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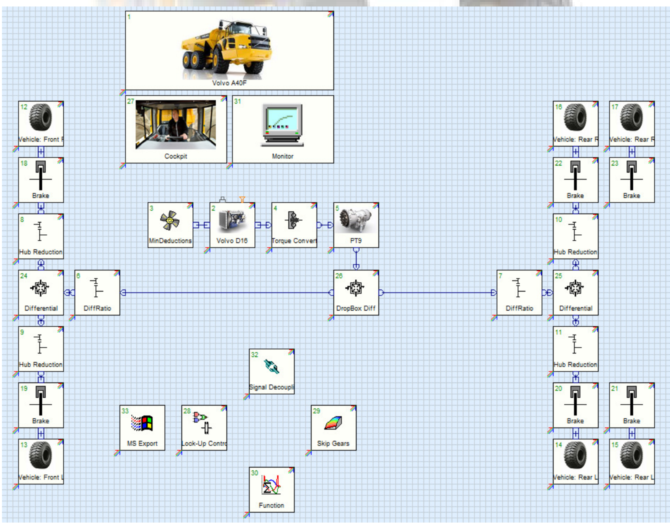

Off-road Shift Scheduling

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

SEBASTIAN KRAUSE

Department of Applied Mechanics
Division of Dynamics
CHALMERS UNIVERSITY OF TECHNOLOGY
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ISSN 1652-8557
Department of Applied Mechanics
Division of Dynamics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

For passenger cars and on-road heavy duty vehicles, several shift strategies exist. Regarding off-road driven construction vehicles, especially in the case of articulated haulers, which are often heavily loaded and being driven off-road some challenges have still not been overcome. For instance while cruising and then driving on a steep uphill the main problem is to handle enormous vehicle inertias together with rapidly changing driving resistance. The purpose of this project is to develop gear shift strategies which support the driver in critical driving situations off-road. Simulation results have shown that it is possible to optimize both travelling time and fuel consumption in critical driving situation in order to help the driver. A software based solution is cheaper compared to a mechanical reconstruction of the gearbox.

Key words: Gear shift strategy algorithm, off-road, construction vehicle, hauler, articulated hauler, AVL Cruise

PREFASE

The present thesis has been carried out at the AVL Powertrain Scandinavia Södertälje in cooperation with division of Dynamics Chalmers University of Technology. The supervisors of the project are Joakim Karlsson AVL/SE and Viktor Berbyuk, Dynamics, Chalmers. Examiner of the project is Prof. Viktor Berbyuk.

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I would first of all thank my supervisor Joakim Karlsson who has always been there to answer my questions I had. I would also like to give a very special thanks to Alfred Johansson, who gave me an introduction to the simulation software CRUISE as well as for answering and helping me with all the questions I had regarding CRUISE.

I also would like to give a special thanks to Fredrik Ekenved for lending me his car in order to conduct some measurement on it. Therefore I would like to thank Fredrik Dunert for helping me with installing the equipment in Fredrik Ekenved's car.

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Last but not least I also would like to thank those people who helped me in reading my thesis. This is mainly directed towards, Joakim Karlsson, Viktor Berbyuk and Oskar Strand.

Contents

List of Abbreviation

The following list of abbreviation is provided for a better reading of the following thesis. The abbreviations are listed in the chronological order as they appear in the text.

Abbreviation	Full Word
NEDC	New European Driving Cycle
WHSC	World Harmonized Stationary Cycle
WHTC	World Harmonized Transient Cycle
h-rpm1	Gear shift schedule where shifting is done at high rpm's
h-rpm2	Gear shift schedule where shifting is done at high rpm's
h-rpm3	Gear shift schedule where shifting is done at high rpm's
h-rpm4	Gear shift schedule where shifting is done at high rpm's
s-Trpm1	Gear shift schedule where shifting is done at smoother rpm's
s-Trpm2	Gear shift schedule where shifting is done at smoother rpm's
h-T1	Gear shift schedule where shifting is done at or close to the highest torque
h-T2	Gear shift schedule where shifting is done at or close to the highest torque
NVH	Noise Vibration and Harshness
Bsfc	Brake specific fuel consumption

1 Introduction

This chapter gives the reader an introduction of its background of this thesis work as well as the scope of the thesis. A brief description of the articulated hauler as well as the simulation software used will sum up this chapter.

