Robustness Analysis of Look-ahead Control for Heavy Trucks

Thesis work

of

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Aufgabenstellung Studienarbeit (3 Monate):

Simulative Robustness Analysis of Look-ahead Control for Heavy Trucks

With growing fuel prices and existing CO_2 problem, saving fuel has become a very important issue, both economically and environmental and is likely to be even more important in the future. A big potential for reducing the fuel consumption remains in anticipatory driving regarding the road slope ahead of the vehicle. This is especially true for heavy trucks, as their power to mass ratio lets even moderate slopes have a big influence on driving dynamics. Implementing an anticipatory driving strategy into a driver assistant system allows a reduction in fuel consumption, which is not reachable with a normal cruise control.

Linköpings Universitet has in cooperation with Scania developed "Look-ahead Control", a system for heavy trucks that utilizes GPS positioning and a road topography database in order to upgrade a normal cruise control with a fuel-optimal algorithm, concerning the road slope ahead of the vehicle. This allows e.g. gaining speed prior to significant uphill links or avoiding braking on the downhill.

Not completely known so far is the characteristic of the system towards model errors. Parameters such as the estimated vehicle mass, the stored values of the road slope or the measured position may differ from the true values. Their impact on the control system's behaviour needs to be determined.

The task of Wolf Krahwinkel within the scope of this thesis is therefore to analyse the robustness of the system by simulation using Matlab/Simulink. It is to be explored, which different model errors occur and how they are related. The goal is to make a statement about the model errors' effect on the control system and, if possible, to give a numerical range of acceptable model errors that still allows sufficient results.

The thesis is to be conducted according the effective diploma examination regulations at TU Braunschweig, Germany.

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Linköping, 2009-10-29

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Abstract

This thesis work provides an approach to analyse the robustness of a fuel-time-optimal controller for the longitudinal dynamics of heavy trucks. The analysed look-ahead control system uses a predictive control strategy, developed in a collaboration of Scania and Linköpings Universitet. It utilizes GPS positioning data and a road slope database to compute the optimal fueling, braking and gear choice. In this study, the robustness towards parametric uncertainties is tested in various simulations on a Matlab/Simulink model. The experiment vehicle, which is modeled, is a Scania tractor with semitrailer of 15 to 40 tonnes with a 310Hp engine. The main focus within these tests is on uncertainties of the vehicle mass.

The simulation model is based on the evaluation model from [Hellström et. al 2010], which was used to simulate the look-ahead control prior to and after practical experiments. The model has been modified to include perturbations of the vehicle mass and positioning data. The various simulations consist of a set of runs on a modeled 120km long motorway link between the two Swedish cities of Norrköping and Södertälje and the uncertainties are being analysed by changing one factor at a time in the simulation model.

In conclusions, the analysed controller acts very robust towards uncertainties in mass, though the effects of a wrong estimated mass get bigger at lower masses. At 15t of true mass, an estimated mass over 19t would lead to a fuel-time consumption that is higher than the comparable cruise controller result. A true mass of 20t does already require an estimated mass over 40t to get insufficient results. Lower estimated masses result in the worst case in the same fuel-time use as the cruise controller. At higher true masses all tested estimated masses cause satisfactory fuel consumption and trip time. However, since the estimated mass is not very likely to exceed ±10% of the true mass, the controller should be practically robust in all tested scenarios.

Uncertainties of the GPS position have been analysed in a large range and the results display the controller very robust towards these errors as well. The algorithm is even with bigger uncertianties capable of lowering the fuel consumtion without increasing the trip time.

Keywords: fuel-optimal control, robustness, cruise control, predictive control, truck

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ACC	adaptive cruise control
CAN	controller area network
CC	cruise control
CO_2	carbon dioxide
E4	European route 4
GPS	global positioning system
LA	Look-ahead control
NE	northeast
OEM	original equipment manufacturer
S-function	Matlab system function
SW	southwest

TABLE OF SYMBOLS

A_a	cross section area of the vehicle
a_e	engine constant
b_e	engine constant
c_1	constant
c_2	constant
c_4	constant
c_e	engine constant
c_r	roll resistance coefficient
c_w	air drag coefficient
g	gear
g_0	gravitational acceleration
I	fuel time equivalent cost function
i	gear ratio
J_l	clutch, propeller shafts, drive shafts, wheel inertia
M	fuel mass
m	vehicle mass
n_{cyl}	number of cylinders
n_r	number of crankshaft revolutions per cycle
r_w	wheel radius
T	trip time
T_b	braking torque
T_e	engine torque
u	control vector
u_b	braking level
u_f	fueling level

u_g	gear selector
v	velocity
$\hat{v}$	stationary speed
x	state vector
α	road slope
β	fuel time equivalent weighing factor
Δlat	latitude offset
Δlon	longitude offset
η	combined efficiency
ρ_a	air density
ω_e	engine speed

1 Introduction

The development of more fuel saving means of transportations has become increasingly important lately. Since the worldwide resources of fossil fuels are being depleted and the largest still existing oil in places is located in countries with unstable political situations, the price for fossil fuels rose dramatically over the last years and is likely to rise even more in the near future. Another aspect is the growing problem of CO_2 emissions, particles and other health and climate harmful emissions that are related to the use of fossil fuels. Therefore, a change from fossil fuels to renewable energies has many reasonable arguments, economic as well as environmental and social. However, this is a very long process and it requires systematic improvements in details and optimization of the existing technology, in order to make road transportation more competitive and environmental friendly. One step in this development is to lower the fuel use of current transportation means, which can be achieved by modern control engineering.

A big potential for reducing the fuel consumption remains in anticipatory driving regarding the road slope ahead of the vehicle. This thesis deals with a driver assistant system that is based on cruise control and uses an anticipatory driving strategy to minimize fuel use. An especially big potential lies in the control of heavy trucks. First, trucks carry the largest part of inland freight. In 2007, 76.5% of Europe's freight transport (total inland freight tonne-km) was carried on roads [Eurostat 2009]. Therefore, even moderate savings in fuel consumption have a great impact on the overall vehicle fleet, assuming an adequate penetration of the market with fuel saving systems. Second, heavy trucks benefit a lot from an anticipatory driving strategy, as their power to mass ratio lets even moderate slopes have a big influence on the truck's driving dynamics.

The basic idea is to use the GPS system to position the vehicle and match its position with a database of road topography data. The road slope ahead of the vehicle is then considered in the computation for an optimal cruise controller set speed. This way, it is possible to e.g. gain speed prior to significant uphill sections or avoid braking in the downhill.

Linköpings Universitet has developed in cooperation with Scania "Look-ahead Control", a system for heavy trucks that utilizes GPS positioning and a road topography database in order to upgrade a normal cruise control with a fuel-optimal algorithm, concerning the road slope ahead of the vehicle. This project is presented in chapter 2.

The next step would be to implement a look-ahead control system in a hybrid drive train, to optimise fuel consumption even more.

1.1 Aim of study

This study is to examine the look-ahead system's robustness towards model uncertainties. The objective is to get information in which way the system behaves, when the truck model that is used to synthesise the controller differ significantly to the real truck plant. This can be through uncertain parameters or model simplifications. The analysis of the system's robustness is going to be done by simulations with the use of Matlab/Simulink software and a modified model of the one that is used for the controller's design.

1.2 Structure

This thesis is divided into five parts. The first chapter gives a short introduction to the subject. In chapter two, a brief overview of the look-ahead system and the underlying model is given. Chapter three lists the most relevant model uncertainties that are likely to play a role and give first approaches, how these uncertainties can be modeled to analyse them by simulation. The simulation setup and environment are described in chapter four and the results are interpreted. The final, fifth, part summarizes the conclusions from the simulations.

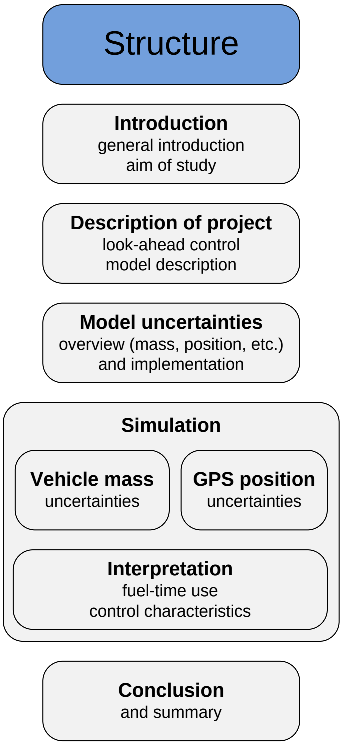


Figure 1: Structure of the study

2 Description of the project

2.1 Look-ahead Control

Look-ahead control is a predictive control strategy that uses road topography data in order to minimize fuel consumption and trip time of heavy trucks. It has been developed in collaboration between Scania and Linöpings Universitet and can be implemented as an extension for a cruise control system.

The basic idea is to use positioning by the GPS in order to get information of the road topography, especially the road slope, ahead of the vehicle and adjust the control signals, such as fueling level, braking level and gear, to minimise fuel consumption. This can be done by avoiding braking on the downhill and gaining speed prior to uphill segments. The optimisation process uses an algorithm, which is based on dynamic programming and is able to choose the optimal set speed and gear online.

In the course of the project a demonstrator, based on a Scania truck, has been developed to get experimental results. For these practical tests, the controller has been modified in order to match the hardware. The control output of the look-ahead control for the demonstrator is the set speed for the normal OEM cruise control system. Gear shifts are not controlled by look-ahead control but by the normal automatic gearbox. However, the gear shifts have been modeled and taken into consideration, when the optimal set speed is computed. The tests took place on an about 120 km long motorway link on the E4 between the Swedish cities of Norrköping and Södertälje. Therefore the exact road slope and corresponding position has been measured on this link prior to experiments and stored in a database.

Alongside the practical experiments, the most important means to evaluate the optimisation algorithm are simulations using Matlab/Simulink. Thus, a vast variety of setups and the influence of different parameters can be examined reproducible and with a low expenditure of time. The Simulation model, which is used, is described in the next paragraph.

2.2 Model description

To examine the effects of model uncertainties by simulation, a simulation model is required that describes the vehicle motion depending on the road topography and control states, foremost the fueling level u_f.

The simulation model is largely taken over from the evaluation model in [Hellström et. al 2010], which is based on the experiment vehicle, a Scania tractor with semitrailer. The engine is a 5 cylinder diesel engine with a displacement of 9 dm³, a maximum torque of 1550 Nm and a maximum power of 310 Hp. The gearbox is a 12 speed. The model consists of a vehicle and environment model in Simulink and the controller, which uses the three software modules supervisor, optimisation and database. These modules are written in C++ and the Simulink model is interacting by using the s-functions sfun_control and sfun_measurement with the executable files. This way, a faster calculation and better real time optimisation can be achieved.

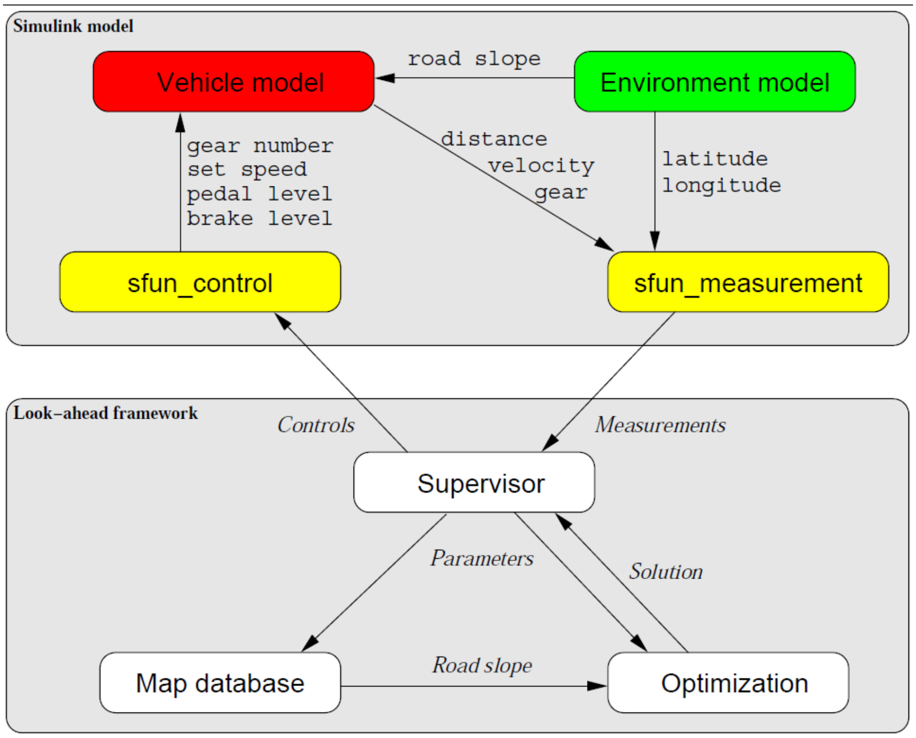


Figure 2: Information flow [Hellström et. al 2009]

The truck model is split up into three sub models, engine, driveline and chassis, as shown in figure 3.

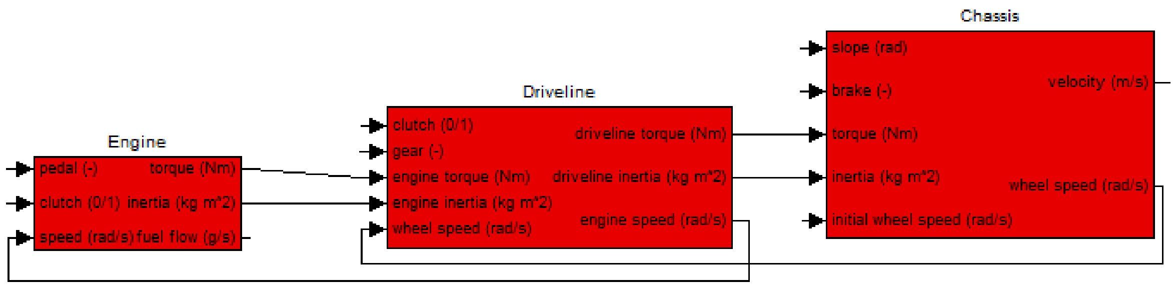


Figure 3: Vehicle model

These models are based on commonly used relationships and physical principles for each part. The engine model is build by using a linear relation of the inputs engine speed and fueling level and the output engine torque:

$$T_e(\omega_e, u_f) = a_e\omega_e + b_e u_f + c_e$$

However, the fuel flow itself is depending on the engine speed and the pedal position.

In the driveline model, all propeller shafts and wheels are assumed stiff. Using a simpler model has advantages in complexity but distorts the simulation results. Approaches with a more complex model can be found in [Nilsson 2009].

