from classical mechanics that calculates losses acting on a vehicle during simulations, this ensures the model to be a realistic model of a vehicle. Newton's second law of motion, presented in (2.1), states that the Force F acting on a object equals the mass m multiplied with the acceleration a.

$$F = m \cdot a \tag{2.1}$$

Physical work W is defined as the product of a force F displacing the object a distance d in the direction of the force.

$$W = F \cdot d \tag{2.2}$$

Energy is the capacity of doing work and mechanical energy is defined as the sum of kinetic energy and potential energy.

$$W_{mec} = W_{kin} + W_{pot} \tag{2.3}$$

From (2.1) – (2.3) physical losses acting on a vehicle can be derived. The vehicle model calculates energy losses due to air resistance, engine friction and brake losses, presented in (2.4) – (2.6).

$$W_{airRes} = \frac{C_d \cdot A_v \cdot \rho_{air}}{2} \cdot v^2 \tag{2.4}$$

$$W_{engLoss} = \int \omega_{eng} \cdot Tq_{eng,loss} \, dt \tag{2.5}$$

$$W_{brakeLoss} = \int F_{brake} \cdot v \, dt \tag{2.6}$$

For calculating the resistance due to rolling, the vehicle model uses a velocity dependent resistance model developed at Scania CV AB. In addition to this the vehicle model uses measurements to estimate transmission losses at a given engine speed through interpolation of the measured values and current engine speed.

When evaluating losses in vehicles, the energy losses is usually represented in the propellant used to power the vehicle. One method for converting energy to fuel is

$$Fuel \; Consumed \approx \frac{W_{tot,losses}}{\rho_{prop} \cdot \eta_{eng}} \tag{2.7}$$

where ρ_{prop} is the energy content of the propellant in J/l and η_{eng} the constant efficiency of the engine.

In reality the engine efficiency depends on torque, speed and engine mode. This is used in the vehicle model provided by Scania CV AB.

3

Fuel Efficient Driving Strategies

This chapter addresses the investigation of fuel-efficient driving strategies, and how those can be used for the design of a controller that lowers the fuel consumption of a heavy duty vehicle. The main idea is to conduct simulations where different driving strategies can be evaluated and analysed. By creating reference signals where different alterable parameters defines driving strategies, a series of simulations can be conducted from which parameter combinations leading to fuel efficient driving can be identified and analysed. These parameters are further discussed in Section 3.1.2.

3.1   Description

From every simulation, the information presented in Table 3.1 is stored to enable comparison between different simulation results.

Initially the investigation is limited to involve simulated time and consumed fuel to screen out simulations irrelevant for the thesis and thus to ease further and more detailed analysis of the results.

Table 3.1: Signals saved for each unique parameter setting during simulations.

Signals	Unit	Signals	Unit
Simulated Time	s	Retarder Torque	Nm
Distance travelled	m	Gear	–
Vehicle Speed	km/h	Fuel Consumed	l
Engine Speed	rpm	Control Signal (Speed)	km/h
Engine Torque	Nm	Control Signal (Brake)	km/h

3.1.1 Vehicle & Environment Parameters

To facilitate data collection and comparisons between simulations the specifications of the vehicle model were kept constant with the values presented in Table 3.2.

Table 3.2: Vehicle specification used during the investigation of fuel efficient driving strategies.

Specification	Value/Description	Unit
Vehicle Mass	40 000	kg
Engine	DC13147[1]	–
Number of Cylinders	6	–
Engine Power	450	hp
Final Drive	2.59	–
Frontal Area	10	m^2

Other than the vehicle specifications also environmental parameters where held constant during the simulations, all simulations where performed on a flat road and in all cases the simulated distance was set to $5000m$.

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[1]Scania AB [2014]

3.1.2 Drive Cycles

A drive cycle can be split up in acceleration, cruise velocity and deceleration. By introducing a more informative description of a drive cycle with more degrees of freedom than earlier presented in Section 1.2, the results will cover a wider range of strategies. As mentioned in Hooker [1988] it may be beneficial to divide the acceleration. This is fulfilled by splitting it into two phases with different constant levels of acceleration. In Figure 3.1 this is presented together with the remaining parameters used to define drive cycles used during the thesis.

The velocity where the level of acceleration is changed from a_1 and a_2 is defined by the parameter v_{knee}. Cruising velocity v_{cruise} is set to be a constant velocity, as it is the common way to drive a vehicle. The deceleration segment is determined by the distance during which the vehicle will coast R_{dist} before having to brake d, to ensure that the selected distance is completed. With coasting means to release the gas pedal so that no fuel is injected in the engine and deceleration is due to vehicle energy losses. In Table 3.3 all parameters used for the defining the driving cycles are explained.
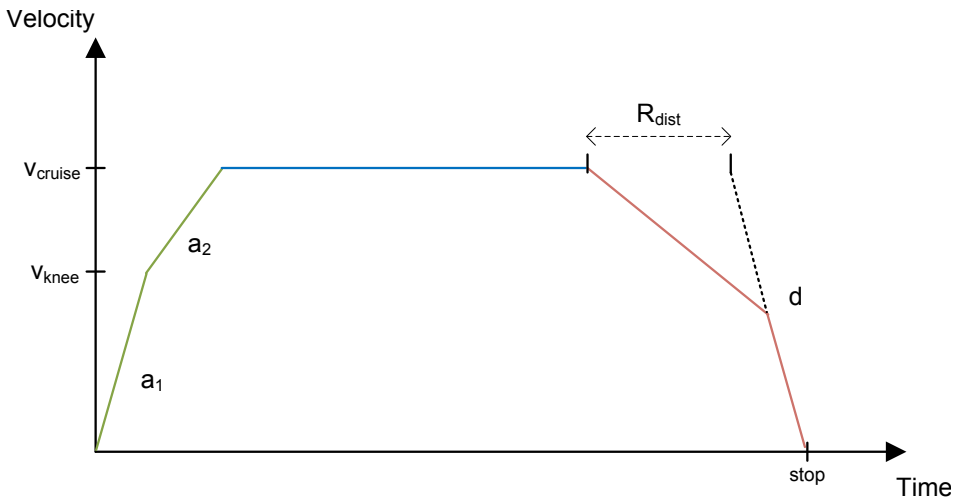
Figure 3.1: *Explanatory figure of a drive cycle and the parameters used to define it.*

Table 3.3: *Description of parameters used for generating trapezoid speed profiles shown in Figure 3.1.*

Parameter	Symbol	Unit
The vehicle's cruising velocity	v_{cruise}	km/h
Acceleration switch point	v_{knee}	km/h
Acceleration up to v_{knee}	a_1	m/s^2
Acceleration between v_{knee} and v_{cruise}	a_2	m/s^2
Distance before braking is initiated	R_{dist}	m
Deceleration to a stop from R_{dist}	d	m/s^2

As explained in Section 2.1.1 the reference signal for the vehicle model is distance based. This enables modification of parameters while keeping the same total distance for every driving cycle.

Since models developed in SIMULINK are driven by time, some adjustments have to be done to the reference in order for the acceleration and deceleration to be linear in time as seen i Figure 3.1. To transform a reference which is linear in time to a distance based reference signal the relationships from (3.1) – (3.3) are used. In Figure 3.2 this is exemplified for an acceleration of $1 m/s^2$ from $0 km/h$ to $50 km/h$.

$$a(t) = a \tag{3.1}$$

$$v(t) = t \cdot a \tag{3.2}$$

$$d(t) = \int v(t)dt = \frac{a \cdot t^2}{2} \tag{3.3}$$
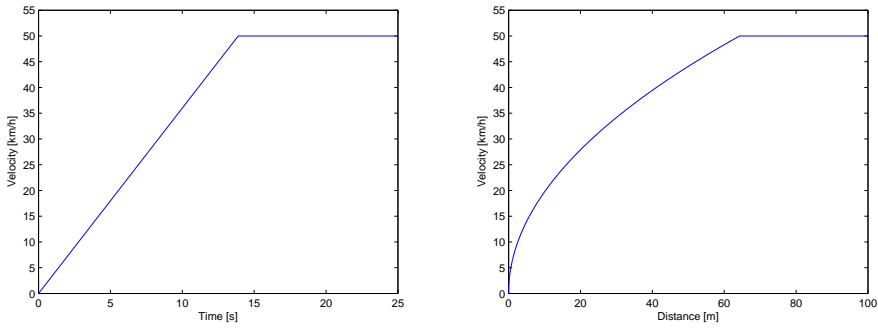
Figure 3.2: *Example of a reference signal transformed from time based (left) to distance based (right).*

3.2   Analysis of Segments

To examine which parameters have the greatest effect on mean velocity and fuel consumption, the drive cycle is divided in to the three segments shown in Figure 3.3.
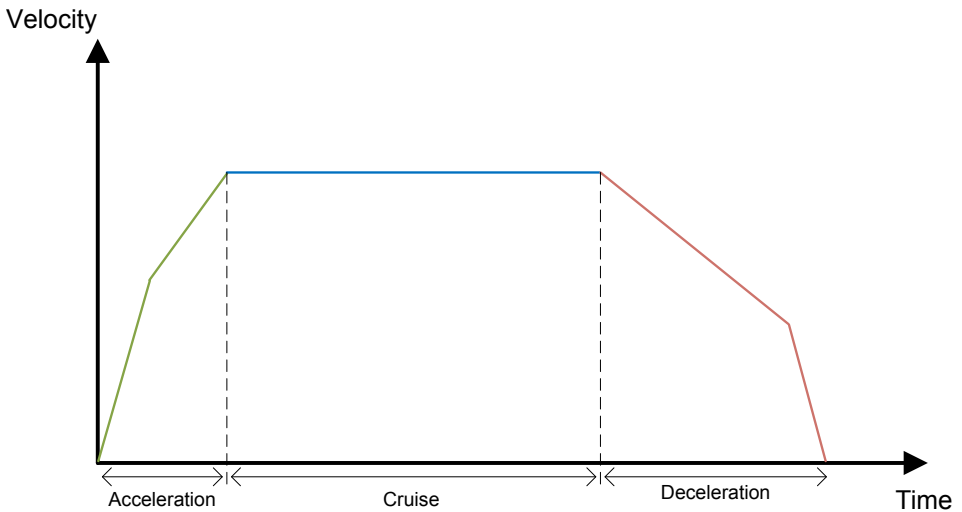
Figure 3.3: *The different segments of a driving cycle.*

These three different segments will be examined separately to increase knowledge about each segment individually and how the fuel consumption is affected by different parameters in different segments of a cycle. When one parameter or a set of parameters are examined all other parameters will be kept constant.