1.1 Background

The population on earth is growing rapidly and the need for the human being to build new housing and expand the road network is an important factor. While doing this, soil is being dug up on top of large vehicles, so called articulated haulers (construction equipment vehicles). These articulated haulers are therefore heavily loaded and very often driven off-road. With an off-road topography that contains many up- and downhill slopes with a relatively high gradient, large rolling resistance and etc. The main problem is to handle enormous inertias together with rapidly changing in driving resistance combined with long gear shift times.

1.2 Objectives

The main purpose of this project is to develop new gear shift strategies that support the driver in so called critical driving situations. Before gear shift strategies can be developed, critical driving scenarios for the articulated hauler will be worked out. The gear shift schedule will be analyzed in terms of travelling time and fuel consumption. In order to get a deeper understanding of how the gear shift process of an automatic transmission with a torque converter works, measurements on a passenger are conducted. Because a simpler engine model is used no emitted emissions will be analyzed.

1.3 Limitations

Due to the fact that a simpler engine model is used no emissions will be analyzed. The introduction work consists of a minor literature study consists (time frame 2 weeks) and measurements on a passenger car. The software AVL CRUISE is used a simulation tool and due to licensing policies MATLAB could not be used.

1.4 Simulation software: AVL CRUISE

The simulation software used in this project is called CRUISE. It is a software provided by AVL itself and is a Vehicle system and Driveline analysis software (AVL 2013a). Cruise is used to optimize the engine and powertrain, i.e. hybrid concepts, different types of gearboxes etc. of several vehicle types like cars, busses, trucks etc. in order to optimize:

- Fuel consumption and emissions for any driving cycle
- Driving performance such as acceleration, hill climbing or braking

With the software Cruise it is also possible to test and evaluate more tasks. For instance it is also possible to analyze different types of gearboxes or test and evaluate different hybrid powertrain concepts. It is also possible to evaluate energy flows of different components.

In ***Figure 1*** below the working view of AVL Cruise is shown

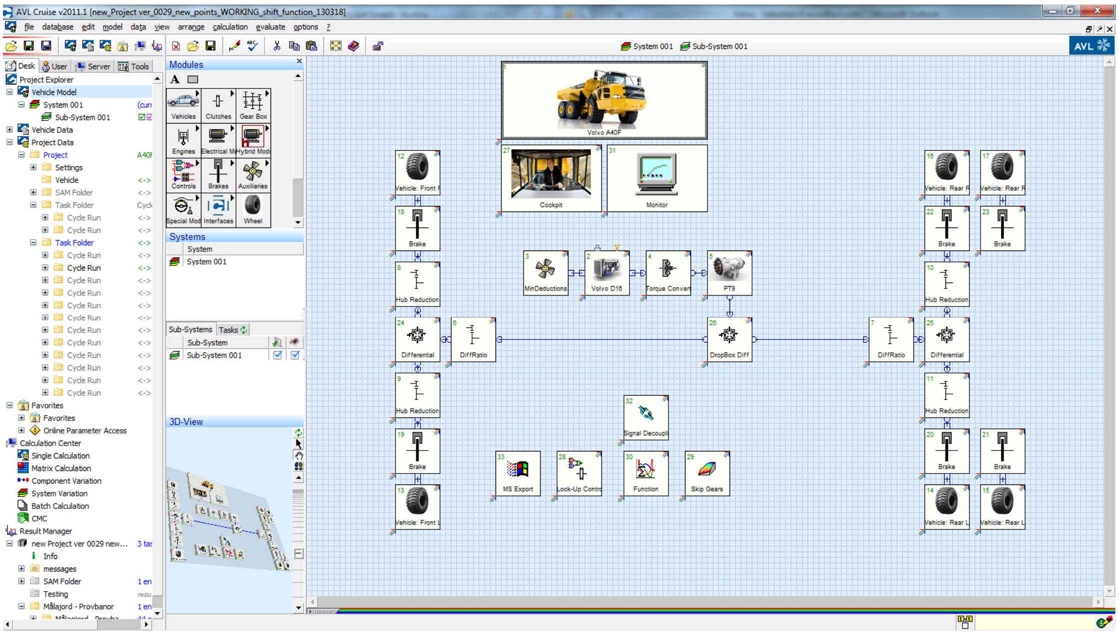

Figure 1 – AVL Cruise simulation software

The simulation software Cruise offers different interfaces (AVL 2013b). For instance, it is possible to build a model in Matlab/Simulink and connect it to the vehicle model in Cruise. Cruise also offers interfaces to AVL software; AVL BOOST (engine cycle simulation) and AVL DRIVE (objective drivability evaluation). An interface to Microsoft Excel does also exist where results of the simulations can be displayed. It is furthermore also possible to replace controlling parts with a Black Box, which enables the user to write own control algorithms in C or FORTAN.