The chassis model contains the four resisting forces air drag, rolling resistance, gravitational force and acceleration resistance. To model the acceleration resistance, each moment of inertia of rotating parts is passed on to the very next sub model and taken into consideration in the motion differential equation in the chassis model. This combined differential equation then looks like:

$$\frac{dv}{dt}(x,u,\alpha) = \frac{r_w}{J_l + mr_w^2 + \eta(g)i(g)^2 J_e}\left(i(g)\eta(g)T_e\left(v,u_f\right) - T_b(u_b)\right.$$
$$\left. - r_w\left(F_a(v) + F_r(\alpha) + F_l(\alpha)\right)\right)$$

with the engine torque T_e, the braking torque T_b and the resisting forces

$$F_a(v) = \frac{1}{2}c_w A_a \rho_a v^2$$

$$F_r(\alpha) = mg_0 c_r \cos\alpha$$

$$F_l(\alpha) = mg_0 \sin\alpha$$

The state vector $x = [v,g]^T$ contains the velocity v and current gear g and the control vector u = $[u_f, u_b, u_g]^T$ contains fueling level u_f, braking level u_b, and gear selector u_g. α is the current road slope.

3 Model uncertainties

In order to evaluate the consequences of model uncertainties to the system, it is important to know, which different types of model errors occur in the first place. In control theory there is a differentiation between outer disturbances and inner disturbances or model uncertainties. Just looking at the model uncertainties, one can distinguish parametric uncertainties and uncertainties of the model structure. Further information about model uncertainties can e.g. be looked up in [Lunze 2007], [Dutton et. al 1997] and [Skogestad/Postletzwaite 1997]. In the following, the most relevant disturbances are listed and a first approach of modeling them and implementing these uncertainties in the given truck model is shown. However, the effects of the different disturbances may be the same or overlap.

3.1 Parametric uncertainties

3.1.1 Wrong GPS position

A positioning by the GPS system is on average accurate to 20m [Mansfeld 2004]. An error in the positioning leads to a wrong looked up road slope in the database. In the simulation, this error can be modeled by shifting the lookup table for the road slope. The easiest way to do this is to add a certain difference in latitude and longitude to the link, which connects the environment model block and the measurement s-function. This simulates a static measurement offset. Dynamic errors can be simulated in a similar way, if the simple summarisation with the disturbance is replaced with a more complex disturbance system.

3.1.2 Wrong road slope in database

If the road slope in the database is not the same as the real road slope at the corresponding link of the road, this can have several causes. One cause could be a measurement error, either in road slope or in position, at the time the road slope is measured. Another cause could be old road slope data that does not match with renewed roads anymore. A similar error occurs often with navigation systems, which map data is not updated.

In this phase of the project, there exists only one test road link with acquired road slope data, on the E4 between Södertälje and Norrköping. The quality of these road topography data is nearly ideal.

The modeling of road slope database errors is similar to the modeling of positioning errors. Only here the disturbances are implemented in the road slope link from the environment model to the vehicle model. The structure is shown in figure 4.

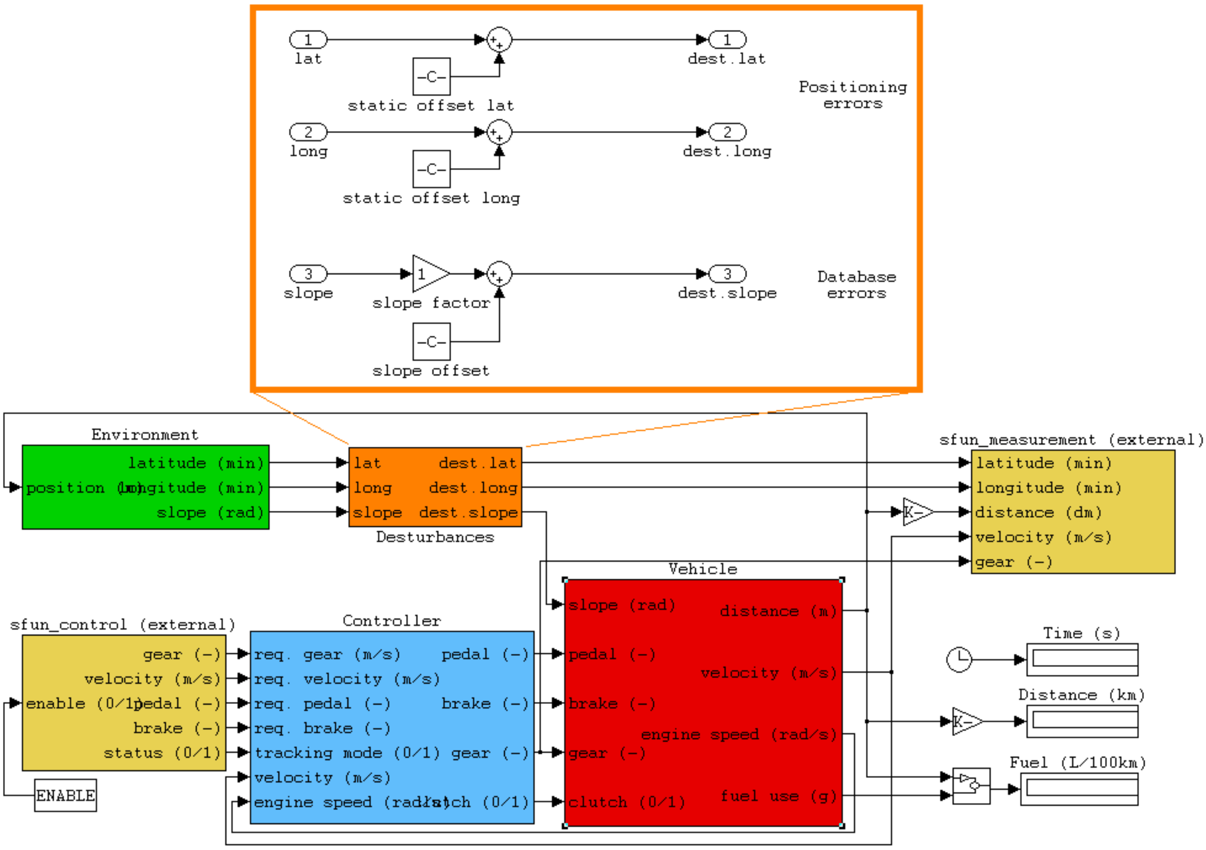


Figure 4: Perturbed model

Road slope uncertainties are not simulated in this study. However, since the road slope is amongst others measured by aid of the GPS, some of the estimated errors through wrong road topography data in the database may have slightly similar properties as the position errors.

3.1.3 Vehicle mass

Probably the most important model uncertainty is a wrongly estimated vehicle mass. The mass is estimated by an onboard control unit and comunicated over the CAN bus.

Modeling a mass uncertainty is a bit difficult. As described in chapter 5, there is a relation between the mass and the road slope. So a difference in mass could be modeled by a difference in road slope as described above. Yet, as it is a very complex function, it is easier to work with two separate mass variables. One estimated mass that is given to the supervisor module and used in the optimisation process and one real mass that is used in the vehicle model to compute the vehicle movement.

3.1.4 Other vehicle parameters

Although the mass is the most influential, there are other vehicle parameters like moments of inertia of certain shafts or efficiencies for transmissions. However, unlike the vehicle mass, these parameters can be estimated quite well and the expected errors are likely to be much smaller as with a wrongly estimated mass. Therefore, this study concentrates on the vehicle mass, because it is the most critical parameter. The examination of the mass as a model uncertainty can be seen representatively for all other vehicle parameters as model uncertainties in some way, as the procedure is the same.

3.2 Neglected and unmodelled dynamics uncertainties

3.2.1 Model simplifications

Using a simpler model keeps the computing complexity within a limit. It is always a compromise between the quality of control and computing complexity. Therefore, some simplifications need to be made. E.g., the propeller shaft is assumed stiff. To keep the simulation model simple, this study concentrates on parametric uncertainties and does not handle model simplifications, which must be analysed with a more detailed, realistic model. Such more complex models for the given problem are discussed in the master's thesis [Nilsson 2009], though mainly regarding the impact on the ride comfort.

4 Simulation

The simulation setup contains several series of experiments to analyse the uncertainties mentioned above.

4.1 Mass

4.1.1 Simulation setup

First of all it is interesting to see, how the controller acts, when the real mass of the truck differs from the estimated mass that is used to synthesise the controller and used in the optimisation process. The vehicle mass is estimated by an OEM software and comunicated to other control units via the CAN-bus. However, this estimated mass can differ from the real vehicle mass and since the mass plays an important role in the mathematical models used to describe the truck motion, this is where the biggest effects are expected to occur.

To implement a mass estimation error, the simulation model is equipped with two variables that store the vehicle mass: *mass* and *realmass*. The variable *mass* contains the estimated mass that is passed over to the supervisor module and used to compute the optimal control signals. The variable *realmass* is just used in the chassis model of the vehicle model and used to simulate the real physical behaviour of the vehicle, regarding to the model simplifications.

Since the engine model is not changed from the one, used in the evaluation model in [Hellström et. al 2010], the simulations are run with the same 310 Hp engine. For this quite small engine, a maximum total vehicle weight of 40 t is a reasonable limit. So the simulations in this first approach are done in a range of 20, 25, 30, 35 and 40 t. Although the expected uncertainties of the estimated mass are in the range of about 10%, the estimated mass in the simulations ranges from the real mass minus 10 t to the real mass plus 10 t, in steps of 250 kg. However, in some of the following simulation results not all of the runs were successful, as for some simulation setups with a very low estimated mass the simulation stops, because the velocity goes down to zero. This is in connection with a bug in the optimisation module and does not occur in later simulations with a fixed version.

The road data for the simulation is an about 120 km long motorway link on the E4 between the cities of Norrköping and Södertälje with moderate road slopes. The following graph shows the road elevation in meters. The road slope is rather moderate and stays between -2% and 2% most of the time. The biggest slopes are around 4%.

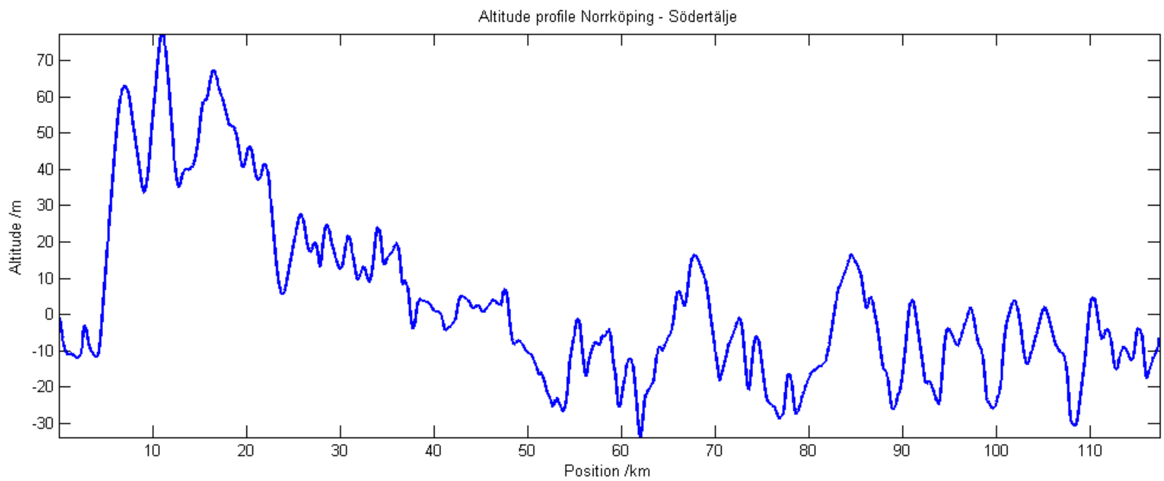


Figure 5: Test track profile

The reference speed is set to 84 km/h with a maximum speed that is 5 km/h higher. Later, also 74 km/h will be tested. This will be sufficient, since it is reasonable to have a buffer of at least 5 km/h before the brake sets in at the speed limit. In most European countries the speed limit on motorways for heavy truck, which is trucks with a gross vehicle weight above 16t, is either 80 km/h or 90 km/h.

A minimal speed of 36km/h is chosen that the velocity must not fall below.

4.1.2 Results

The first set of simulations lead to a wrong result, displaying the algorithm as insufficient at low masses. This was caused by a software error in the optimization module. A detailed description of this first set of simulations can be found in the appendix.

After getting a bug fixed optimisation module, the simulations were rerun and the results are presented in the following graphs. The fuel consumption and time use are illustrated in fuel-vs.-time plots. By putting fuel and time use on both axes, the graphs show the direct relation between these two key quantities. The reference line (cc) is obtained by the cruise controller at different set speeds. The results of the look-ahead control (la) for different estimated masses are displayed as data points. For each true mass, simulations are run in a range of ±10t with a step of 2t.

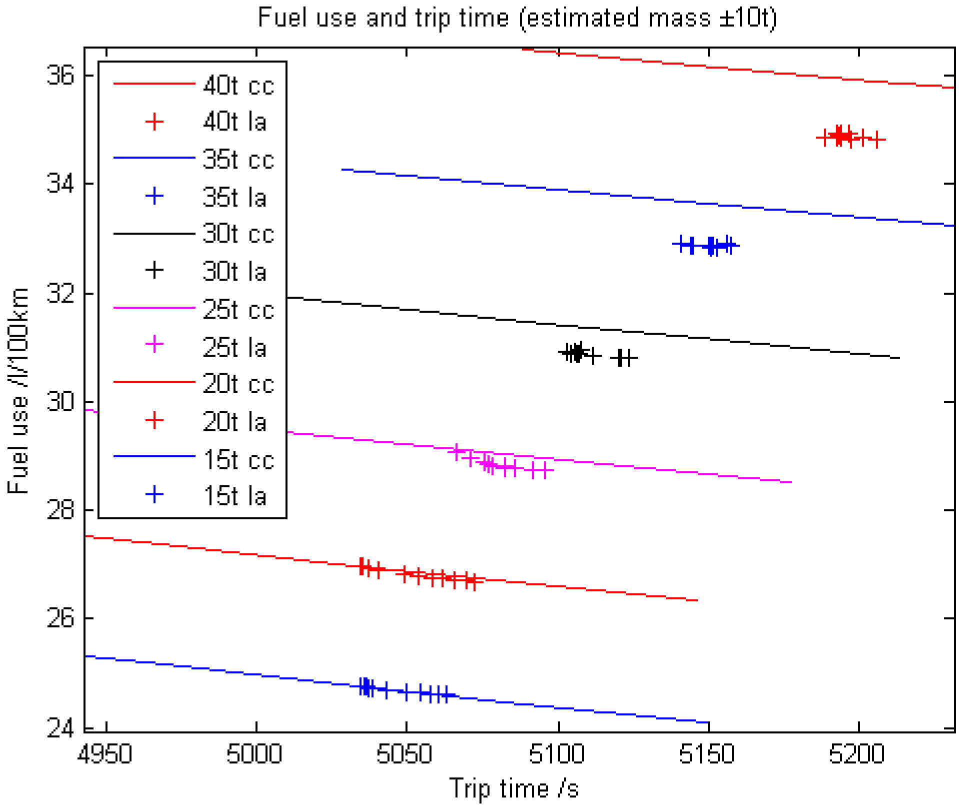


Figure 6: Fuel use and trip time of CC and LA, 15t to 40t

One can recognise the earlier mentioned effect that the benefit from the look-ahead strategy is bigger at higher masses. The lower, respectively the more to the left, the markers of the look-ahead control are located, the more benefit we get from the look-ahead system. At true masses of 30t, 35t and 40t all of the simulated uncertainties still lead to sufficient results. At lower masses, a closer look at the results is needed to search intersection points with the cruise controller line. These intersection points then mark the range of uncertainties through estimation errors, in which the look-ahead controller still works better than the conventional cruise controller.