The goal is to find which parameter settings resulting in the lowest fuel consumption for each segment while a reasonable trip time is maintained, the important of which is mentioned in Roos [2010].

3.2.1 Acceleration Segment

The acceleration segment is defined by the parameters a_1, a_2 and v_{knee}. As mentioned earlier a potentially favourable acceleration strategy may be to initially accelerate fast and as cruise speed is approached reduce the acceleration. This is depicted in Figure 3.4 where a number of strategies for the acceleration segment are presented and analysed, each trip distance is $5000m$ and the remaining parameters are set to the following:

$v_{cruise} = 50km/h$, $v_{knee} = 30km/h$, $R_{dist} = 0m$ and $d = 4m/s^2$
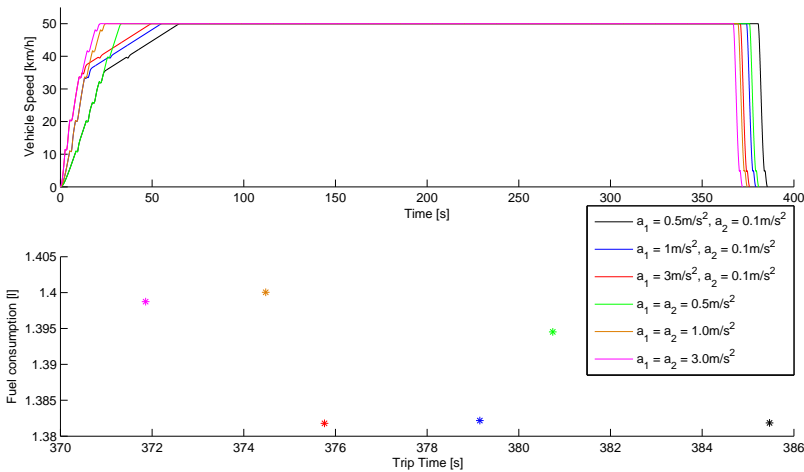
Figure 3.4: Some different acceleration strategies (upper) and the fuel consumption versus trip time for each of them (lower).

Unmistakeable to see is that a strategy with low acceleration, both initially and when kept throughout the whole segment are inefficient strategies to drive the vehicle as the trip time is significantly longer. A fuel efficient strategy where trip time is relatively short is a high initial acceleration followed by a lower one when approaching the cruise speed, which in the figure is the red one where $a_1 = 3m/s^2$ and $a_2 = 0.1m/s^2$ and thus the same fuel consumption.

From Figure 3.4 one can also see that the vehicle model is unable to keep a linear acceleration, this is due to that the gear changes leads to a velocity and time loss compared to the reference. As an example accelerating with parameter settings $a_1 = 3m/s^2$ and $a_2 = 0.5m/s^2$ results in the same output as $a_1 = a_2 = 3m/s^2$, seen in Figure 3.5.
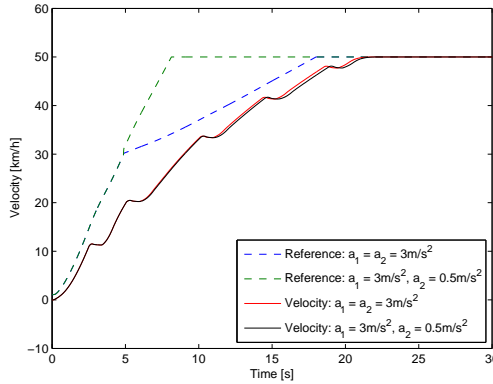
Figure 3.5: *Two different reference signals which results in more or less the same output velocities.*

For a real vehicle it is impossible to keep a perfect linear acceleration so for the vehicle model to behave this way is not viewed as a problem for the investigation. So both of the two parameter settings in Figure 3.5 results in maximum acceleration by the vehicle model.

In Figure 3.6 the effects of varying v_{knee} are shown for a vehicle accelerating to cruise velocity of $50km/h$ for a distance of $5000m$. The following parameter settings are used:
$R_{dist} = 0$, $d = 4$, $a_1 = 3$, $a_2 = 0.1$
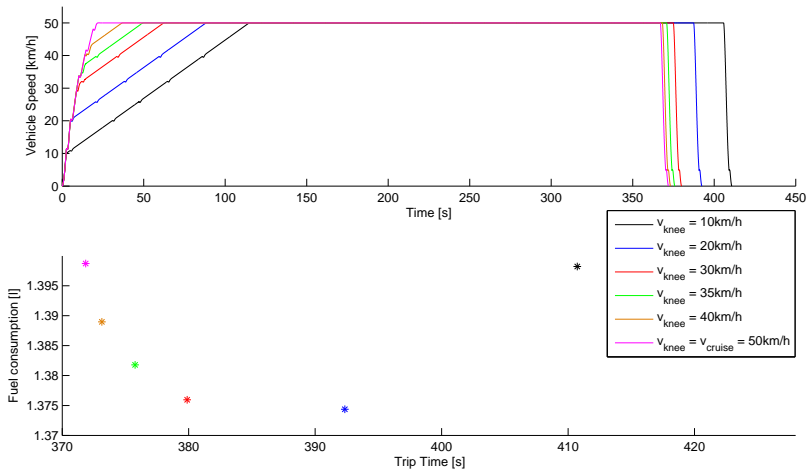
Figure 3.6: *Effects on fuel consumption and simulated time when varying the parameter v_{knee}.*

From Figure 3.6 one can see that the parameter v_{knee} affects the drive mission time more than the parameters for acceleration. Fuel consumption is marginally more affected by v_{knee} than a_1 and a_2.

3.2.2 Cruise Segment

The cruise segment is determined by the parameter v_{cruise}. As different velocities on a flat road leads to different engine speeds and gears a simple option for saving fuel is to increase the speed to enable the engine to work on a higher gear and therefore a lower engine speed and thus lowering the friction losses in the engine. Figure 3.7 shows the effects and potential savings from a deviation in cruise speed for a distance of $5000 m$.
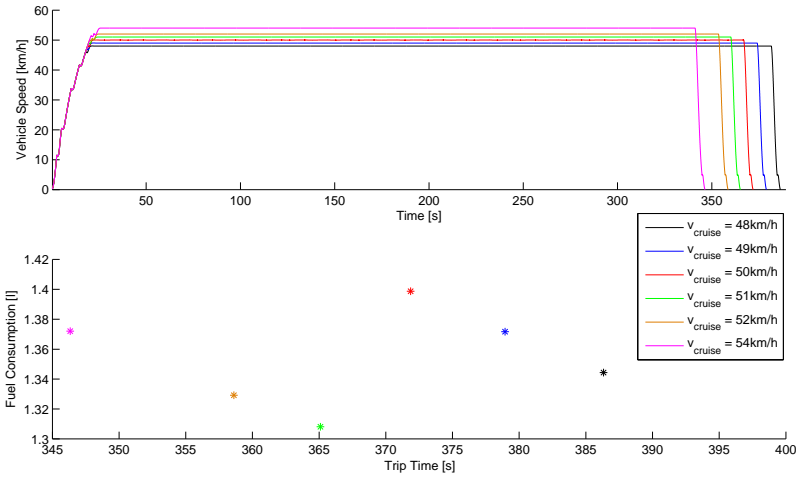
Figure 3.7: *Effects of varying v_{cruise} around $50 km/h$ for maximum acceleration and deceleration.*

From Figure 3.6 it is clear that cruise velocity can be selected to, not only, decrease consumed fuel but also shorten the trip time. For example by increasing the cruise velocity from $50 km/h$ to $51 km/h$ one can achieve greater savings in fuel consumption than it was possible from acceleration in Section 3.2.1 while also decreasing trip time.

3.2.3 Deceleration Segment

The deceleration segment is determined by the parameters R_{dist} and d. In Figure 3.8 the influence of varying the magnitude of d for a vehicle braking from a cruise speed of $50km/h$ and maximum acceleration is presented for a distance of $5000m$.
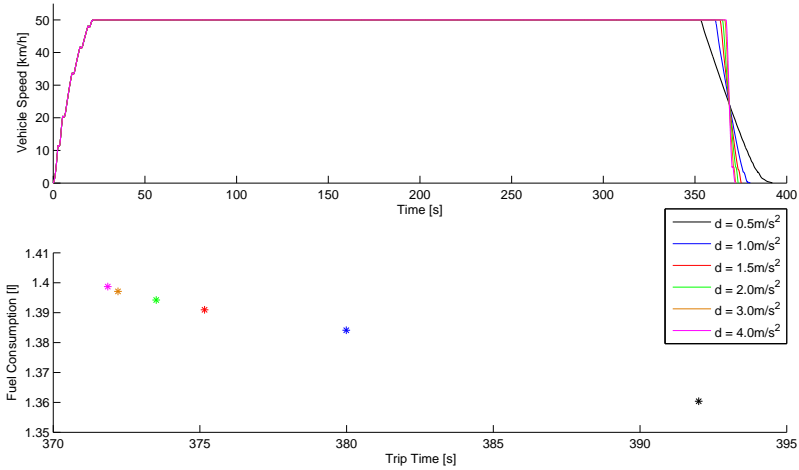
Figure 3.8: *How the parameter d affects fuel consumption.*

The parameter d has a relatively small impact on the consumed fuel as well as the trip time when braking from a high velocity, i.e. there is no obvious setting for the parameter d.