In the figure 2 some results are shown. The left window (black square) collects all main parts of the vehicle powertrain (engine, gearbox, brakes etc.). In the window in the middle (blue square) the subsystems results can be selected and shown in the right window (red square), i.e. power and torque of the engine.

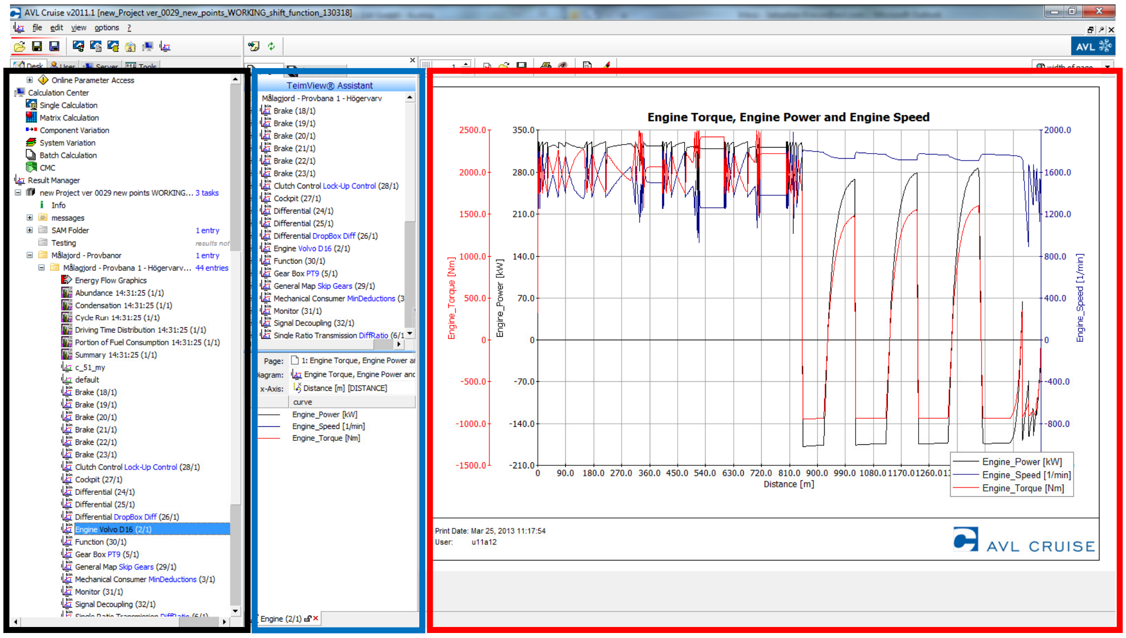

Figure 2 - Cruise results

1.5 Articulated hauler and simulation model in AVL Cruise

The articulated hauler is a vehicle which can be described as a combination of a tractor and a trailer, where one can load material (soil, gravel, etc.) on. The articulated hauler does not steer with its front wheels like most vehicles are doing, the front part of the articulated hauler (engine and cockpit) are connected to the trailer and steered via articulation.

Figure 3 - Volvo articulated hauler (Volvo Construction Equipment 2013)

The Articulated hauler, in ***Figure 3***, is equipped with a diesel engine together with a planetary automatic gearbox with a torque converter and lockup clutch. The benefit of using an automatic gearbox, is that it allows for power shifts (no torque interruption during gear shifts). The sketch of a driveline can be seen in ***Figure 4***.

The tables 1 and 2 describe some fundamental data of the Volvo articulated hauler.

Table 1 – Engine technical data

Engine type	Turbocharged inline 6 cylinder
Maximum torque	2525 Nm (at 1050 rpm)
Maximum power	350 kW (at 1800 rpm)
Displacement	16,1 Litre
Valves	4 valves per cylinder

Table 2 - Gearbox technical data

Gearbox type	Automatic with planetary gears
Number of forwards gears	9
Number of reverse gears	3
Differential ratio	3.091

The gear shifting times for positive torque upshift have been measured to 600 ms for all shifts. Regarding the positive toque downshift the time was measured to 800 ms for all shifts.