The figures 7 and 8 show results of the simulation with 15t and 20t of true mass.

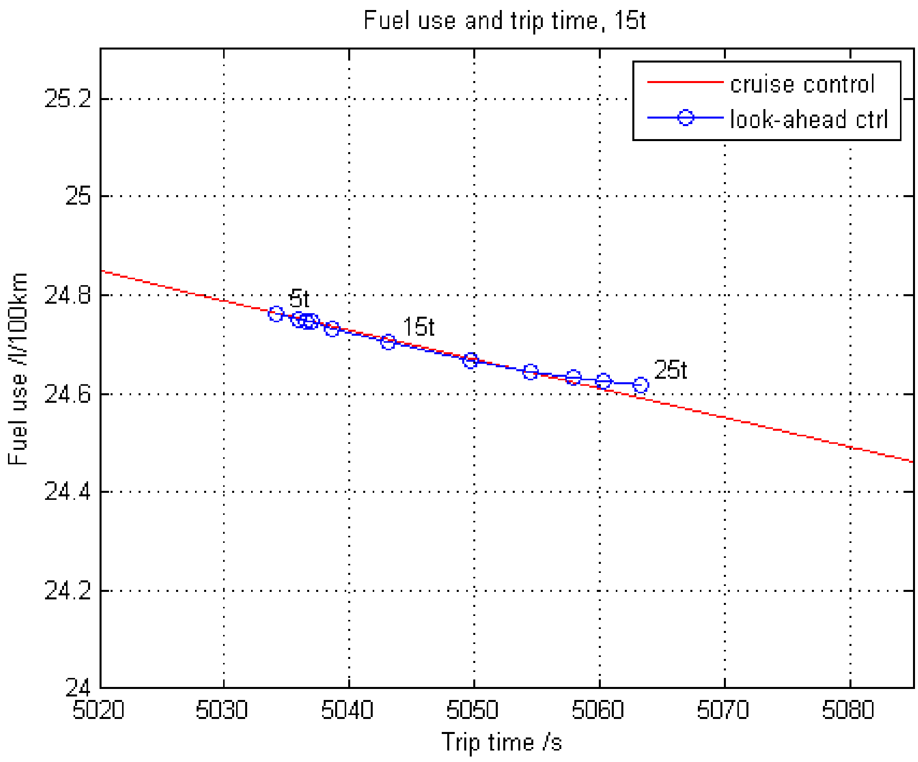


Figure 7: Fuel use and trip time, 15t

In the following diagram with 20t true mass, there are more simulation points used than the previous ±10t, because the point of intersection with the cruise controller line is searched.

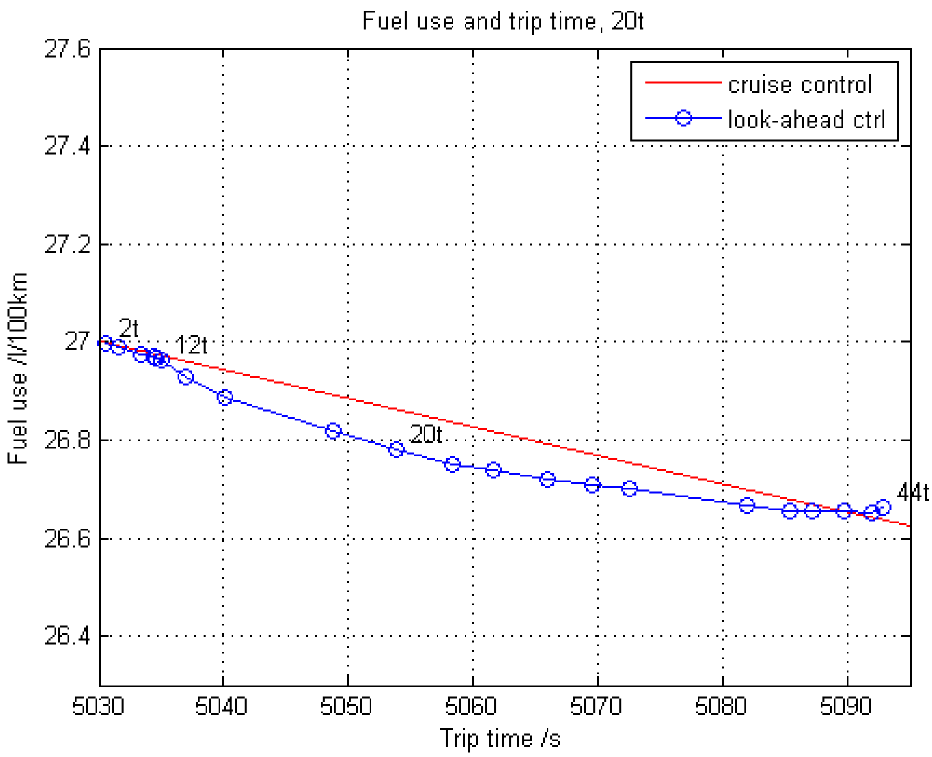


Figure 8: Fuel use and trip time, 20t

The intersection points are 19t at 15t true mass and 40t at 20t true mass. Surprisingly, a too low estimated mass never gives a worse result than the cruise controller in the tested cases. It just gets very close to it. So at 15t true mass, an estimated mass over 19t would lead to a fuel-time consumption that is higher than the comparable cruise controller result. A true mass of 20t does already require an estimated mass over 40t to get insufficient results. Lower estimated masses result in the worst case in the same fuel-time use as the cruise controller. At higher true masses all tested estimated masses cause satisfactory fuel consumption and trip time. However, since the estimated mass is not very likely to exceed ±10% of the true mass, the controller should be practically robust in all tested scenarios.

Another noticeable issue is that the trip time seems to increase with decreasing fuel use at higher estimated masses whereas at lower estimated masses the fuel use gets higher and the trip time decreases.

To analyse these results, we take a look at the velocity trajectory and the control signals on a certain road link, again. To get the most extreme effects, the simulation results of 20t true mass are chosen at 2t, 20t and 44t of estimated mass. The sample road link is again the Strömfors segment for the comparison of 2t and 20t estimated mass.

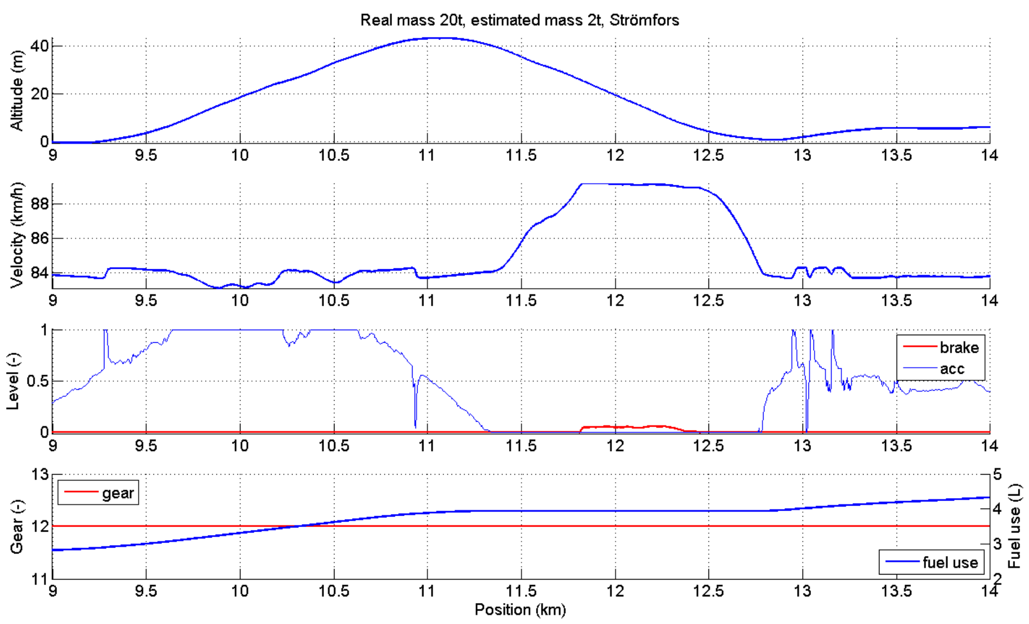


Figure 9: Control signals, 2t estimated

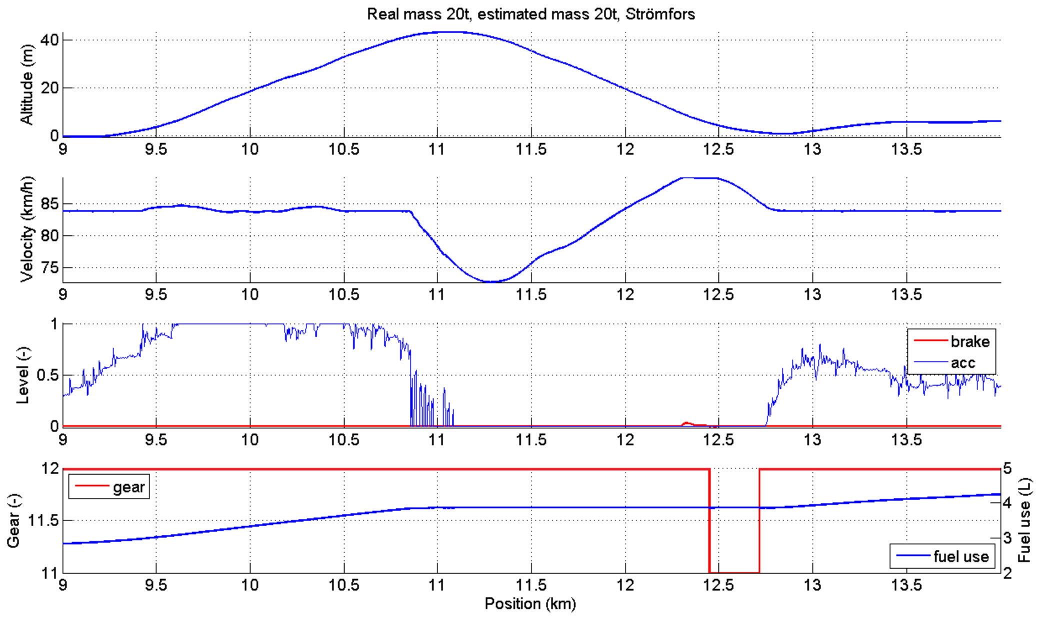


Figure 10: Control signals, correct estimated

The fuel-time diagram showed that a low estimated mass leads to a higher fuel consumption and lower trip time. In Figure 9 one can see, that the engine gets fueled all the way to the hilltop. The missing minimum in the trajectory at the hilltop results in a lower trip time, but also lets the truck reach the maximum velocity earlier in the downhill and forces a much longer braking phase. Since avoiding unnecessary braking is one of the key strategies to save fuel, this is likely to be the main cause for the lower performance with too low estimated masses.

Since the fuel-time use of the look-ahead control does not seem to intersect with the cruise controller but to approach the cruise controller line asymptotically, it might be interesting to compare the trajectory of the extremely low estimated mass with the one of the cruise controller.

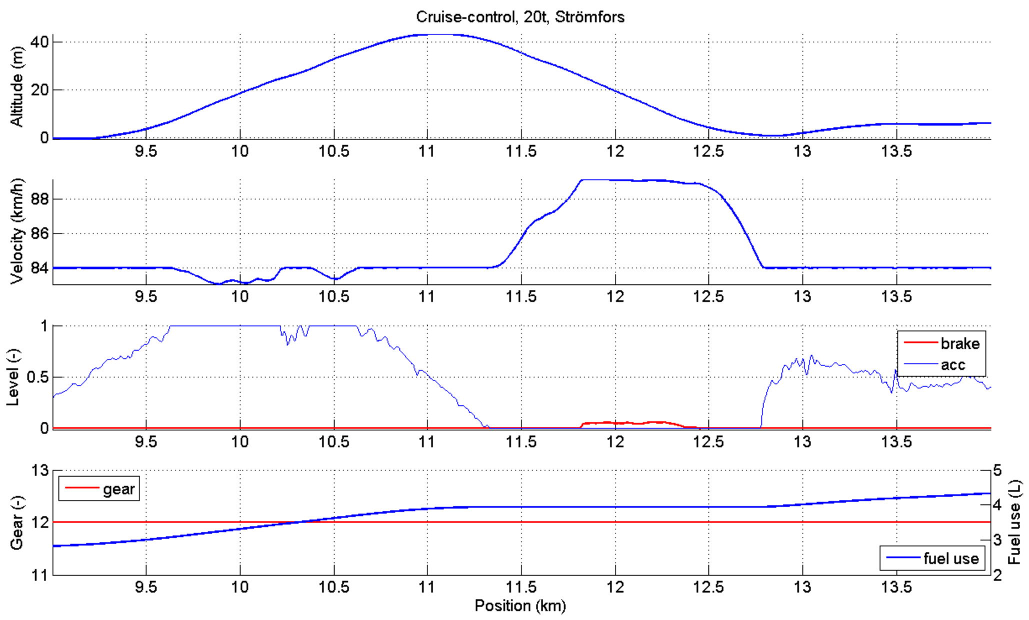


Figure 11: Control signals, cruise control 20t

As expected both, trajectory and control signals, of the look-ahead control system with 2t of estimated mass are very similar to the ones of the cruise controller.

So, in the worst case of a too low estimated mass, the look-ahead controller acts like the normal cruise controller.

To analyse the consequences of an overestimated mass, another cut out is chosen. The figures 30 and 31 show a 10km road link starting at kilometer 25 from Norrköping towards Södertälje. In this section, there are several small hills without big climbs or steep slopes, like for the most part of the test track.

While the trajectory of the controller with correct estimated mass is rather at a constant speed around the reference speed 84km/h, the overestimated mass of 44t leads to many changes in velocity between 79km/h and 89km/h. These repeated accelerations might lead to higher fuel consumption. Another noticeable effect is the oscillating characteristics of the fueling level. The throttle changes very often between full throttle and no throttle.