Figure 3.9 shows how the distance R_{dist} affects the trip time and fuel consumption for a vehicle decelerating to a stop from a cruise speed of $50km/h$ while using maximum acceleration for a distance of $5000m$.
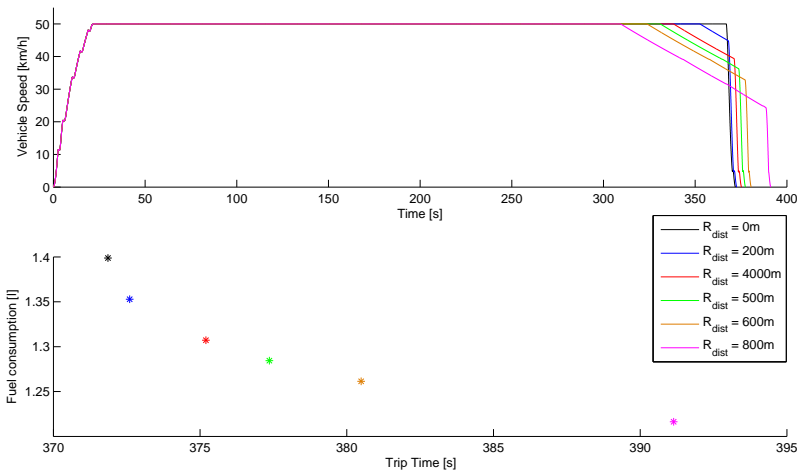
Figure 3.9: *How the parameter R_{dist} affects the fuel consumption and simulated time.*

From Figure 3.9 it is obvious that the parameter R_{dist} possesses a big potential to lower the fuel consumption for a vehicle. Compared to the results of the remaining parameters in Section 3.2.1 and 3.2.2 a relativity small increase of the parameter R_{dist} saves a lot of fuel while only increasing the trip time slightly.

3.3 Combinations

From section 3.2 it is clear that all the parameters have different effects on the resulting fuel consumption and trip time. Therefore in this section the three parameters which had the greatest effect on the results are selected and together varied, these parameters are v_{knee}, v_{cruise} and R_{dist}.

In Table 3.4 one set of parameters for a driving cycle is presented and by varying the parameters v_{knee}, v_{cruise} and R_{dist} separately, Figure 3.10 can be created. When a parameter is changed the remaining ones are held constant with the values presented in Table 3.4.

Table 3.4: *Parameter values for the intersecting cross in Figure 3.10.*

v_{cruise} $[km/h]$	v_{knee} $[km/h]$	a_1 $[m/s^2]$	a_2 $[m/s^2]$	d $[m/s^2]$	R_{dist} $[m]$
50	30	3	0.1	4	450
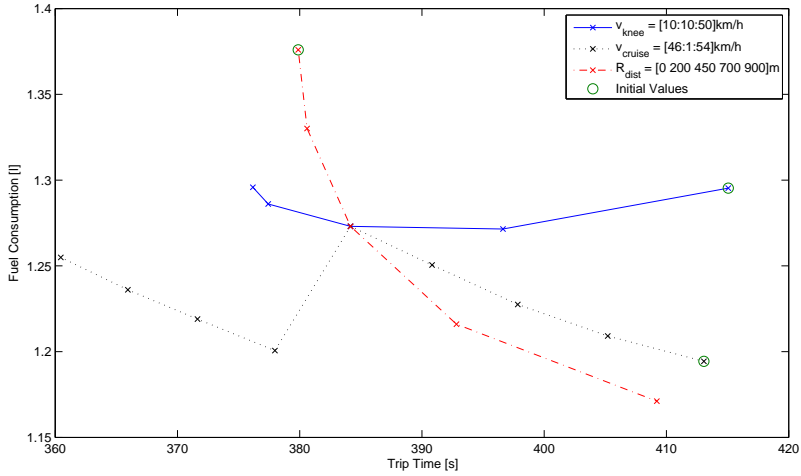
Figure 3.10: *How the parameters v_{knee}, v_{cruise} and R_{dist} affect fuel consumption and trip time. The initial values shows the first value of the parameter interval.*

In Figure 3.10 each parameter's potential for fuel savings are shown. It is clear that the parameter v_{knee} mostly affects trip time as the line representing it is elongated over time and narrow over fuel consumption. The parameter v_{cruise} is unsurprisingly wide over time and quite wide over fuel consumed but compared to R_{dist} one can see which parameter has the largest effect on fuel consumption. As can be seen in the figure, $R_{dist} = 200m$ is almost straight below $R_{dist} = 0m$, i.e. their trip time is more or less the same but with fairly large difference in consumed fuel.

3.4   Extended Simulations

To get an idea of how all the different parameters affect the mean velocity and fuel consumed, a wide range of values for the parameters are selected according to Table 3.5. Simulations are performed for each of these settings separately, resulting in the 23 184 simulations presented in Figure 3.11 where fuel consumed in $l/100km$ is plotted against mean velocity for the simulation in km/h.

Table 3.5: *Parameter intervals for the expanded simulations.*

Parameter	Interval	Step size	Unit
v_{cruise}	27–84	3	km/h
v_{knee}	15–70	5	km/h
a_1	3	-	m/s^2
a_2	0.1 & 0.4	-	m/s^2
d	1 & 4	-	m/s^2
R_{dist}	0–2000	100	m
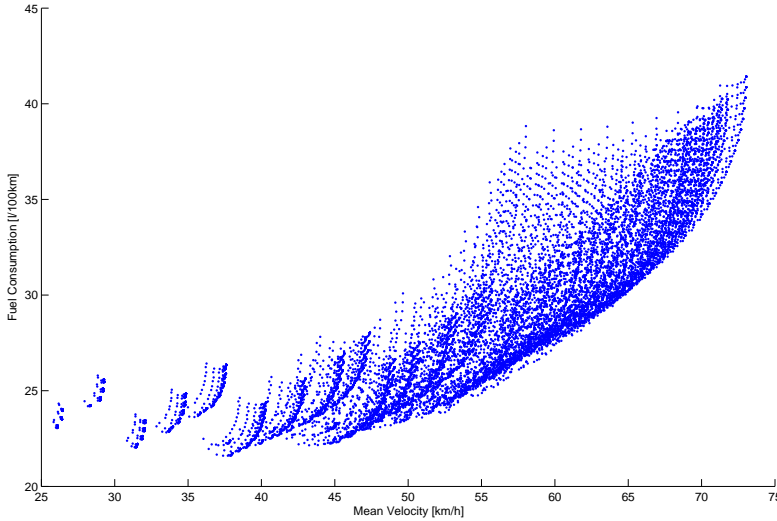
Figure 3.11: *Results from simulations performed with the parameter settings from Table 3.5.*

As can be viewed in Figure 3.11 there exists a vast amount of different strategies resulting in the same mean velocity and/or fuel consumption. But for all different mean velocities there exists a strategy resulting in the lowest fuel consumption for that velocity. These results form a hypothetical line from which all strategies resulting in the lowest fuel consumption given a specific mean velocity can be obtained. To easier understand what distinguishes these strategies from the others a more narrow velocity interval is selected and another set of simulations are performed, the parameter settings for theses simulations are seen in Table 3.6.

Table 3.6: *Parameter intervals used for the second set of simulations.*

Parameter	Interval	Step size	Unit
v_{cruise}	41–59	1	km/h
v_{knee}	10–60	10	km/h
a_1	3	-	m/s^2
a_2	0.1, 0.2 & 0.4	-	m/s^2
d	1 & 4	-	m/s^2
R_{dist}	0–1200	100	m

In Figure 3.12 the results from simulations with the parameters from Table 3.6 are presented. Three strategies which result in the same mean velocity but differs a lot in fuel consumption are marked for further analysis and are described in Table 3.7. The three strategies are selected after having roughly the same mean velocity as a vehicle driving $5000m$ at $50km/h$.
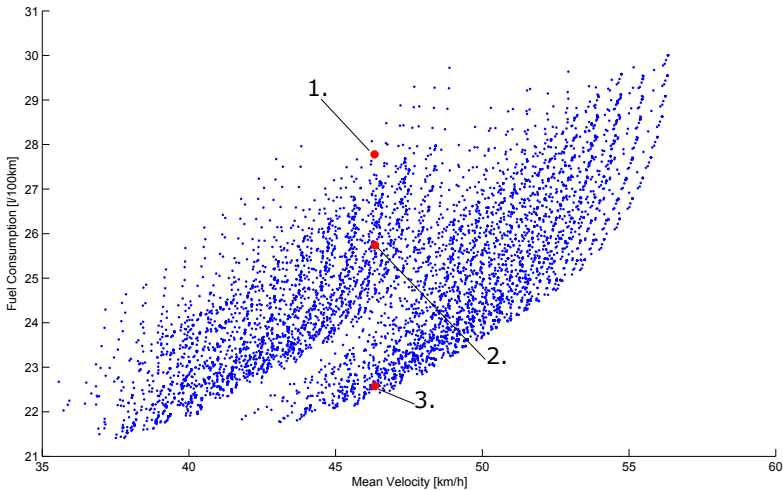
Figure 3.12: *Results from 6 840 simulations performed with the parameter settings specified in Table 3.6.*

Table 3.7: Parameter settings for the three marked results in Figure 3.12.

	v_{cruise} [km/h]	v_{knee} [km/h]	a_1 [m/s²]	a_2 [m/s²]	d [m/s²]	R_{dist} [m]
1.	50	10	3	0.2	4	0
2.	49	20	3	0.2	4	300
3.	53	30	3	0.2	1	900

From Table 3.7 it is clear that the first intuitions from Section 3.2 were correct. The parameter which differs most for these three strategies is R_{dist}. The time lost during rolling is compensated with higher values on parameters which have a smaller impact on the fuel consumption. In Figure 3.13 the velocity and engine speed for the three different strategies are presented and Figure 3.14 shows the distribution of energy losses for the strategies.