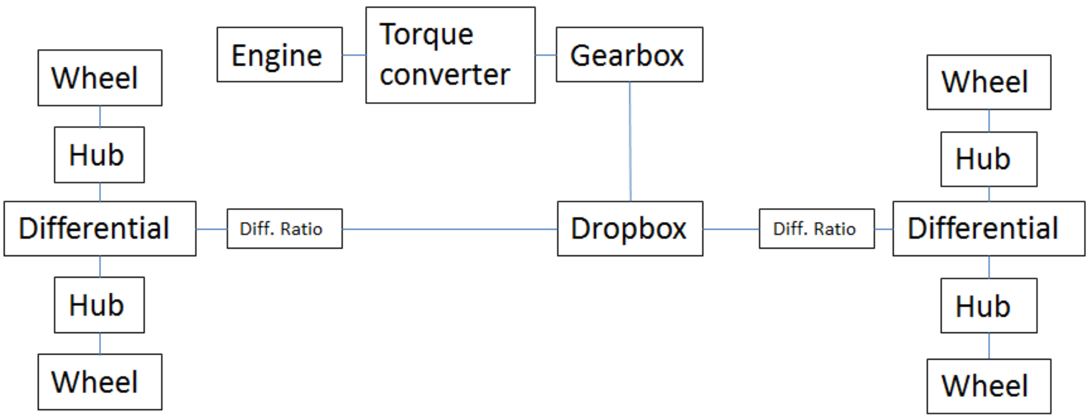

Figure 4 - Driveline of the Volvo articulated hauler A40F

The gear shift strategy algorithms that is to be developed will be simulated and evaluated for a Volvo A40F articulated hauler.

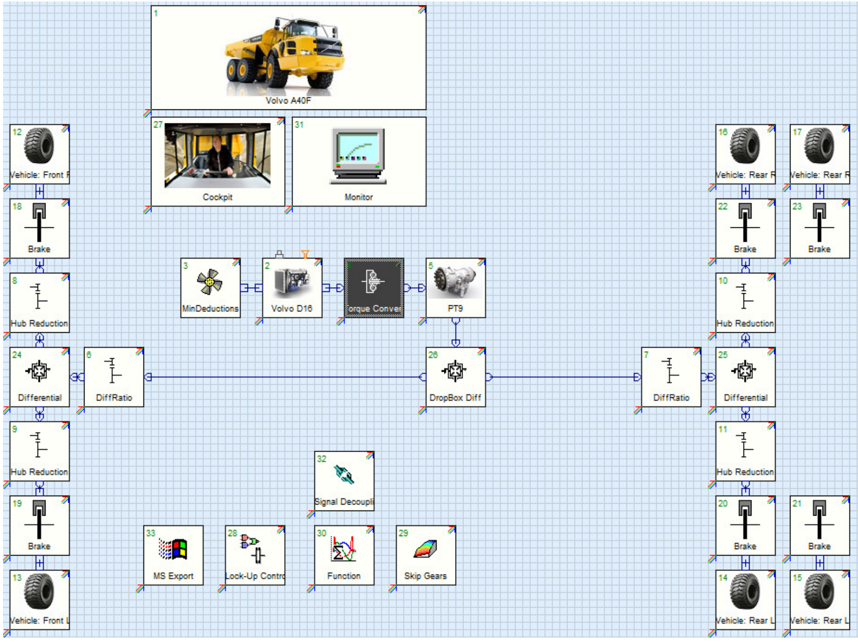

Figure 5 - Cruise simulation model of the Volvo A40F

Regarding the driveline, the Dropbox differential, which can be seen in ***Figure 4*** and ***Figure 5***, has an unlocked differential lock, with a torque split factor of one. The differential ratio (final drive) for both front and rear axle has a ratio 3.019. The differential for both front and rear axle has the same parameters as the Dropbox differential, an unlocked differential with a torque split factor of one. All six wheels are having the same rolling radius of 886 mm.

In order to set up data of the vehicle, i.e. nominal weight, vehicle body dimensions or load dependent characteristics, this can be done in the *Volvo A40F* window, which can be seen in ***Figure 5***. In the cockpit window brake and accelerator pedal characteristics can be set up. The *Monitor* window is not a part of the vehicle directly. Here it is possible to set up which parameters can be seen while a simulation is running. Like the *Monitor* window, the *MS export* window is also not part of the vehicle directly. Here signals and parameters for a running simulation can be seen in an Excel sheet, as soon as the simulation is finished.

In *Lockup control* window, the opening and closing speeds for the lockup control function can be set up and be adjusted. In the *Function* the gear shift schedule will be developed using the programming language C. All relevant parameters for the gear shift schedule can be adjusted and named here. The *Signal Decoupling* window is maybe the most important part of the simulation model. Here all the different parameters and signals are coupled together and in-/out-parameters of the different windows can be set up.