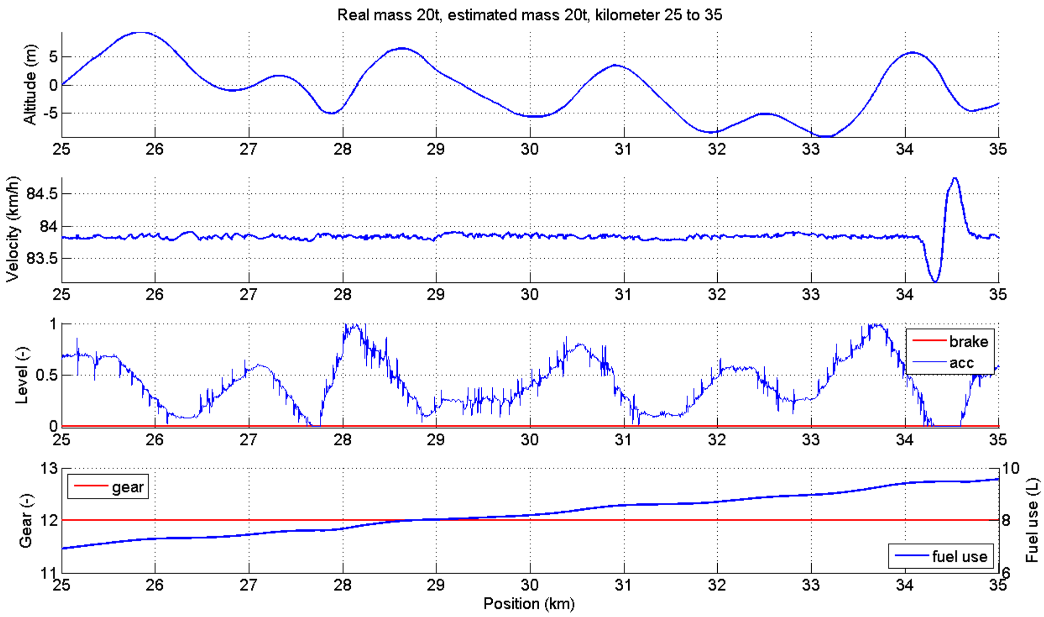


Figure 12: Control signals, correct estimated

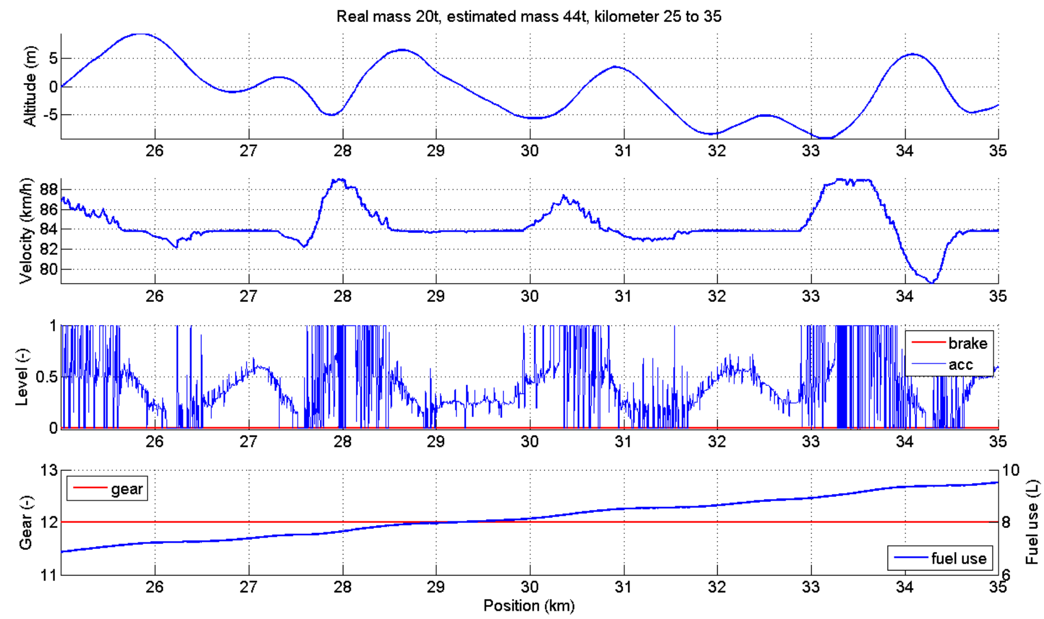


Figure 13: Control signals, 44t estimated

The influence of a wrongly estimated mass gets smaller at higher true masses. The results of the simulation runs with higher true masses (25t to 40t) are shown in figures 32 to 35. Apart from the fact that the look-ahead control results are moving further away from the cruise controller line with growing mass, one can see that the link between uncertainty and fuel-time relation is getting more blurred. Especially the results of 35t and 40t of true mass seem quite random. In fact, the results of 40t seem to show more or less the opposite of the current findings that lower estimated mass leads to a shorter trip time and higher estimated mass to a reduced fuel consumption. However, this is just a coincidence of the few (11) used data points. In another plot with 81 data points it gets clear, that the distribution is rather random like in the 35t graph. This large statistical spread may occur because of the relative short simulation distance of 120km, which leads to results that are not really statistically confirmed. A more precise simulation could possibly be achieved with more road data.

With such a random fuel-time use distribution, it is impossible to interpolate the given results for high true masses in order to search for intersection points with the cruise controller line that marks the boundary of the beneficial area. So, in contrast to the simulation runs with 15t respectively 20t, it is not possible to give a numerical range of allowed mass uncertainties from these simulation outcomes. However, in all cases the results are far in the beneficial area, even at uncertainties that exceed the practically probable estimation error of ±10% by far.

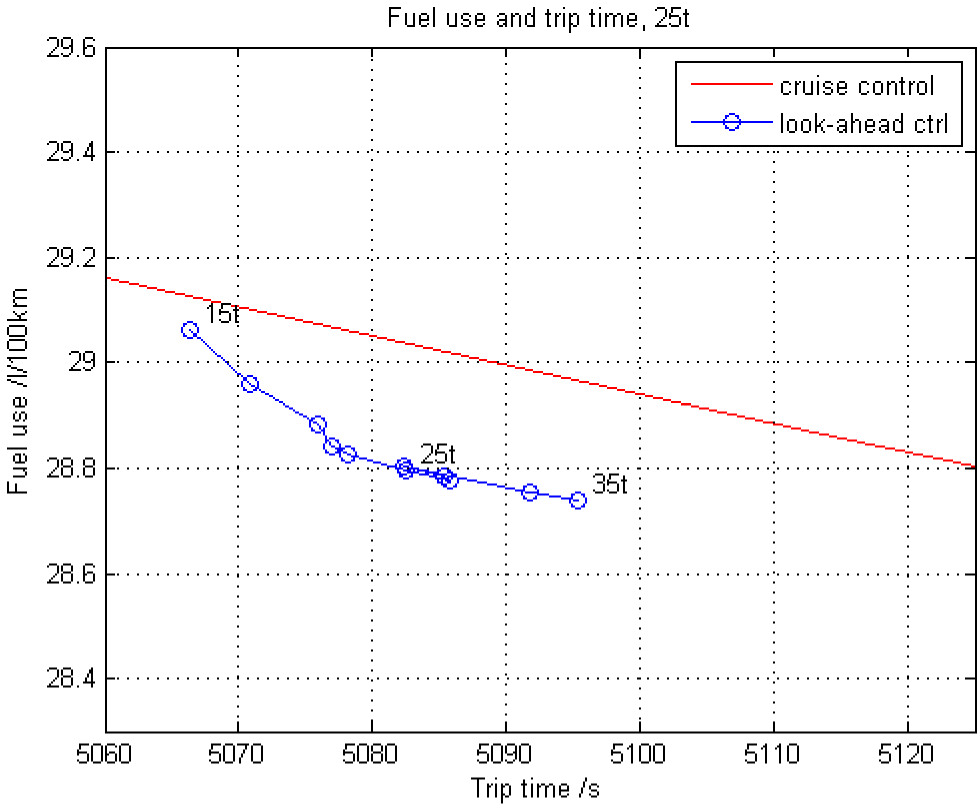


Figure 14: Fuel use and trip time, 25t

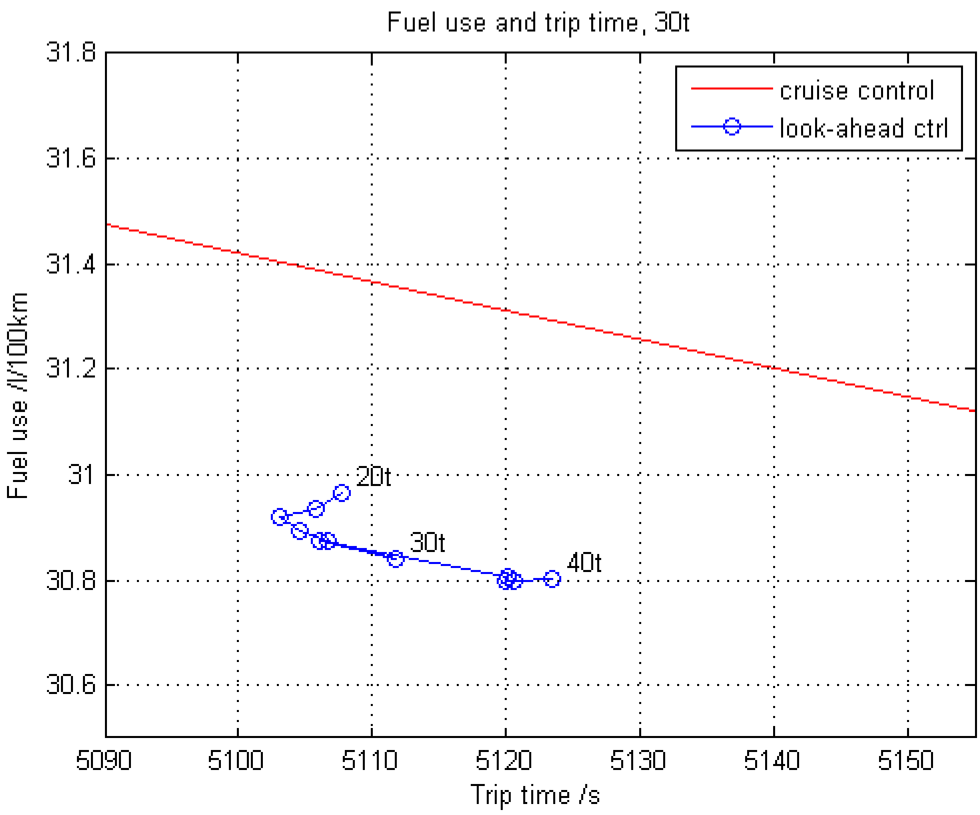


Figure 15: Fuel use and trip time, 30t

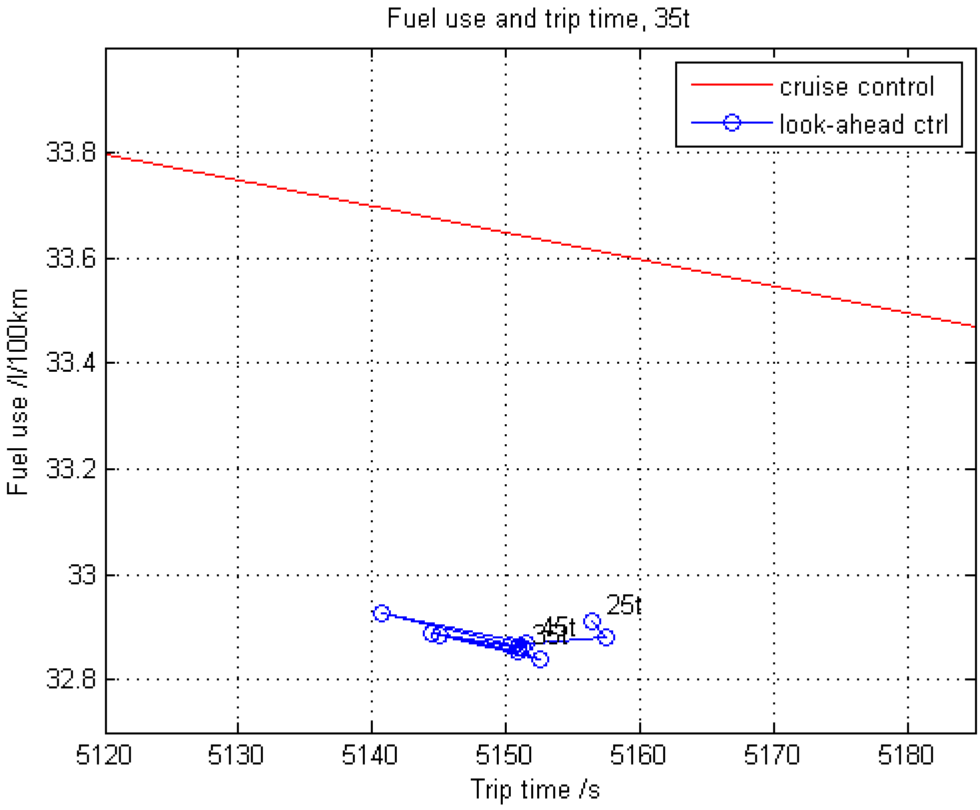


Figure 16: Fuel use and trip time, 35t

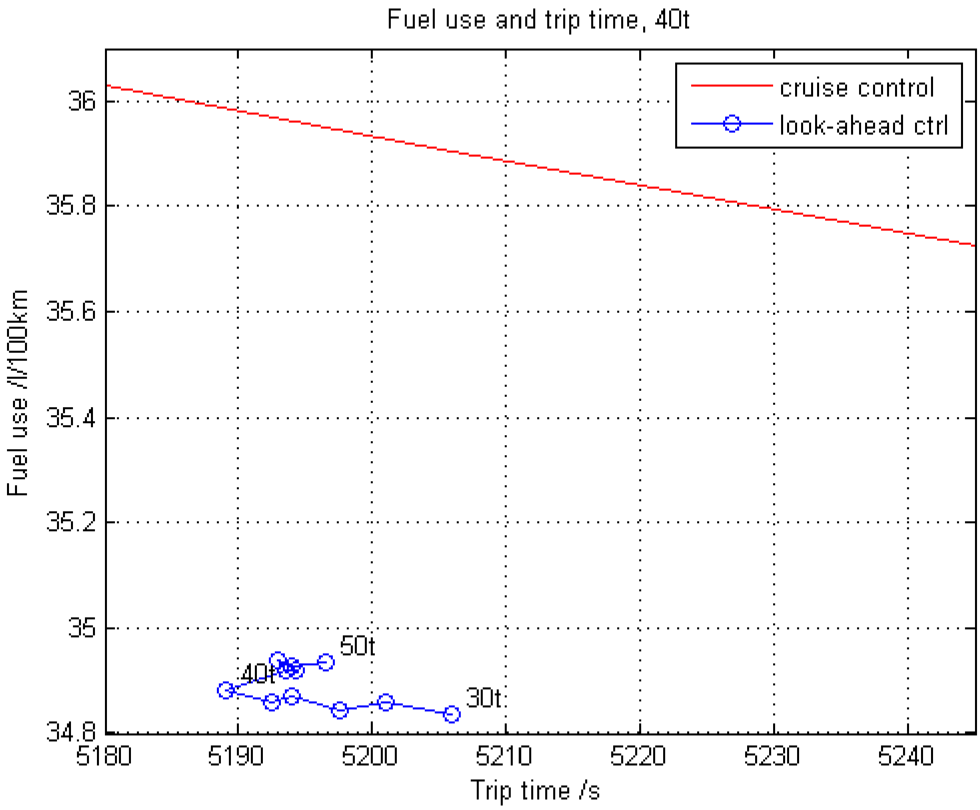


Figure 17: Fuel use and trip time, 40t

4.2 Position

4.2.1 Simulation setup

The position error that results from the GPS positioning varies due to many different influences such as satellite constellation, receiver layout, environment, atmospheric effects, etc. However, in practical use the positioning error stays most of the time in a range of 20m [Mansfeld 2004].