Figure 3.13: Vehicle speed (upper) and engine speed (lower) for the three strategies from Figure 3.12.

Figure 3.14: *Energy losses for the three different strategies from Figure 3.12.*

The largest differences for the three strategies presented are from brake losses and engine friction, where strategy 3 is considerably lower than the remaining two. For strategy 3 a higher gear is used for the cruise segment which leads to lower engine friction. As transmission losses also depends on engine speed this loss is marginally lower, due to higher speed in strategy 3, the air resistance is a bit higher 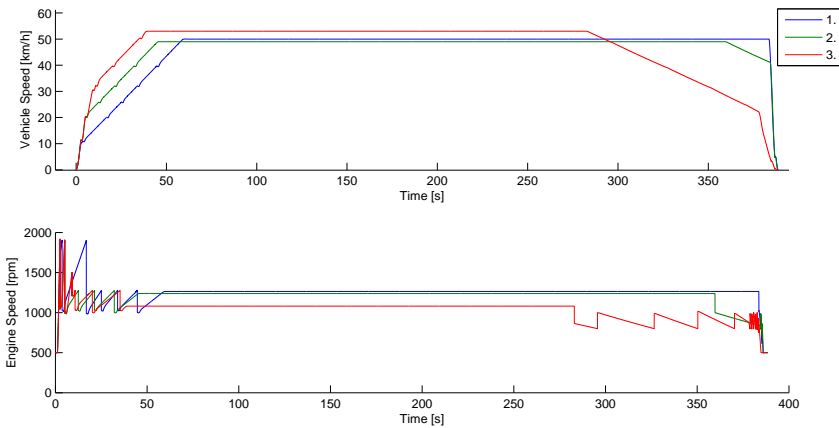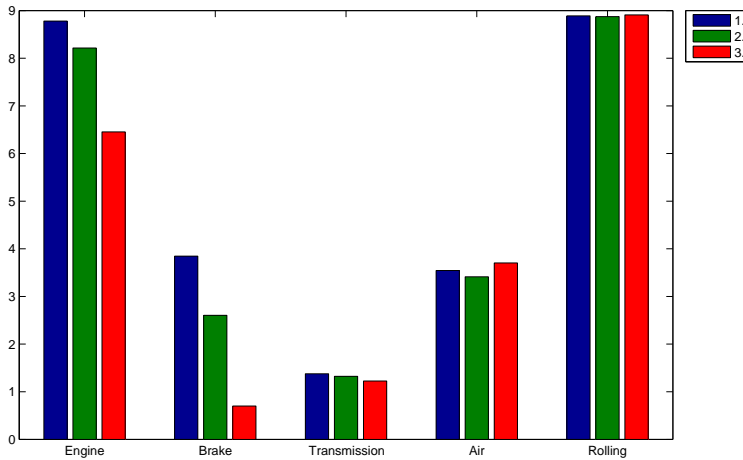than for the others. Rolling resistance is more or less the same for all the strategies as velocity only differs $1km/h$ between the different strategies and the travelled distance is the same for all strategies.

3.5   Summary

In conclusion a couple of strategies to drive a vehicle in a fuel efficient way are identified. As the influencing energy losses on the vehicle consistently has a braking effect on the vehicle, the most fuel efficient strategy is to coast the vehicle as long distance as possible before having to use the brakes, i.e. choosing a long R_{dist}. In this way the amount of fuel injected into the engine is reduced while the trip time is only marginally affected. Through combining a longer coasting distance with, for example a higher acceleration or cruise velocity the vehicle is able to lower the fuel consumption and still keep an acceptable trip time. For some combinations the trip time can even be shortened compared to following the reference.

To achieve a better and more extensive analysis, more simulations should be conducted with different vehicle parameters such as vehicle mass and final drive. Including road slopes would also make the analysis more complete, as well as implementing a more sophisticated gear selection algorithm than the one used.

4

Controller Design

In this chapter the controller design is presented, the design enables the controller to use the fuel-efficient driving strategies discussed in Chapter 3. For the controller to be realistic driveability has to be taken into account, this will limit to what extent the strategies can be used.

To design a realistic controller to be used in a real environment it must be robust against external influences. It must guarantee the vehicle to stop at predetermined distances as well as keep speed limits according to a reference. The controller does not have to follow exactly the optimal driving strategy, but has to enable the vehicle to continuously alter the velocity based on current events, i.e. the input to the controller only need to consist of information about the upcoming segment of the driving cycle, for example up to a roundabout or a left turn.

4.1 Reference Window

To ensure a realistic controller, driveability aspects are taken into account for the controller design. As mentioned in Section 3.5 the most fuel efficient strategy is to do coasting for lowering the velocity before braking. The distance the vehicle coasts however needs to be restricted as a driver would have a hard time accepting the vehicle losing speed over a too long distance. For example in Figure 3.9, the vehicle coasts from $50km/h$ to 0 during $800m$. This however takes more than one minute, which may be unacceptable for a driver using the controller.

To avoid unacceptable strategies a window for the reference speed is defined by the parameter dev_{Ref}. Within this window the controller is allowed to select the most fuel efficient velocity. The parameter dev_{Ref} is a percentage of the reference

signal and a measure of how much the controller allows the velocity to deviate from the determined reference. This will limit for example the coasting distance as the deceleration velocity selected by the controller needs to be within the reference window. In (4.1) how dev_{Ref} relates to a reference velocity v_{Ref} is presented.

$$Ref_{window} = v_{Ref} \pm v_{Ref} \cdot dev_{Ref} \tag{4.1}$$

In Figure 4.1 an example of an acceleration segment is presented where the reference window is set to be ±10% of the reference signal.
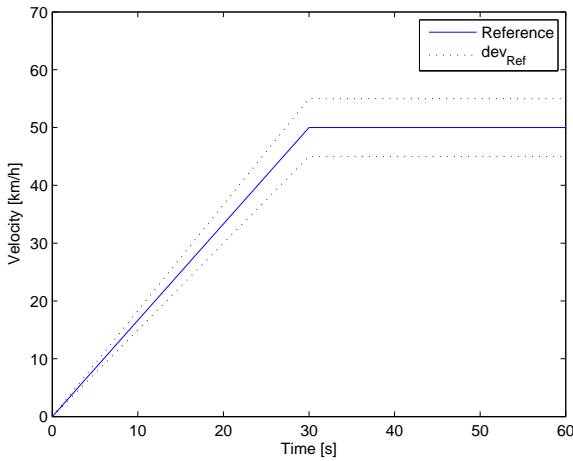
Figure 4.1: *Description of the reference window determined by dev_{Ref} in which the controller is allowed to select the most fuel efficient velocity.*

The controller is allowed to alter the velocity to lower fuel consumption or save time provided it remains within the boundaries set by dev_{Ref}.

4.2 Simulation Setup

During the thesis the reference velocity signal is given at the beginning of the simulation, all information about the driving cycle is therefore known beforehand. For the controller to be robust and not be affected by external effects, a simulation environment is set up where a input signal to the controller is created. In Figure 4.2 how the controller is coupled with the vehicle model is presented. The controller feeds the vehicle model with a reference for the cruise and brake velocity ensuring the resulting velocity to be within the reference window. Feedback to the controller consists of losses and current velocity and altitude.

Figure 4.2: *Overview of the system and how v_{ref} is transformed for the vehicle.*

This signal provides the controller with information about upcoming events to simulate a continuous flow of information into the controller to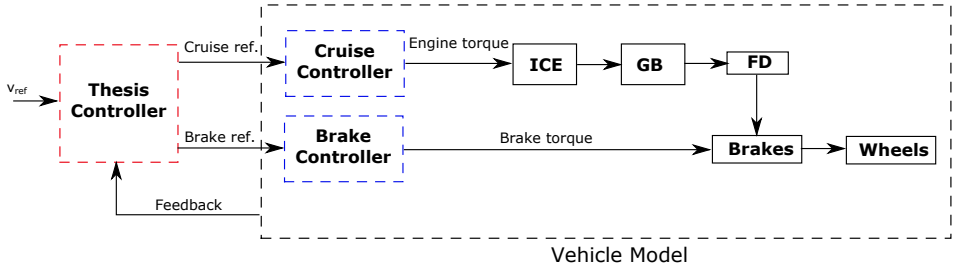 make it more realistic. The controller only needs information about events about the next event, for example up to a stop sign or traffic light.

In Figure 4.3 a block diagram of the simulation setup is presented. In the figure the information specified in text is forwarded through the arrow to the next block where it is processed, $v_{vehModel}$ in the figure is the input reference converted to be readable by the vehicle model.
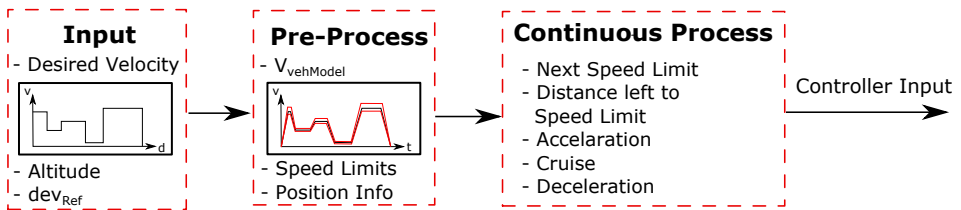
Figure 4.3: *Block diagram of the functions providing the input for the controller, every dashed block is further described in section 4.2.1 – 4.2.3.*

4.2.1   Input

The input is a drive cycle consisting of a reference velocity signal based on distance and the altitude for that same distance. The reference speed can consist of just steps in velocity that describes at which distance a certain velocity is requested. This is to make the controller generic as driving cycles often are described that way at Scania and the goal is to enable any reference as input.

4.2.2   Pre-Process

This block enables the vehicle model to use the input signal by ensuring that the reference is linear in time as described in Section 3.1.2. In addition to this the pre-process block extracts information about which velocity is requested at which distance.

In reality there are functions obtaining this information from external sources e.g. GPS data or road signs. How the controller receives the information is of less interest in the thesis.

4.2.3   Continuous Process

The continuous process block creates the input signal for the controller continuously, this ensures that the controller makes decisions according to present information and does not need access to information about the whole cycle. Except for the information from the input and pre-process, also all signals from the vehicle model described in Section 2.1 are available to the block.

During simulations the controller determines if the vehicle is accelerating, cruising or decelerating. This is achieved by using current and previous reference velocity together with the position of the vehicle and information provided by the pre-process. With this information the controller also estimates the next cruise velocity as well as the distance left to it and the altitude at that distance.

4.3   Controller Design

The overall design of the controller is presented in Figure 4.4. The different blocks and functions of the controller are further explained in Section 4.3.1 – 4.3.3. The vehicle model signals described in Section 2.1 are all available to the blocks of the controller as well as the information generated by the continuous process block described in Section 4.2.3.
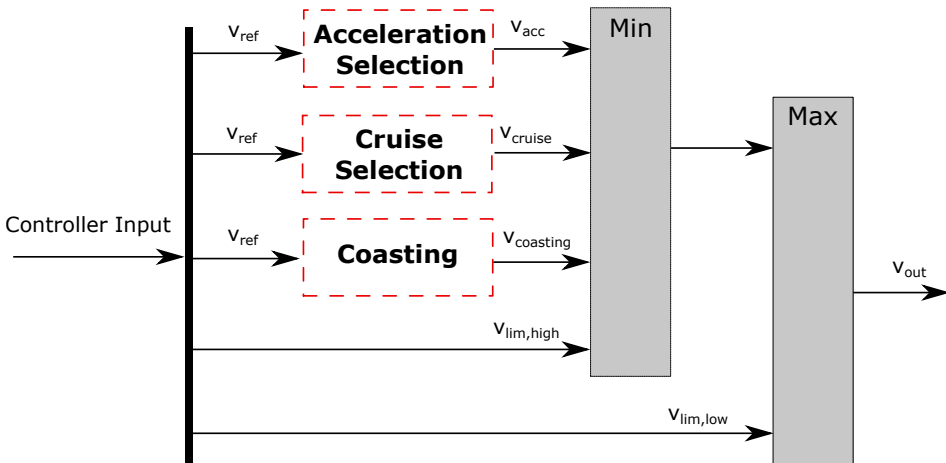

Figure 4.4: *Block diagram of the controller, dashed blocks are functions in the controller.*

Every block in the controller calculates a velocity parallel to the other blocks. As the outputs passes through the min/max blocks the final output reference is ensured to be within the boundaries set up by dev_{Ref}.

4.3.1   Acceleration Selection

As identified in Section 3.5 the acceleration ought to be as high as allowed to ensure that time is saved for more fuel-efficient strategies, as well as to avoid driving at low speeds i.e. where the engine friction losses accounts for a large portion of the losses. In every acceleration segment the controller will follow the highest allowed acceleration, which is determined with the parameter dev_{Ref}.

4.3.2   Cruise Selection

Increasing the cruise speed is carried out according to two strategies. The first is to always increase cruise velocity if the vehicle is operating below the optimal vehicle speed limit. The other is to increase velocity if that increased velocity results in a higher gear and thus lower engine speed. Naturally the increase in velocity is limited by the boundaries set by dev_{Ref}.

The optimal vehicle velocity is a known parameter depending on vehicle specifications. In Figure 4.5 fuel consumption as a function of velocity for a specific vehicle is presented where the steps in fuel consumption over velocity is due to gear changes. From the figure one can see that the lowest fuel consumption is achieved somewhere between the velocities 30 and 50. If the vehicle increases its speed from around 28 to above 30, the fuel consumption is lowered due to a change of gear. Depending on the aggressiveness of the controller one can modify at which velocity the controller will increase the velocity. If a higher velocity is selected it will result in shorter trip time as well as lower fuel savings. But by using this saved time with other fuel saving strategies, such as coasting, the total amount of saved fuel would still be lower.
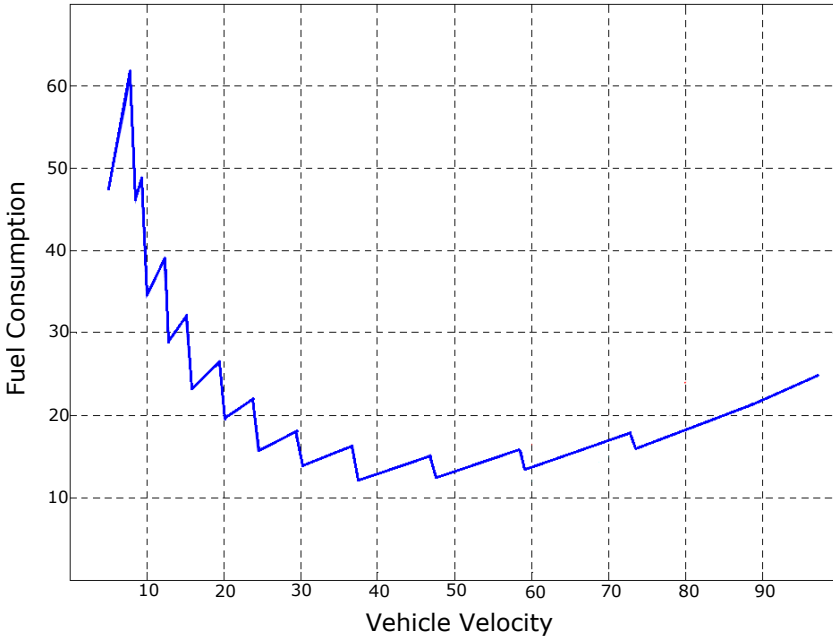
Figure 4.5: *Fuel consumption as a function of vehicle speed, the axis units and values are modified due to confidentiality.*

The controller uses signals for engine speed together with vehicle velocity to determine how far in velocity the vehicle is from a gear-change. As engine speed is proportional to velocity and the engine speed limits for gear changes are known to the vehicle model the velocity from a gear change Δv can be calculated as

$$\Delta v = \left(\frac{v_{veh}}{\omega_{eng}} \cdot \omega_{upshift} \right) - v_{veh} \tag{4.2}$$

where $\omega_{upshift}$ is at which engine speed the gear is changed.

The controller will give priority to increase speed when it is below the optimal velocity, since the probability for this increase in velocity to lead to an up shift is higher at lower speeds as seen in range $10 - 30 km/h$ in Figure 4.5.

4.3.3 Coasting

In Chapter 3 the potential of coasting with a heavy duty vehicle was investigated and proven to be the most effective method to save fuel among the ones presented. Naturally the function handling the parameter R_{dis} is where most fuel can be saved by the controller. As the controller has information about the upcoming speed limits and altitude profiles along with current velocity and altitude, it is able to estimate the distance that the vehicle is able coast and still remain within the reference window.

By applying the law of the conservation of energy together with estimations of vehicle losses and signals from the model, the controller is able to estimate the coasting distance. In (4.3) – (4.4) the potential and kinetic energy relations needed by the controller are presented and these are explained in Figure 4.6.

$$\Delta W_{pot} = m_{veh} \cdot g \cdot \Delta h \tag{4.3}$$

$$\Delta W_{kin} = \frac{1}{2} \cdot m_{veh} \cdot \left(v_1^2 - v_2^2 \right) \tag{4.4}$$

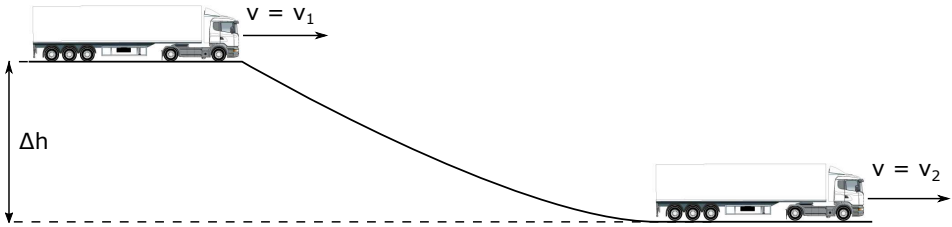**Figure 4.6:** *Description of the energy relations between two positions explained in (4.3) and (4.4).*

The velocity v_2 for the controller will be the velocity which the vehicle wants to reach before having to brake i.e. the lowest cruise velocity allowed by the reference window. One exemplification of this is shown in Figure 4.7 where the current velocity v_1 is $50km/h$ and the reference window set to be 10%.
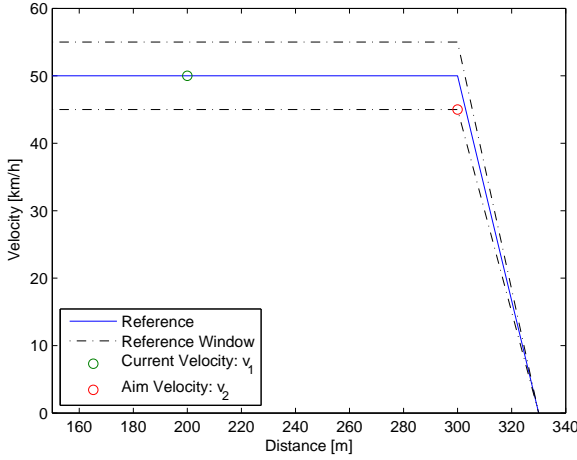
Figure 4.7: *Description of how the velocities v_1 and v_2 relate to the reference window.*