Since the algorithm tracks the nearest position on the road, the biggest effects of a wrong estimated position are most likely to be expected at a measured position that is located on the road ahead of the vehicle or behind it. This could be modeled by taking the current curve progression of the road into consideration. However, since the trial route lies mostly in southwest-northeast orientation, in these experiments a simpler setup is chosen by simply adding a certain offset to the measured position in SW-NE direction. The offset in arc minutes that e.g. represents a circular error of 20m can be calculated with the approximate latitude of the region. The examined road link is located at about 59° north. The diagonal error distance of

20m are about $\sqrt{\frac{(20m)^2}{2}} \approx 14m$. Assuming an earth circumference of 40000km, the latitude offset is about $\Delta lat = \frac{14m\ 360°}{40000000\ m} = 0.000126° = 0.00756'$, since the latitudes have a constant distance. The longitude offset requires additionally the cosines of the region's latitude: $\Delta lon = \frac{14m\ 360°}{40000000\ m}\cos(59°) \approx 0.5\frac{14m\ 360°}{40000000\ m} = 0.000063° = 0.00378'$.

The simulation contains several runs. For each direction Norrköping – Södertälje and Södertälje – Norrköping one test is run without position errors and the others with different positioning errors of 20m to 100m towards northeast and southwest.

4.2.2 Results

Figures 18 and 19 show the fuel and time use of the different simulation runs compared to the ones of a cruise controller.

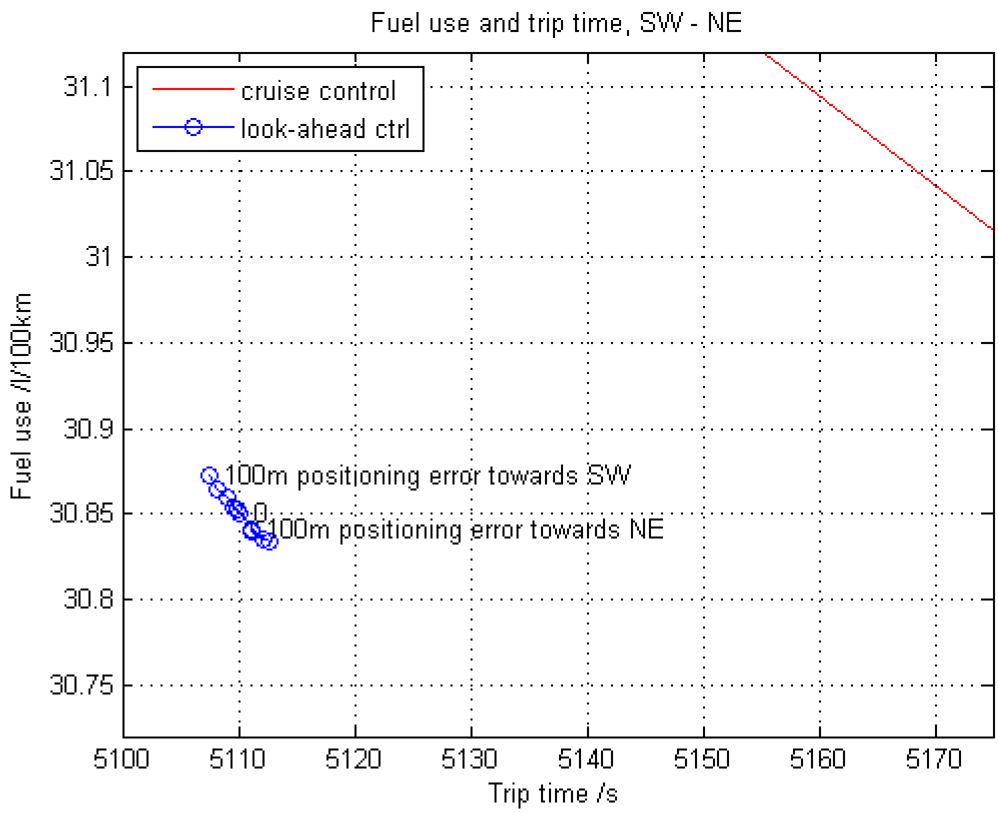


Figure 18: Position errors, Nkpg - Stlj

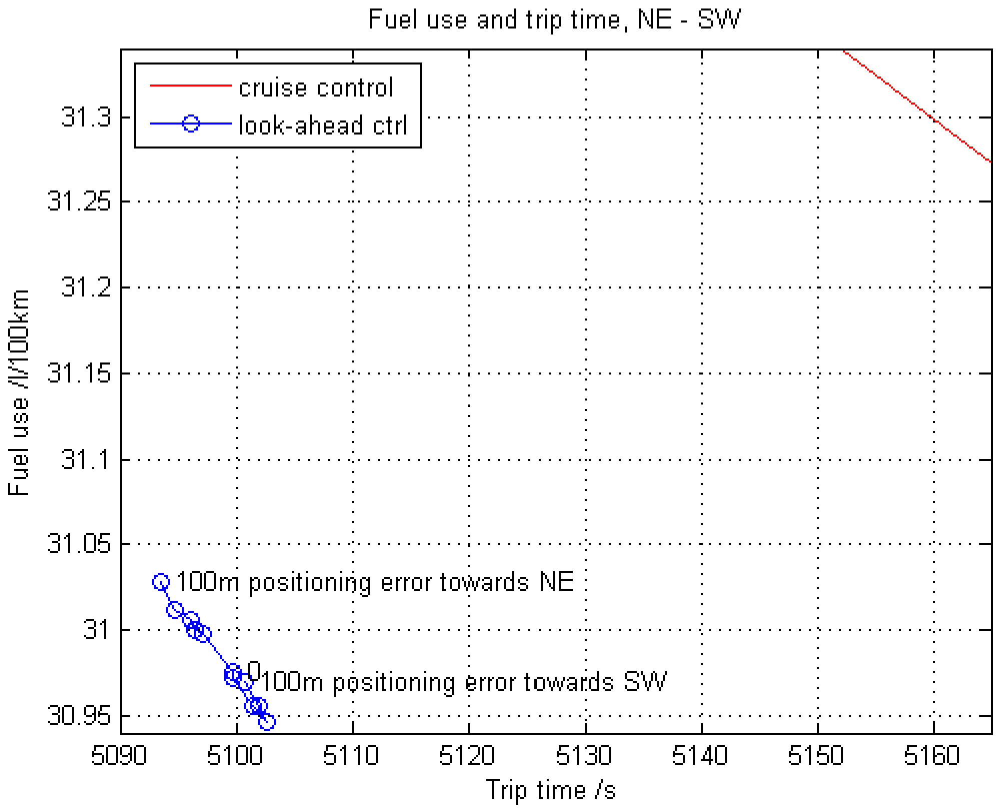


Figure 19: Position errors, Stlj - Nkpg

In figures 20 and 21, the vehicle trajectories as well as fueling and braking level in the Strömfors segment are shown to explain the controller's behaviour. An error of 40m is chosen. This is twice as much as the usual GPS positioning error.

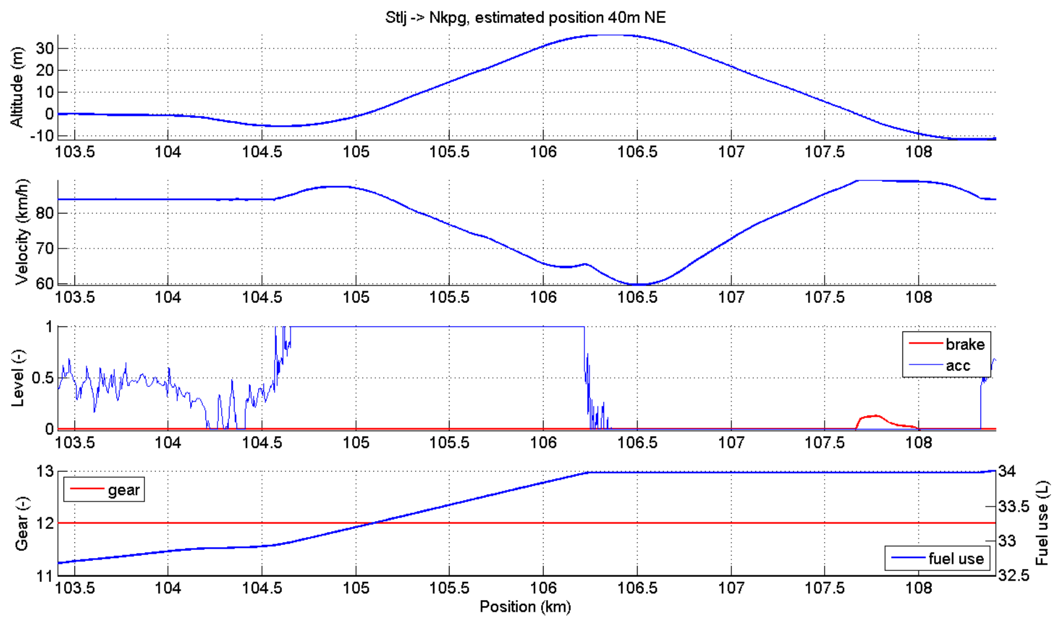


Figure 20: Control signals, positioning error NE

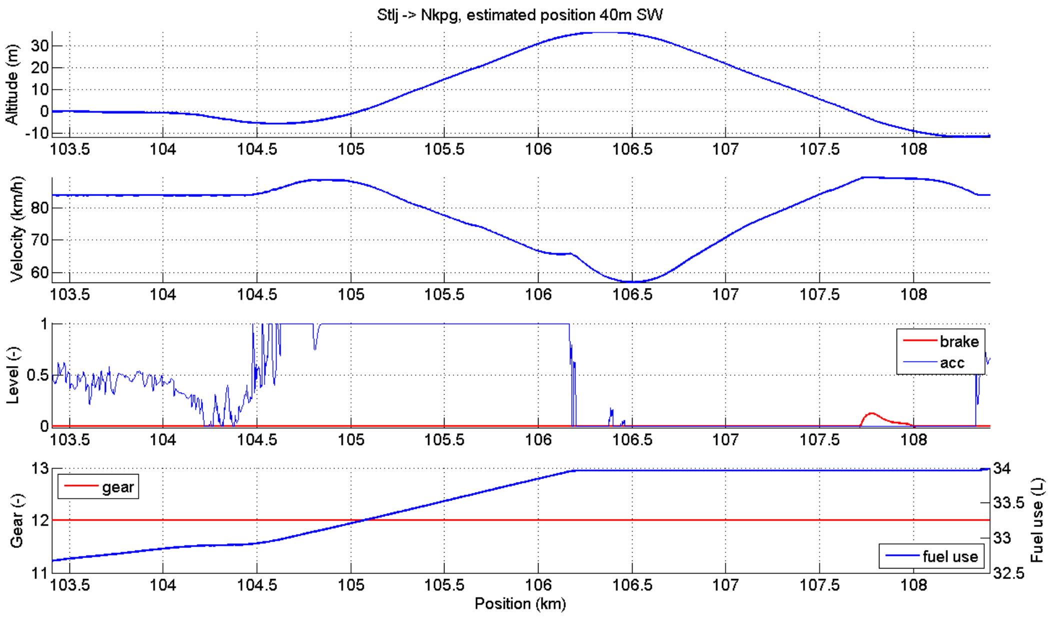


Figure 21: Control signals, positioning error SW

In the upper diagram the controller 'thinks', it is located on a position that is actually about 40m behind the real position. One can see that the controller forces a longer full throttle phase in the uphill section, almost until the very top of the hill. In the lower diagram (estimated position ~40m ahead) the throttle is released earlier, causing a lower velocity of about 55 km/h on the hilltop, compared to the upper graph (~60km/h). This higher initial speed for the downhill section requires a longer braking phase, when the velocity reaches the maximum speed.

The avoiding of unnecessary braking is the most effective mean, to lower the fuel consumption. The combination of longer full throttle and braking phases results in a higher fuel use, although it also reduces the trip time a bit. However, the effects are very little in the expected error ranges. The system gives still very sufficient results for a GPS position error that lies within the normal deviations.

5 Conclusion and summary

The control algorithm of the look-ahead control has been analysed regarding robustness and a variety of parametric uncertainties of vehicle mass and position have been simulated. It seems, the controller acts very robust in all typically expected ranges of uncertainties. The results of the analysis of uncertainties in the vehicle mass are the following: A lower estimated mass results in higher fuel consumption with a slightly shorter trip time. A higher estimated mass leads to a slightly reduced fuel use but a longer trip time. The correct estimated mass gives the optimal solution in fuel and time benefit, compared to the cruise controller. Looking at the robust performance, an underestimated mass is never a problem. In the worst case, the look-ahead control system acts simply in the same way as a conventional cruise control system. Overestimated masses may though lead to a performance that is lower than the one of a comparable cruise controller. The range of estimation errors that still allow an enhancement in fuel and time use depend on the true vehicle mass. The higher the true mass, the more robust the algorithm acts. In a simulation with a true mass of 15t, the upper boundary for an estimation error is +4t, which is 26.67% of the true mass. In a simulation with 20t true mass, the beneficial area is not left before an estimation error of +20t, which is a relative error of 100%. For higher true masses the acceptable relative error gets even bigger. On other test tracks with more and steeper hills, the uncertainties may have a slightly higher influence. However, in practical use, the estimation error is not likely to exceed 10%. Therefore, mass uncertainties in a typical range should not affect the performance of the look-ahead control system; especially not for trucks with a high mass, where this system earns most benefit.