In (4.5) – (4.7) the computations performed for estimating the losses in the vehicle are presented. When calculating the losses in the model, the mean values between the two points are used and are calculated with respect to the difference in the velocities v_1 and v_2.

$$\bar{F}_{eng} = \frac{1}{2} \cdot \left(\frac{\omega_{eng} \cdot Tq_{eng,loss}}{v_1} + \frac{\omega_{eng} \cdot Tq_{eng,loss}}{v_2} \right) \tag{4.5}$$

where $Tq_{eng,loss}$ is the motoring torque, which is the required torque to rotate the engine at a given engine speed including friction and pumping losses, this is estimated with measured data in the vehicle model.

$$F_{roll} = C_r \cdot g \cdot m_{veh} \tag{4.6}$$

$$\bar{F}_{air} = \rho_{air} \cdot A_{veh} \cdot C_d \cdot \left(\frac{v_1^2 + v_2^2}{4} \right) \tag{4.7}$$

The transmission power losses are estimated by interpolation with respect to current engine torque in the vehicle model and the contributing force due to this as is presented in (4.8).

$$\bar{F}_{trans} = \frac{1}{2} \cdot \left(\frac{P_{trans,loss}}{v_1} + \frac{P_{trans,loss}}{v_2} \right) \tag{4.8}$$

where $P_{trans,loss}$ is the transmission power loss estimated and interpolated from engine speed in the vehicle model.

When calculating the mean losses from the transmission and engine, the same engine speed, motoring torque and transmission power loss is used for the two points. This is not the case in reality, but as the two vehicle velocities are used and a mean value calculated, the estimation is acceptable. The difference between the velocities are being limited by the reference window and will therefore be limited.

With (4.3) – (4.8) the coasting distance for the vehicle can, with the definition of work in (4.9), be estimated as presented in (4.10).

$$W = F \cdot d \tag{4.9}$$

$$d_{roll} = \frac{\Delta W_{tot}}{F_{tot}} = \frac{\Delta W_{pot} + \Delta W_{kin}}{\bar{F}_{eng} + F_{roll} + \bar{F}_{air} + \bar{F}_{trans}} \tag{4.10}$$

As the controller has information of current position and the distance left to the next speed limit it will set the reference velocity to the lowest allowed by dev_{Ref}. This is in order to ensure that even if there is an uphill between current distance and distance to aim the vehicle is unable to roll below the limited velocity. The vehicle will begin coasting when

$$d_{remain} \leq d_{roll} \tag{4.11}$$

where d_{remain} is the remaining distance to the next speed limit. Both the distances are updated in every time step.

One disadvantage with the strategy presented is that calculation of the coasting distance due to Δh will be inaccurate in the event of an uphill between the two positions used when calculating. As the reference window will ensure the velocity to be kept within its limits a coasting over a hill will lead to the vehicle driving at the velocity determined by the lower limit.

5

Results and Discussion

This Chapter addresses the simulation results obtained in the thesis. By comparing results from simulations conducted on the same input signal where the developed controller is deactivated with results from simulations where the controller is activated one can see how the new controller affects fuel consumption and trip time. Also different settings for the parameter dev_{Ref} is compared to investigate how the width of the reference window affects fuel consumption and trip time. The input used in the comparisons is further described in Section 5.1.

First the results from the different parts of the controller are presented to make sure that they perform as expected. Then the fuel savings and trip time of the developed controller will be compared to results from simulations with the new controller deactivated.

5.1 Input

During the evaluations, the reference signals used have been developed at Scania from recorded data from a vehicle driving back and forth between Södertälje and Trosa, [Lööf, 2014]. As the cycle is developed from recorded measured data for the use of evaluating distribution vehicles at Scania CV AB, it reflects a realistic cycle for a vehicle operating in an urban environment. In Figure 5.1 the velocity reference and altitude for the cycle is plotted against distance. The mean velocity for the drive cycle is $50 km/h$ which is what one would expect from a cycle representing urban driving.
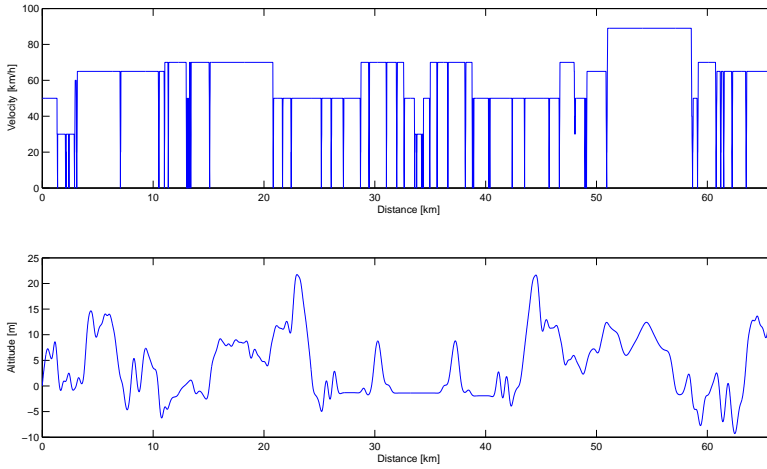
Figure 5.1: *Reference for velocity (upper) and altitude (lower) for* $6351m$ *long cycle used during the evaluation of the controller.*

This input needs to be pre-processed for enabling the vehicle model to use it as a reference signal. The pre-process provides the controller with information of speed limits and stops throughout the cycle.

For the vehicle to better represent one used in urban environments, the vehicle parameters were change according to Table 5.1.

Table 5.1: *Vehicle specification used during the evaluation of the developed controller.*

Specification	Value/Description	Unit
Vehicle Mass	18 000	kg
Engine	DC09113[2]	–
Number of Cylinders	5	–
Engine Power	280	hp
Final Drive	2.59	–
Frontal Area	10	m^2

To be certain this would not influence the driving strategies identified, investiga-

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[2]Scania AB [2013]

tions with the new parameters were conducted. The results shows that even with a much lower weight and a different engine, the strategies identified in Chapter 3 are the most fuel efficient.

5.2   Functionality

Here the results from the controllers main parts are described and compared against result when the new controller is deactivated. Initially one function at a time is presented although the controller has all its functionality activated so some results may show effects from more than one function. The main parts for the controller are the functionality that selects acceleration, cruise velocity and calculate the coasting distance. In all comparisons the allowed reference window is set to be ±10% of the input reference.

5.2.1   Acceleration

In Figure 5.2 an acceleration segment is presented, the reference for the new controller selects the highest possible acceleration as wanted. One can also see that the controller selects a higher cruise velocity resulting in a lower engine speed, this is due to the function selecting cruise velocity, further discussed in Section 5.2.2.
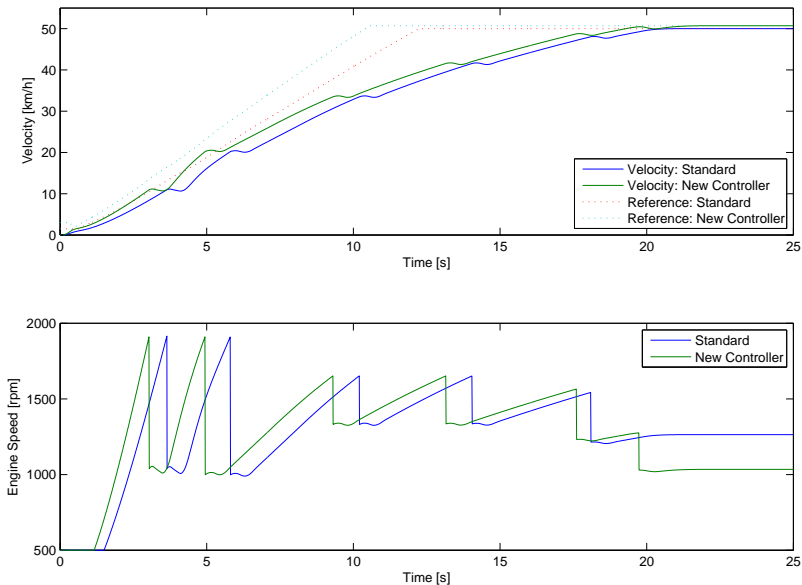

Figure 5.2: *Resulting velocity (upper) and engine speed (lower) of the controller selecting the highest acceleration.*

As can be seen in the figure both accelerations are unable to follow the reference. The reason that the acceleration with the new controller is higher is due to the proportional gain in the vehicle model's PI controller that is to follow the reference signal. The bigger the error between reference signal and velocity the faster the model will accelerate to reach the reference velocity. As the error is larger in the case when the new controller is activated, the vehicle model will accelerate faster.

5.2.2 Cruise

As mentioned in Chapter 4 the cruise strategy increases the velocity according to two cases. Figure 5.3 shows when the new controller selects a higher cruise velocity to initiate a up-shift and thus lowering the engine speed and friction for the upcoming cruise segment.
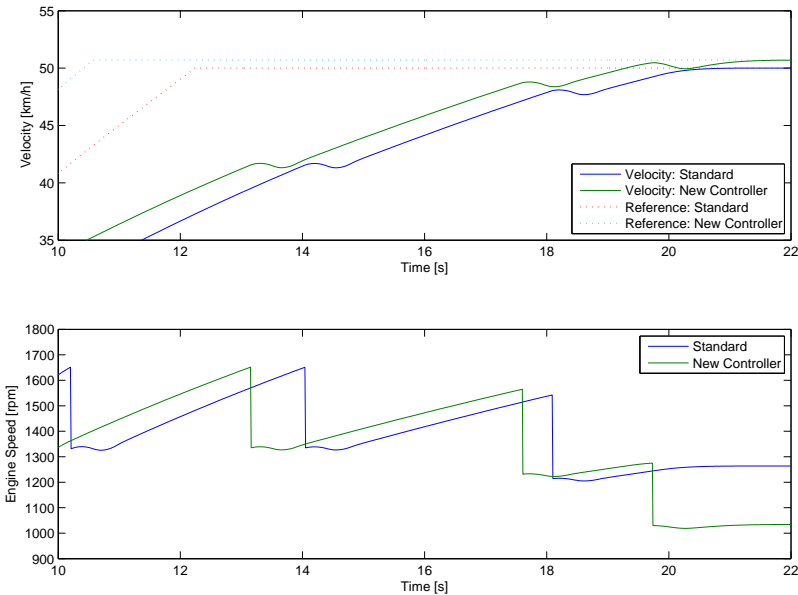

Figure 5.3: *Resulting velocity (upper) and engine speed (lower) of the controller selecting a different cruise velocity to initiate an up-shift.*

The gear change in the figure occurs when the engine speed and velocity drops for a short period. As seen the reference were the new controller is activated gets an extra up-shift compared with the controller deactivated by increasing the cruise speed $\Delta v\ km/h$, in this case is $\Delta v < 1km/h$. In a real vehicle the gear changes are not solely based on engine speed and this strategy is therefore not entirely realistic, this is further discussed in Section 6.1.1.

In Figure 5.4 the new controller selects a higher cruise velocity as the reference cruise velocity is below the optimal velocity of $40km/h$ for the vehicle. The controller increases the velocity according to the reference window set by dev_{Ref}, the velocity is set to be no higher than $0.5km/h$ from the upper limit of the reference window.
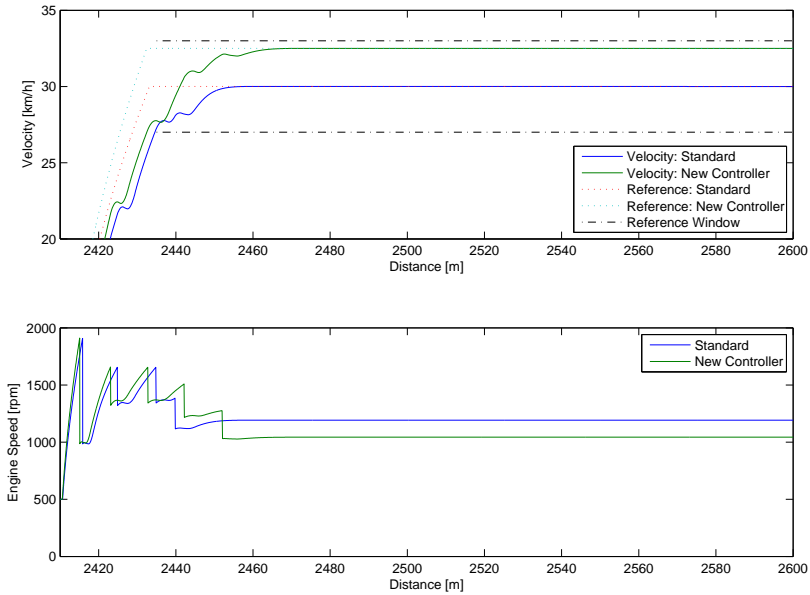

Figure 5.4: *Resulting velocity (upper) and engine speed (lower) of the new controller selecting a higher cruise velocity due to the reference being below the optimal velocity of $40km/h$.*

5.2.3 Coasting

In Figure 5.5 the controllers strategy for coasting i presented for a segment in the drive cycle together with the altitude. As can be seen the calculation of the distance where to begin coasting is in this case correctly calculated as the resulting velocity maximizes the coasting distance without hitting the lower limit of the reference window to minimize lost time during coasting.
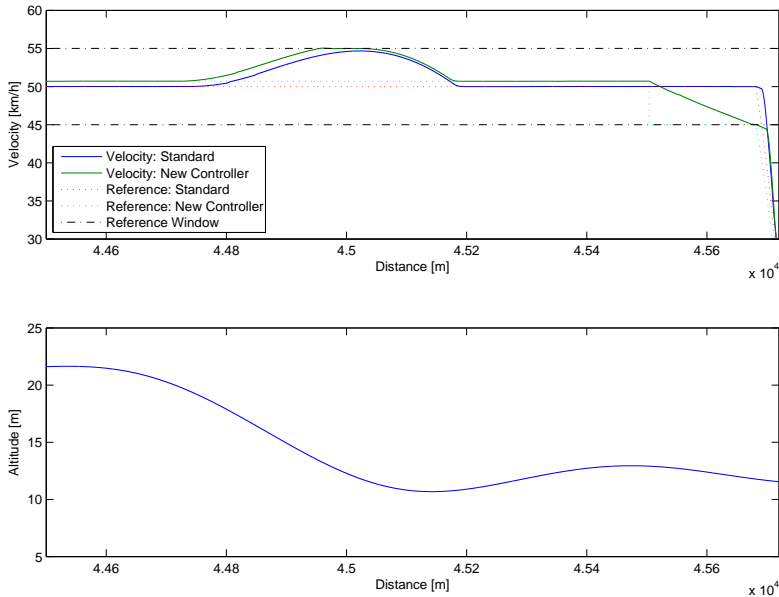
Figure 5.5: *Resulting velocity (upper) and altitude (lower) of the new controller initiating costing to minimize braking.*

The topology of the road results, in this situation, in the vehicle rolling up in speed. Noteworthy is how the vehicle, in the case when the new controller is activated brakes to prevent it from achieving a higher speed than allowed by the reference window. This is obviously not ideal, as the strategy just converts potential energy to heat, in Section 6.1 a solution to this is discussed.

In Figure 5.6 a coasting segment is presented where an error in the distance calculation has occurred due to road topology. As the distance is calculated with respect to two different points, what occurs in-between is not taken into account. In the example presented in Figure 5.6 there is an uphill between the two points. This leads to that the calculation of d_{roll} will be incorrect as the controller will prevent the vehicle from reaching a lower velocity than the reference window allows. In Section 6.1 a solution to this problem is discussed.
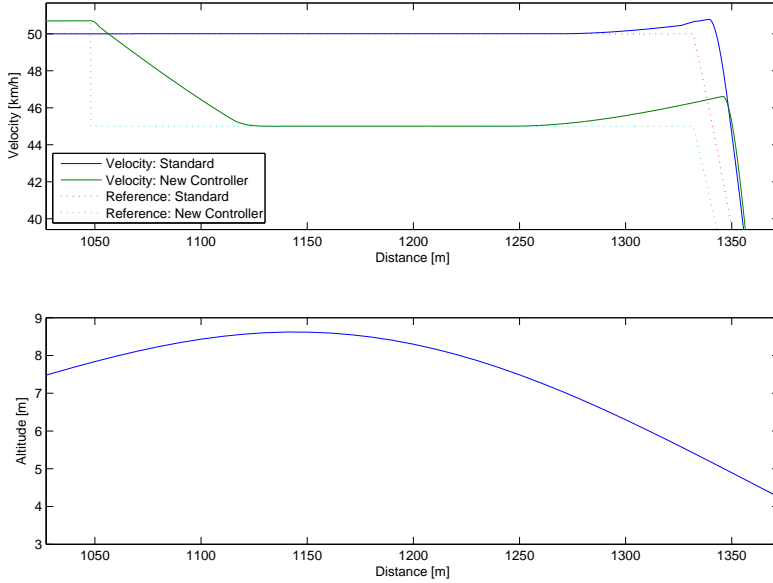
Figure 5.6: *Resulting velocity (upper) and altitude (lower) of the new controller attempting to coast over a hill.*

5.3   Performance Evaluation

In Table 5.2 results from simulations with the new controller activated and deactivated are presented. During comparison, the reference window for the controller is set to be 10% of the reference signal. Simulations are performed with the input presented in Section 5.1.

Table 5.2: *Comparison between new controller deactivated and activated for a reference window of* 10%.

	Deactivated	Activated
Fuel Consumption [$l/100km$]	36.4	34.1
Total Time [s]	4636	4582
Δ Time [%]	0	−1.5
Δ Fuel [%]	0	−6.3
Mean Velocity [km/h]	49	50

The new controller not only lowers the fuel consumption with 1.5l but also decreases the trip time with 54s for the drive cycle used. In Figure 5.7 the losses from the two simulation are presented.
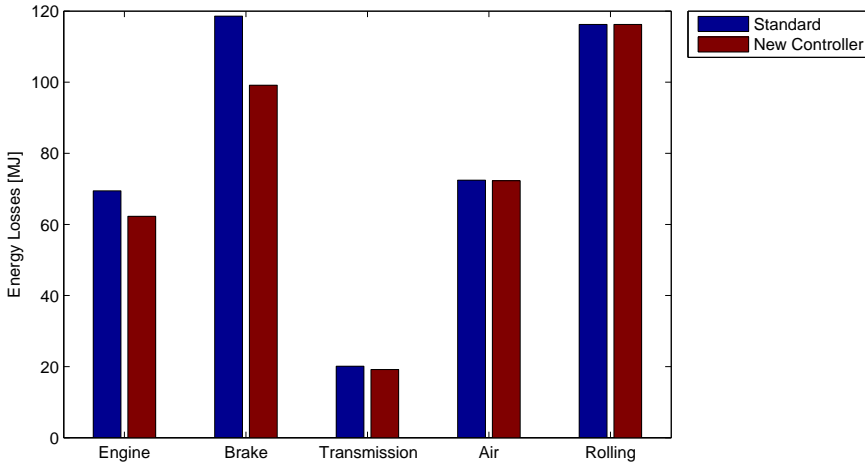

Figure 5.7: *Comparison between losses from simulation results with and without the controller activated and dev_{Ref} set to* 10%.