The second issue that was analysed is the influence of positioning errors of the GPS system. For this reason, a set of simulations have been run that displace the virtual position of the vehicle of a certain offset towards northeast or southwest. This simplification has been made, since the trial route follows this direction most of the time and the algorithm tracks the nearest grid point on the road. In conclusion, these simulations also present the algorithm as very robust. Even with a positioning error of 100m the control outputs of the algorithm are still only slightly different from the optimal solution, leading to a similar fuel and time use.

So basically, with the given truck model and the trial route between Norrköping and Södertälje as a simulation basis, it can be said that the look-ahead control algorithm is robust enough for typical expected uncertainties. How well the control strategy works on a different experiment vehicle or with another set of road data with much steeper hills, could be an interesting theme for another study.

Appendix

First set of simulations

The first set of simulations is run with the perturbed model. From all 81 simulations of each run, every 4th result is taken and plotted as a data point on the fuel-time grid. The cruise controller lines mark the boundary of the beneficial area for the look-ahead control for each mass. These have been recorded using different set speeds, leading to the given fuel-time use curve. The look-ahead set speed is 84km/h at all times. The lower, respectively the more to the left, the marker of the look-ahead control is located, the more benefit we get from the look-ahead system.

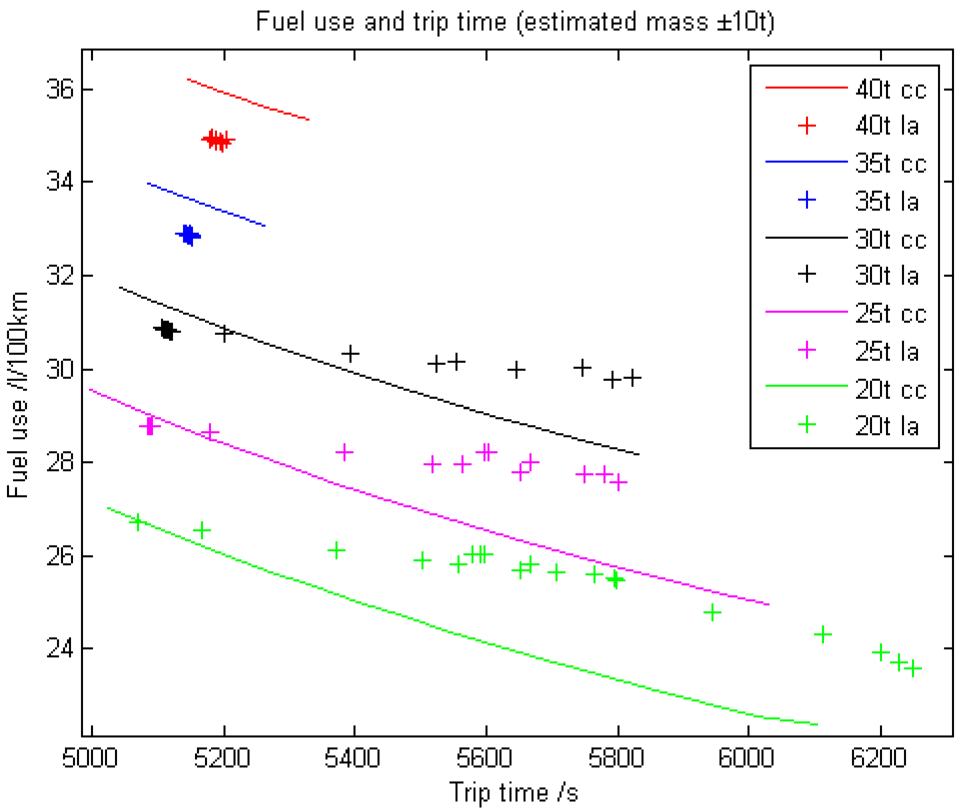


Figure 22: Fuel use and trip time of CC and LA, 20t to 40t

As can be seen in figure 22, there is probably an error in this set of simulation runs, as for true masses of 20t, 25t, and 30t there are some results far outside the expected range. To analyse this better, we take a closer look at one set of runs. As an example, the diagrams for 30 and 25 tonnes of true mass are cut out and enlarged.

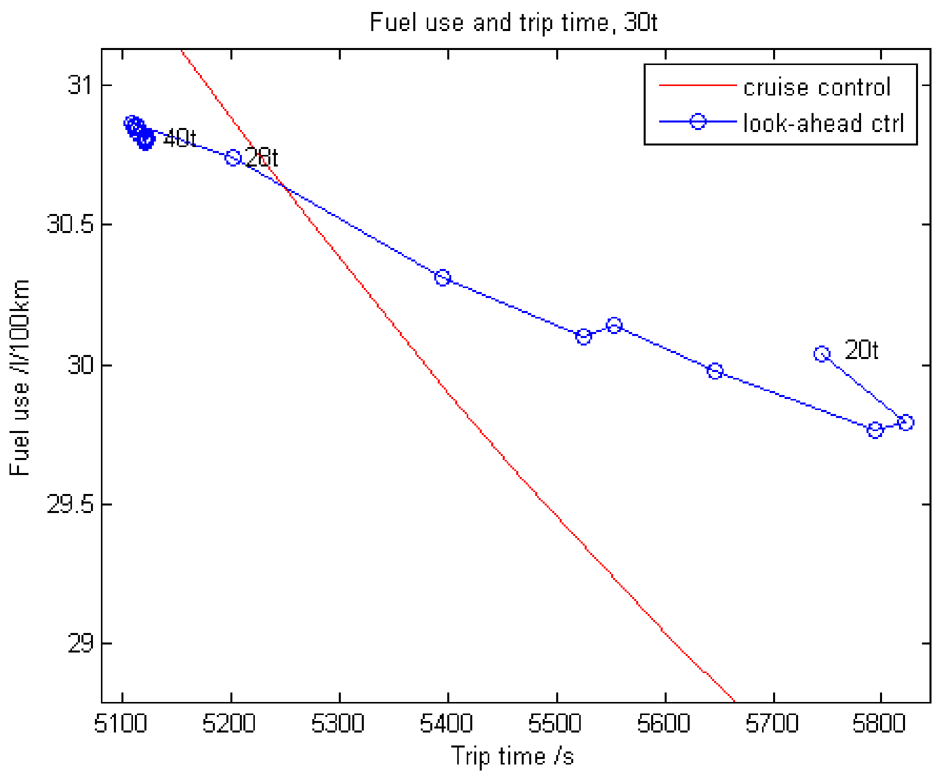


Figure 23: Fuel use and trip time, 30t

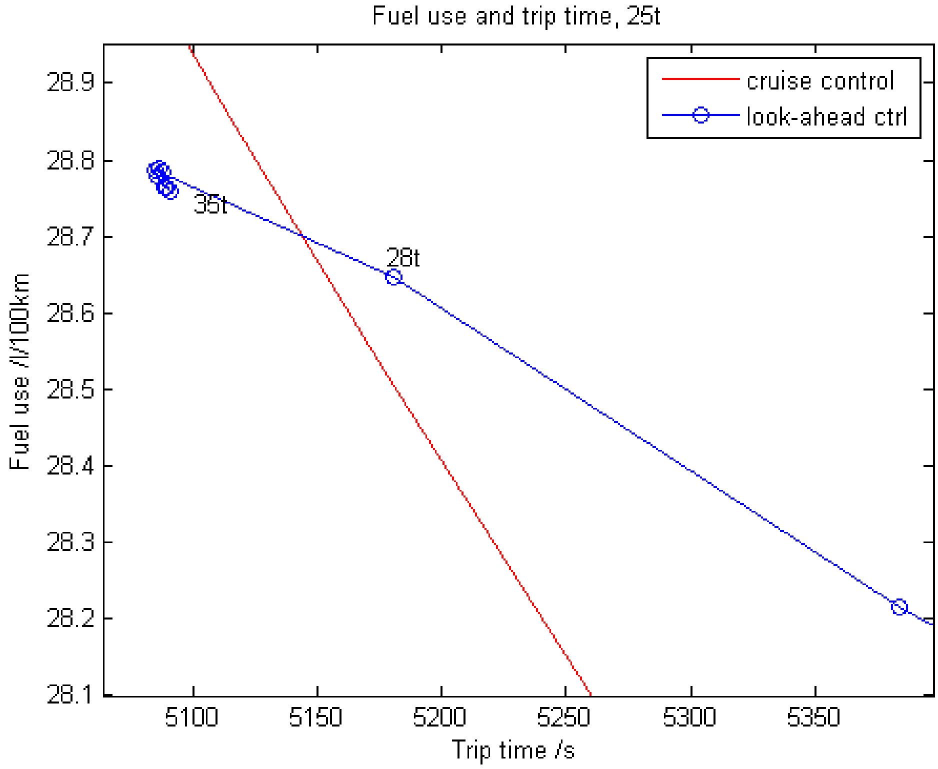


Figure 24: Fuel use and trip time, 25t

Now it can be see that the controller is quite robust, but only for estimated masses over about 28t. It seems that, independent on the real mass, the algorithm is working fine with any estimated mass higher than 28t, although best with the correct estimated mass. If the estimated mass is lower than 28t, the simulation runs with the look-ahead controller leads to a much longer trip time but only a slightly reduction of fuel use. Even if the real mass is lower than 28t, the controller shows this strange behaviour. So for real masses lower than 28t the best fuel-time results are being achieved with an estimated mass of 28t, not with the correct estimated mass.

To search for the cause of these results, we take a look at the velocity trajectories of two typical simulation runs from each set, under and above 28t. The following figure shows the trajectories of the two extreme estimated masses 20t and 40t for a real mass of 30t. One can see the 20t trajectory touching the minimum velocity of 36km/h nine times during the whole simulation. This is at uphill sections, as shown in the cut outs below. This behaviour of running into the lower velocity boundary seems to cause the difference in fuel use and trip time for low and high estimated masses.

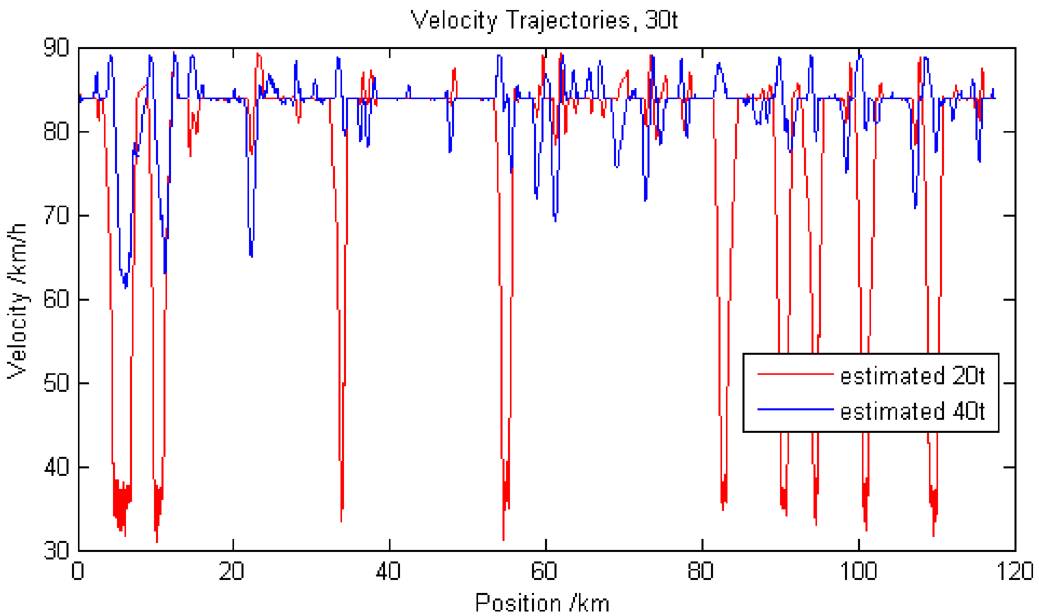


Figure 25: Velocity trajector, 30t

In order to examine the controller’s characteristics on these critical uphill sections, we take a closer look at the Strömfors segment, 14 km northeast of Norrköping. This hill at the junction Nr. 126 is part of the Getå segment, which contains one of the largest ascents of the whole test track. Here the effects of a too low estimated mass are getting best visible.

Figures 26 and 27 show the velocity trajectory as well as the fueling and braking level and gear shifts for a mass of 30t and an estimated mass of 20t respectively 40t.

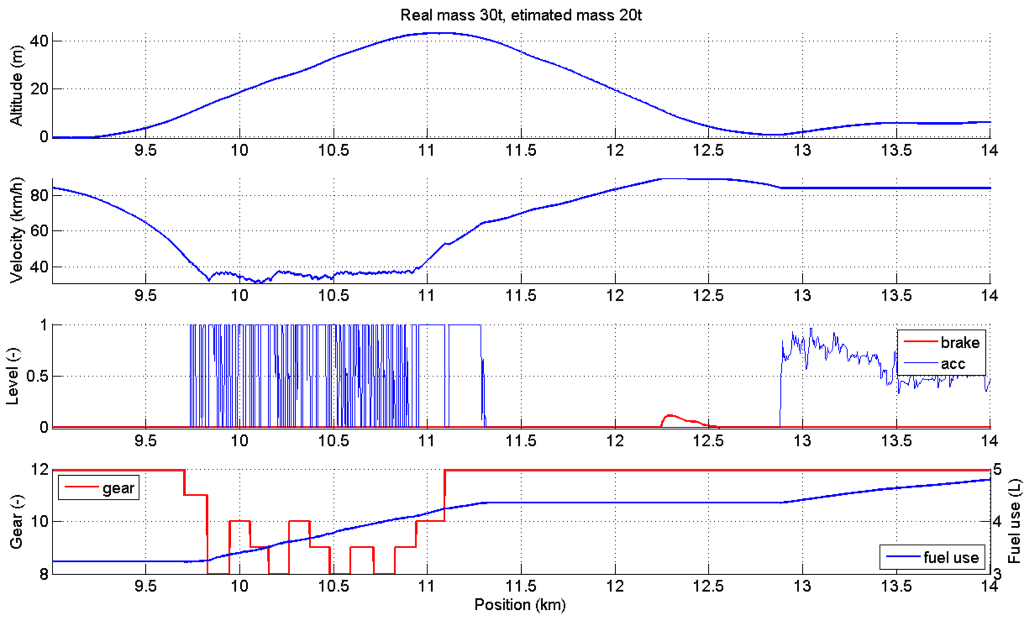


Figure 26: Control signals, real 30t, estimated 20t

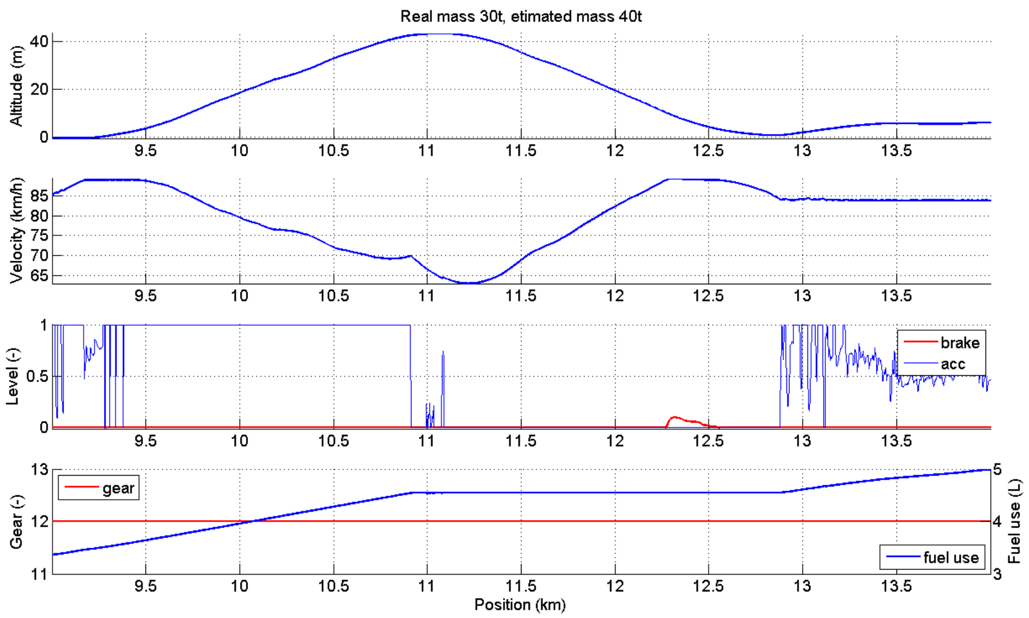


Figure 27: Control signals, real 30t, estimated 40t

As one can see, the controller works quite normal with a high estimated mass (40t). However, with a low estimated mass of 20t the truck's velocity is dropping rapidly on the uphill, until it reaches the preset minimal velocity, in this case 36km/h. Then the fueling level is oscillating very much with many gear shifts. This low average speed on uphill links leads to a much longer trip time but the oscillating fueling and running in low gears causes a fuel consumption that is not as low as with a normal cruise controller for the same trip time.

The under-fueling in the uphill is not really surprising, since a too low estimated mass leads to a too low estimated downhill slope force. Therefore, the real resisting forces are larger than the estimated resisting forces, causing the engine fueling to be lower than necessary. However, the throttle in the beginning of the uphill links is most of the time zero, meaning the controller does not try to gain speed prior to the uphill, which can only result from an error in the control- or optimisation process. The lower the estimated mass gets, the more uphill sections will show up, where the vehicle velocity reaches the minimal velocity boundary and runs into the shown oscillating control characteristics. Another unexpected issue is that this loss of performance seems to occur only on estimated masses lower than about 28t, independent of the real mass. So for a real vehicle mass of e.g. 25t, even the correct estimated mass leads to this behaviour.

However, for estimated masses above 28t the system seems to act very robust and the results are almost equal for all estimated masses larger than 28t; and this, independent on the real vehicle mass. Figure 28 shows the simulation results for an estimated mass of 40t. The real mass varies from 30t to 50t. The wrong and the correct estimated mass seem to cause very similar fuel consumption in each run. It is also noticeable that the benefit from the look-ahead control, compared to the normal cruise control, is bigger at larger masses.

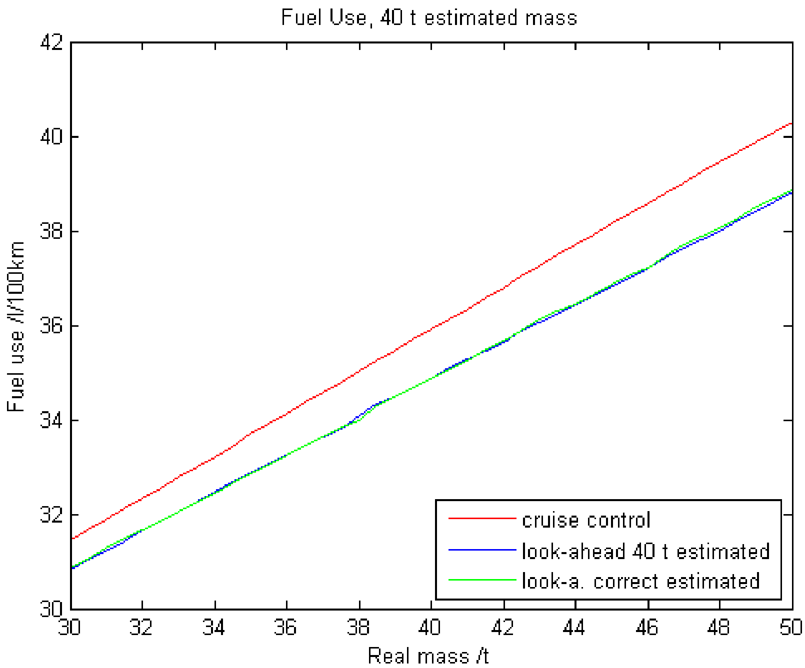


Figure 28: look-ahead and cruise ctrl at different masses

Problem

The controller seems to act very different for estimated masses under and over 28t, regardless to the true vehicle mass. In simulations with an estimated mass lower than about 28t, even for correct estimation, the controller does not have a sufficient performance, such as it forces an insufficient fueling level in uphill sections and does not gain speed prior to uphills. This results in an oscillating full-throttle/none-throttle characteristic, to keep the vehicle at the minimum speed (36km/h in the simulations). The outcome is a much longer trip time with only slightly lower fuel consumption. The most possible explanation for this is a code error or bug in the optimization algorithm that triggers for low masses. Since the problem occurs also for correct estimated masses, another set of simulations with correct estimations is done to get a more detailed picture of the error characteristic and find the source. This is described in the next chapter.

Error finding with correct estimated mass

The results from the simulations mentioned above show the necessity to analyse the controller’s behavior on different operation points of vehicle mass, regardless to the estimation errors and uncertainties. Therefore, a set of simulations with a correct estimated mass are run. This is to study, whether a lower boundary of mass exists, which will still allow sufficient results without the error mentioned above. As a reference, the fuel and trip time use of the conventional cruise control are again used for comparison.

Since the sudden loss of performance seems to appear at about 28t of vehicle mass, the following simulations are run between 25t and 30t with a step of 0.1t to get a higher resolution. To reduce simulation time, the road data in these simulations is not the whole 120km link between Norrköping and Södertälje, but only the about 14km long Getå segment, slightly northeast of Norrköping. This is where the longest uphill sections are located and since the analysed effects get best visible on long uphill links, where the vehicle speed reaches the minimum velocity, this might be adequate. The Strömfors segment, that was used to illustrate the controller’s behaviour in the previous chapters, is one of the hills in the Getå segment. The simulations are run one time with look-ahead control enabled and one time with a cruise control set speed of 84km/h as a reference.

The graphs on the following pages display the results of both and show a typical control characteristic for 26t, 27.5t and 29t. In the cost-diagrams the fuel-time equivalent β is used to weight fuel and trip time use. This is a different approach to display the results. It makes it possible, to give more information about the vehicle mass in high resolution, since the mass is scaled on the horizontal axes. The fuel-vs.-time plot would get quite confusing with too many data points and labels.

The fuel-optimal algorithm in [Hellström 2007] uses a cost function

$$I = M + \beta T$$

with the fuel mass M and the trip time T to compute the optimal control signals. The fuel-time equivalent factor β is a function of a stationary speed $\hat{v}$.

$$\beta = c_4 \hat{v}^2 (2c_1 \hat{v} + c_2)$$

with the constants

$$c_1 = \frac{r_w c_w A_a \rho_a}{2i\eta b_e} \qquad c_2 = -\frac{i}{r_w}\frac{a_e}{b_e} \qquad c_4 = \frac{n_{cyl}}{2\pi n_r}\frac{i}{r_w}$$

This fuel-time equivalent cost function can also be used to present the results of fuel and time use in these simulations, if for the speed $\hat{v}$ the reference speed of 84 km/h is used. The cost function that results from this β crosses the cost function of the normal cruise controller at a similar point as in the fuel-vs.-time plots in figures 8 and 9, at about 28t.

Additionally to the cost function, the 'raw' fuel consumption and trip time that are used for the computing of the cost function are plotted in the small diagrams.

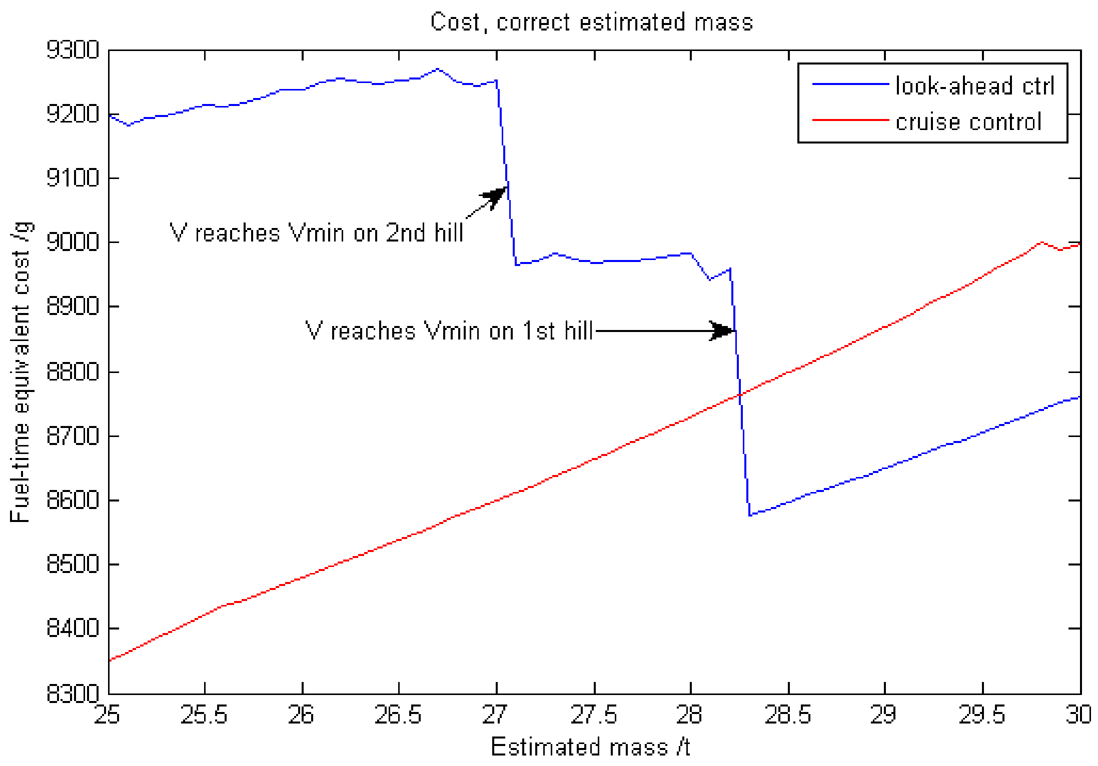
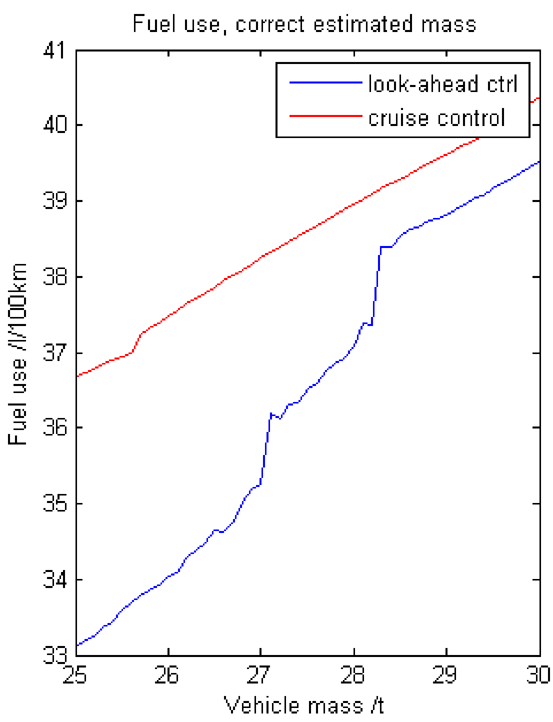


Figure 29: Cost, correct estimated mass, Vref = 84km/h



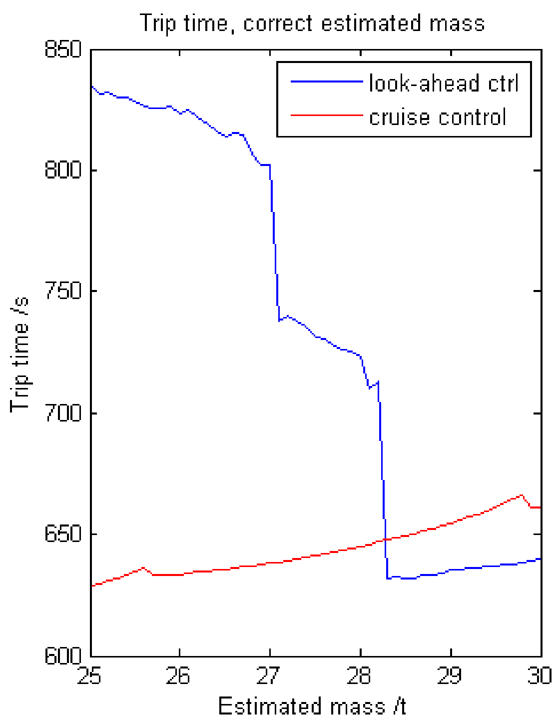


Figure 30: Fuel use, correct mass **Figure 31: Trip time, correct mass**

The graphs show two steps that are caused by the velocity reaching the minimum velocity and leading to the unwanted oscillating control characteristic.

Three samples of the velocity trajectories and control signals from the three areas between the steps are shown in the diagrams below. One can see the same behaviour like mentioned before.