As all the functionality implemented either increases the cruise velocity to lower the engine speed or coasts to minimize braking, the two results that differs the most are brake and engine losses. The resulting transmission losses is, due to coupling with engine speed, a bit lower when the controller is activated. Losses due to rolling resistance and air resistance are on the other hand more or less the same as those losses are very dependent on velocity and as presented in Table 5.2 the mean velocity for the two simulations are more or less the same.

5.4   Width of Reference Window

To evaluate the potential of the new controller, simulation results for different values of the parameter dev_{Ref} are investigated and analysed as well as how the different functions in the new controller are affected by a wider reference window.

In Table 5.3 the resulting trip time and fuel consumption for varying dev_{Ref} between 5% and 20% is presented, all of which are compared to the results where the new controller is deactivated. Results for the controller deactivated can be seen in Table 5.2.

Table 5.3: *Results for different settings of dev_{Ref} in the new controller compared to being deactivated, which results in a trip time of 4636s and fuel consumption of 23.1l.*

dev_{Ref} [%]	Δ Time [s]	Δ Time [%]	Δ Fuel [l]	Δ Fuel [%]
5	−27	−0.6	−0.4	−1.8
10	−54	−1.2	−1.4	−6.3
15	−43	−0.9	−2.1	−9.1
20	−26	−0.6	−2.7	−11.8

As can be read from the table, a higher value of dev_{Ref} leads in all cases to a lower fuel consumption. This is because coasting can be used to a greater extent, which is the most fuel efficient strategy presented. The wider the window in which the velocity is allowed, the longer the vehicle is able to coast and thus has the ability to lower the fuel consumption considerably increased. This can also be seen in Figure 5.8 where the resulting losses from the simulations are presented. Not surprisingly is it the energy losses due to braking that differs the most between the results followed by engine and transmission losses.
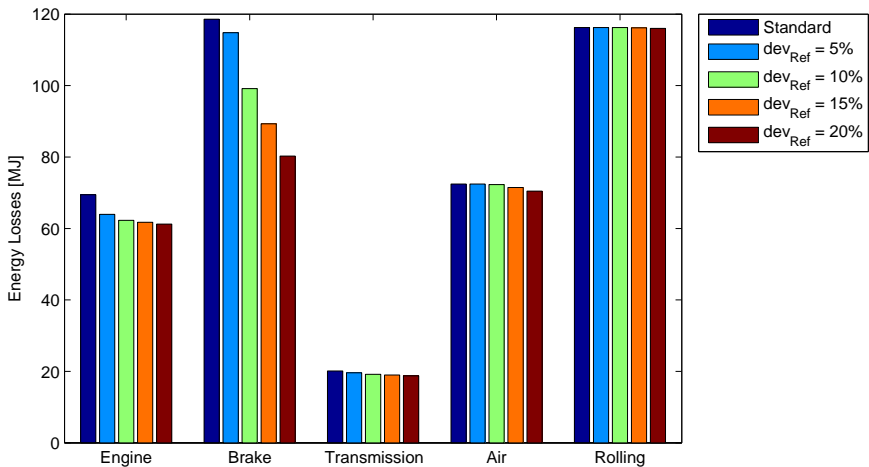

Figure 5.8: *Losses for different values of dev_{Ref}.*

The trip time decreases for all the simulated values on dev_{Ref}. For $dev_{Ref} = 10\%$ the largest differ in trip time is achieved. This is because that reference window leads to shorter distances to engine roll than the wider reference windows but still shortens the trip time in the cruise segments compared to the narrower

window. This can also be seen in Figure 5.8 where dev_{Ref} = 5% has nearly the same brake losses as the standard but a little lower engine losses as it still increases cruise velocity to initiate up-shifts. For the higher values of dev_{Ref} brake losses are considerably lower as the vehicle is able to coast for a much longer distance. As the wider reference window also permits the controller to select a higher velocity when driving under the optimal, the trip time is still shorter than for standard.

5.5 Summary

The fuel efficient strategies identified in Chapter 3 are successfully implemented in a way that enables the new controller to make decisions accordingly to lower the total amount of fuel consumed. Important to remember is that the used drive cycle have a great impact on the savings presented as all decisions made by the new controller are affected by the distribution of the velocities over the cycle. For example would a cycle consisting of few segments with a cruise speed below the optimal speed and the majority of the cruise segments at high speeds result in a lower fuel consumption and a longer trip time than the ones presented in this thesis. This because the new controller would not be able to increase speed as often in low speeds and would coast longer at high speeds.

Losses due to auxiliary systems like generators and air systems are not taken into account in the results as there are no models for this implemented in the vehicle model. As the auxiliary systems are running whenever the vehicle is running. As they are more or less constant over time, the total losses due to them are decreasing with shorter trip time. Which in this case would benefit the new controllers results.

The reference window introduced in the thesis has a large effect on both the trip time and the fuel consumption for a vehicle. Important to remember is that all comparisons are done with results from a vehicle trying to follow the reference one hundred percent, which it obviously fails to do. This is also not necessarily how a driver would drive the same cycle if asked to do so. Probably would the driver release the gas and coast before beginning to brake when decelerating the vehicle and not drive head on before having to brake which the reference does. So the fuel savings achieved and presented in Section 5.3 are probably a little lower in reality. However is the trip time notably decreased with the use of the new controller and this is because of the alteration in cruise velocity. In Section 6.1 the idea of implementing a time quote feedback in the new controller is discussed. This would lead to a lesser difference in trip time and an even larger reduction in fuel consumption as the time difference could be used for more fuel saving strategies.

There is nothing in the developed controller that prevents it from being implemented in an actual vehicle. All signals used from the vehicle model exists as estimates or measurements in a vehicle. Scania CV AB posses software, which with simulations provides the vehicle with information about how far the vehicle would free roll given the gas is released at the current time. This can be used for estimating the coasting distance for the vehicle and is further discussed in Section 6.1.

6

Conclusions

In conclusion of the thesis the fuel consumption can be reduced through quite simple strategies without extending the trip time for a vehicle. The trip time is, for all results presented, decreased compare to simulations where the developed controller is deactivated.

The goal of the thesis was to develop a controller which uses strategies to lower the fuel consumption without significant changing the trip time. With the strategies identified and the implementation of a reference window, the developed controller can reduce the fuel consumption significantly. The controller design developed in the thesis demonstrates the potential in allowing the velocity differ within specified boundaries and despite the presented profits, there are some improvements that can be done.

6.1 Future Work

One improvement to be done is to improve how the engine braking distance is calculated. As seen in, for example, Figure 5.6 the velocity misses the target velocity during the coasting because of the topology of the road. To only use two point when calculating the distance with aspects to the vehicles energy losses is not always enough and will lead to errors when there is, for instance, an uphill between the two points. As mentioned in Section 5.5, Scania CV AB has software which together with road map information and GPS, simulates the vehicles free rolling. With this function implemented instead, or in combination with the energy based distance calculation the problem would most likely be solved.

Another possible implementation with existing software is for eliminating situations when the vehicle is rolling up in brake reference, as shown in Figure 5.5. Existing software knows with information from road maps when the velocity will increase due to topology of the road and will allow the velocity to exceed the limit of the brake reference when passing the slope.

6.1.1   Time Quote Feedback

As the results in Section 5.3 showed the developed controller, not only saves fuel, but also shortens the trip time compared to the reference. This earned trip time could be used for saving even more fuel while keeping the difference in trip time close to zero. During the thesis an early version of a controller using feedback was developed and partly implemented with the vehicle model.

One problem to be solved was to determine how the time quote for the feedback would be formulated. During the thesis this could be solved by simulating the drive cycle without the controller and saving the time based on distance for this simulation. This could later be used for calculating the difference in percent between the new controller activated and deactivated continuously during simulation. In reality the calculation of this quote is not as simple, as driving the same road with and without the new controller in order to get the data would be unacceptable. One way to do it to calculate the time difference between the input reference velocity and current velocity, but this requires that the vehicle is able to keep the reference in order for the quote to be somewhat accurate. The most promising method would probably be to only calculate the difference when the controller actively makes a decision and with the predictive software earlier discussed estimate when the velocity will be affected by, for example a downhill. This would make the vehicle roll from the reference and affecting the quote despite that this increase in velocity would occur without the controller activated as well.

With the time quote known, the controller was extended with a feedback. Enabling it to alter the velocity depending on the size and value of the time quote. If, for example the controller has decreased the trip time, the quote is positive and the new controller has additional trip time compared to when deactivated. This trip time can then be used to, within the limits of the reference window, lower the velocity at high speeds. This decreases the losses due to air resistance and will lead to a lower fuel consumption for the vehicle. One more advantage of decreasing the velocity at high speeds is that the probability for it leading to a down shift and thus increased engine speed, is lower than at low speeds, as can be seen in Figure 4.5. In the event of the trip time being negative, the controller would instead increase velocity to eliminate the time difference.

The feedback of the time quote will, depending on the size and value of the time quote, control the vehicle towards a negligible difference according to fuel efficient strategies. This implementation will make the controller much less affected by the distribution of the velocities over the cycle, a problem mentioned in Section 5.5. As the controller now will be able to catch up the time lost from coasting.

As mentioned in Section 5.2.2 the logic behind the gear selection in vehicle model is not entirely realistic, in fact, quite simplified compared to how it is solved in a real software. Different vehicle manufactures has different logical systems for how and when to initiate a change gear, but based on that knowledge, implementation of a software which estimates if a gear change is reachable is not impossible. The estimations do not have to be exact, as long as the probability for a gear change is high the controller will benefit. This because even if a increased velocity does not result in a higher gear the trip time will still be shortened. With the implementation of a time ratio feedback this extra time can be used for other fuel-efficient strategies.

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