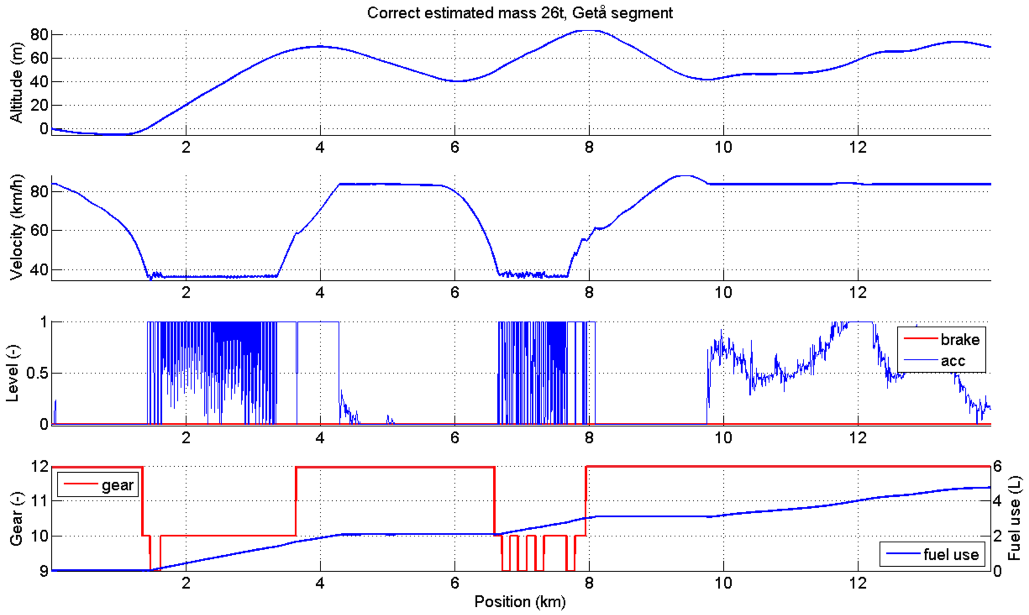


Figure 32: Control signals, 26t

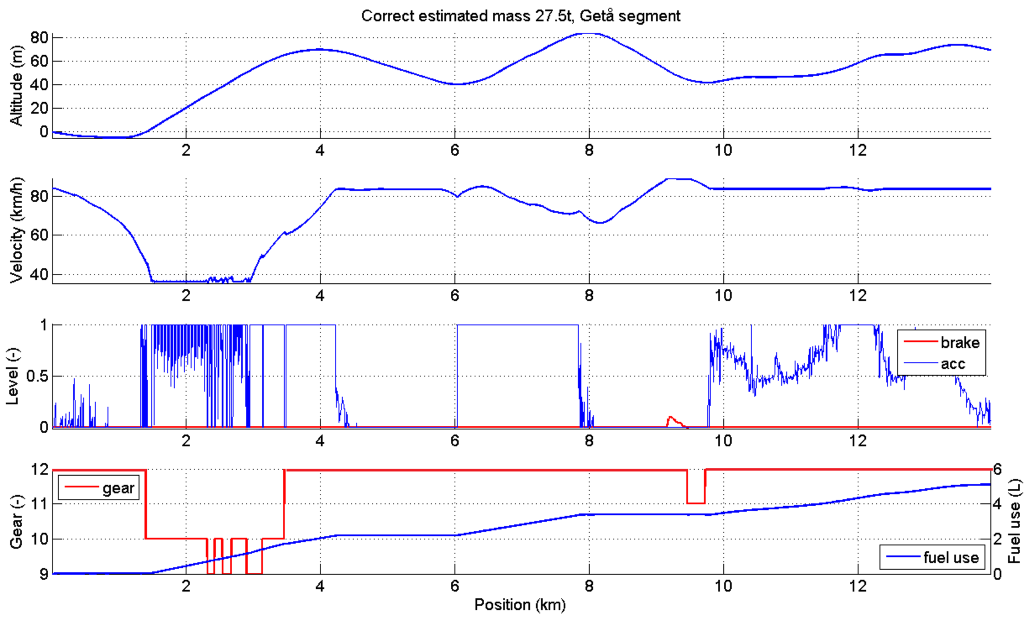


Figure 33: Control signals, 27,5t

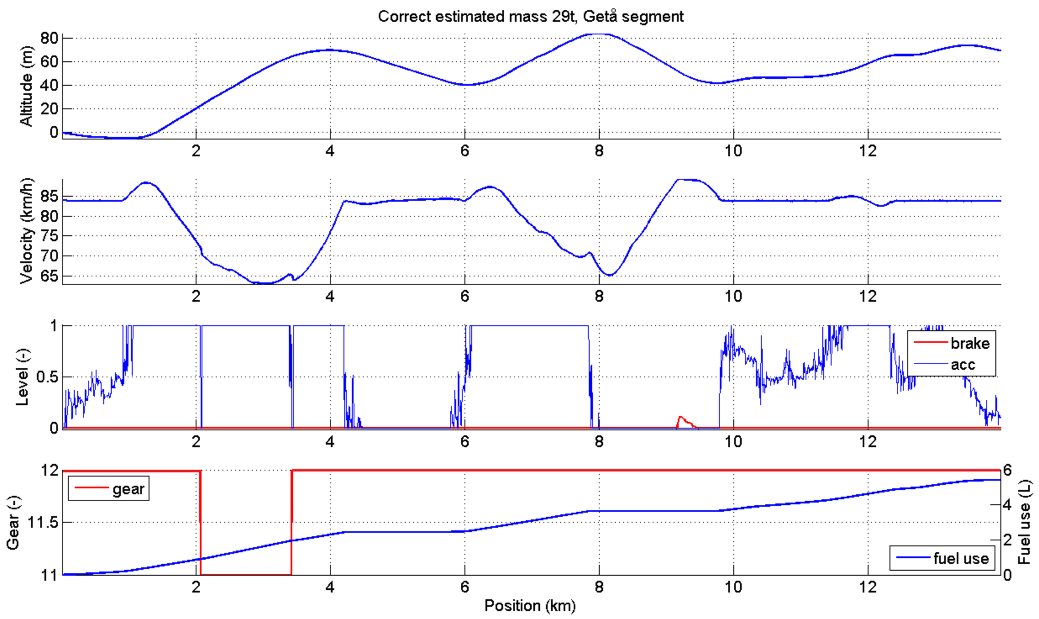


Figure 34: Control signals, 29t

The controller does not seem to output the true optimal velocity trajectory and control signals, as there is no gaining speed prior to some of the uphill sections in the cases of too low mass. This makes the truck loose velocity until it reaches the minimum and falls into the described oscillating control scheme.

Another interesting issue might be the influence of the reference speed or look-ahead control set speed. To test this, another simulation series like the one above is run with 74km/h instead of 84km/h and 79km/h as a maximum speed instead of 89km/h. These two set speeds will be adequate, since the speed limits for heavy trucks on most European highways is either 80km/h or 90km/h and one will be able to identify the major differences and drifts.

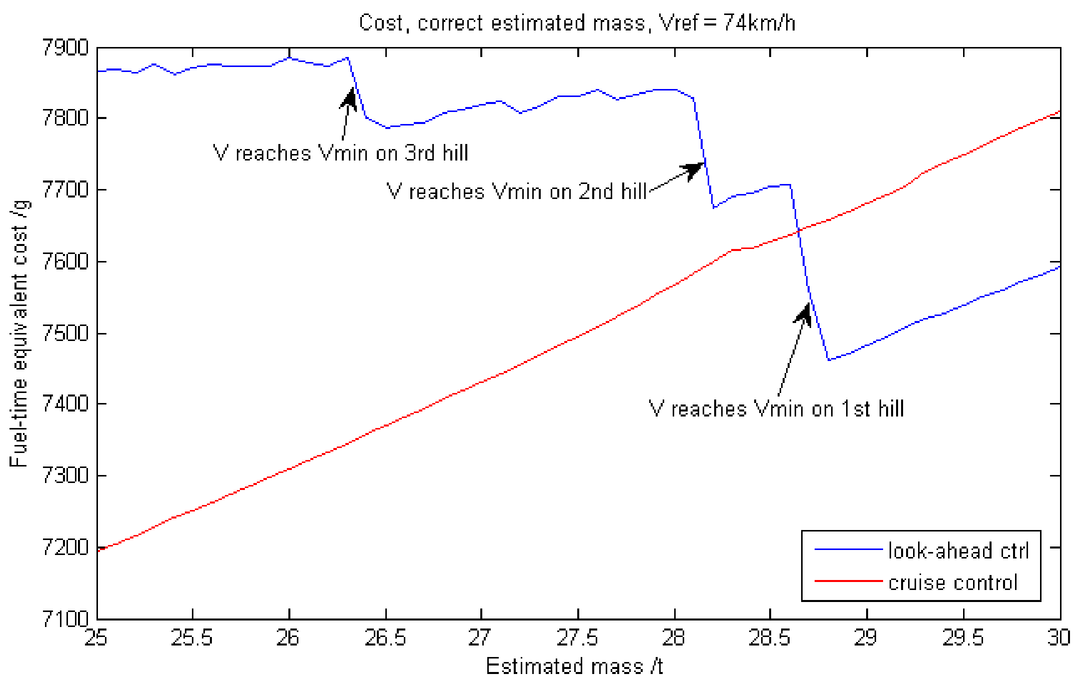
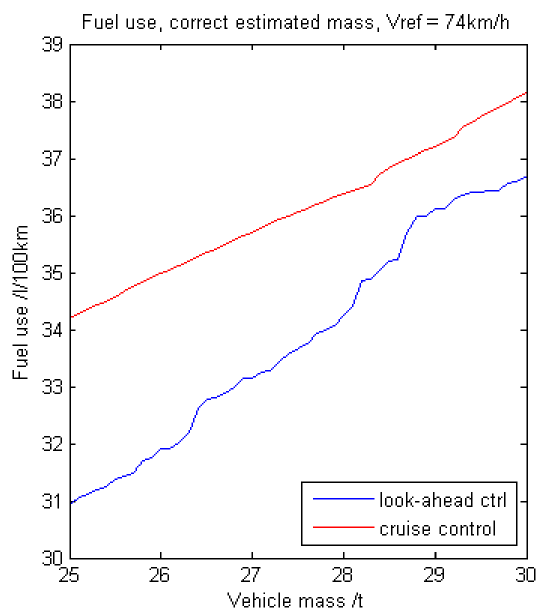


Figure 35: Cost, correct estimated mass, Vref = 74km/h



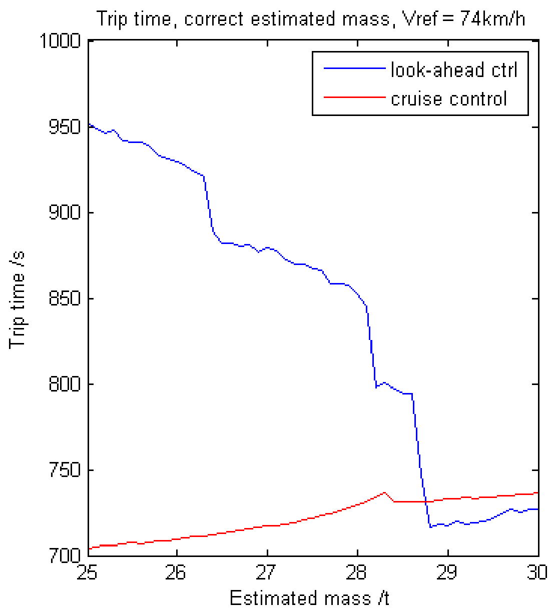


Figure 36: Fuel use, correct mass **Figure 37: Trip time, correct mass**

With a reference speed of 74km/h and the same minimum velocity boundary of 36km/h the ineffective state is reached even at higher masses, because the available velocity margin is lower than in a simulation with a reference speed of 84km/h. Also, there is a third step that is caused by the velocity reaching the lower limit on a third uphill section, as seen in the trajectory in the graph below.

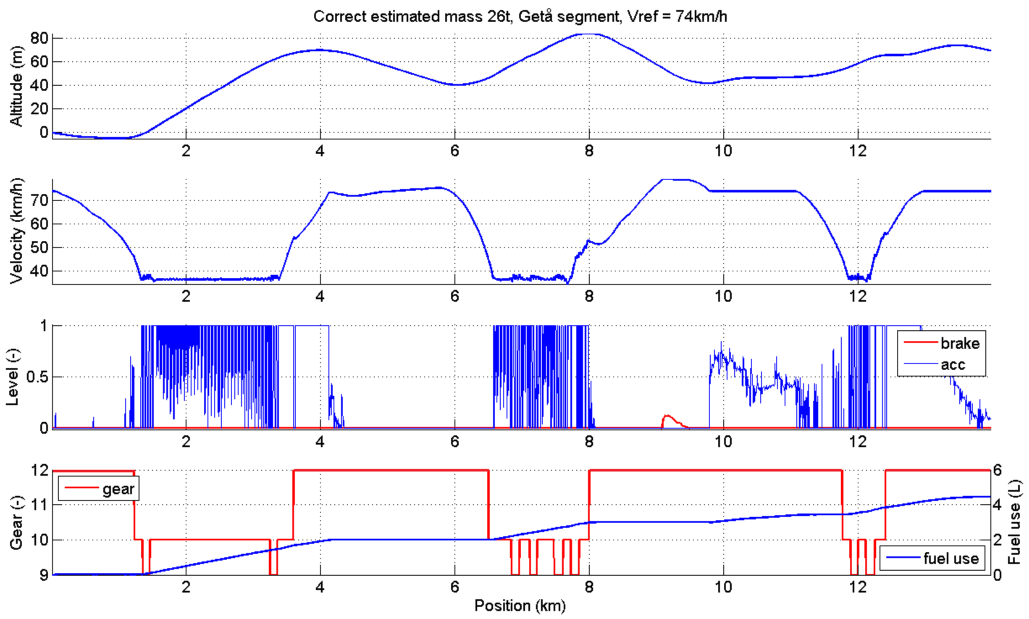


Figure 38: Control signals, 26t, Vref = 74km/h

The graphs above show that the fueling level prior to uphill sections and in the beginning of uphill sections is zero, although it should have another value. This state remains until the minimal velocity is reached. The first proposal was to search for an error in the modeled cruise controller. The 'controller' block in the Simulink model contains basically an s-function that models the cruise controller that is fed with a set speed taken from the optimal trajectory and puts out the corresponding fueling and breaking level and the gear choice. However, the 'optimal' trajectory, that is computed by the optimisation module and passed on to the controller block, already contained the noticed errors, so the source had to lie in the optimization module itself. The errors were finally traced to a bug in the optimization code. It was in the code that avoids behavior that cannot be part of an optimal solution. The algorithm searches for an optimal solution in a state space that is spanned by the state vector $x = [v,g]^T$ containing the velocity v and current gear g and the control vector $u = [u_f, u_b, u_g]^T$ containing fueling level u_f, braking level u_b, and gear selector u_g. The dynamic programming technique is usually not designed for problems of so many dimensions. This is why some heuristic rules are set up that sort out solutions, which are obviously not a candidate for an optimal solution. A simple example for this is simultaneous use of throttle and brake. Such rules known from analytical reasoning can be quite beneficial for complexity. However, one of these rules, concerning the gear shifting strategy has been written incorrectly, which caused the algorithm to sort out the optimal solution at low masses and lead to the behaviour mentioned above. Paragraph 4.1.2 contains the series of simulations with a fixed version of the optimisation algorithm.

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