In the e*ngine* window all parts of the Engine can be set up. The gearbox set up, number of gears, gear ratios etc. are adjusted in the *gearbox* window.

Data has already been given in section 1.3, so they won't be mentioned further here.

1.6 Shift time

Regarding the term “shift time” the definition often differs. A more detailed explanation will be explained now.

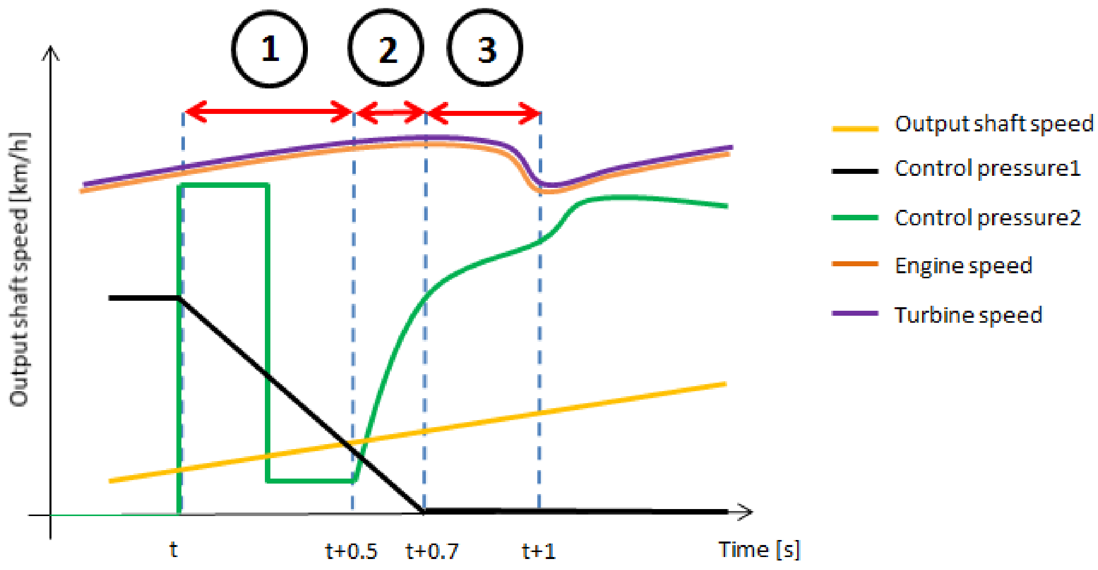

Figure 6 - Gearshift process

1. During the first stage the oncoming clutched is filled oil. The gear *i,* which was active before the shift process started is still active.

2. In the second stage the torque is being handed over from the off-going clutch to the on-coming. Gear *i* is still active.

3. The oncoming pressure is being increased and controls the actual speed change. Gear *i+1* is now active

With the term “gear shift time” the all three stages from time *t* to *t+1* is meant.

2 Research method

The thesis work is divided into 3 major parts, establishing of the project, concept and simulation phase and evaluation and documentation phase. All major phases are further divided into sub phases.

The first of the major phases was to conduct a literature study about gear shift strategies for both light- and heavy duty vehicles. As part of the introduction work measurements on a vehicle will be performed in order to get a deeper understanding of the gear shift process. The second phase, concept and simulation phase concerns the major part of this thesis, to develop new shift schedule algorithms that support the driver in critical driving situations. This was performed by using the software package CRUISE, which is provided by AVL itself. The main focus is rather put on a functional solution but it should also be seen as a compromise between the "best" solution and the most fuel efficient solution.

Regarding the literature study articles and written papers about gear shift strategies will be analyzed and evaluated. References are listed at the end of the report.

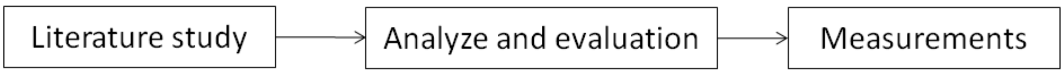

Figure 7 - Research method

3 Empirical findings

This literature study describes how gear shift strategies are used on light and heavy duty vehicles. The study focuses on giving a better view in how shift strategy works in general

3.1 Light duty vehicles

For light duty vehicles, i.e. passenger cars, shifting is controlled by accelerator pedal (the actual load), which is requested by the driver, displayed in ***Figure 8***. Depending on how much the vehicle is loaded or in which gearbox program (Sport- or Winter-mode) the gearbox is running on, the shifting points varies.

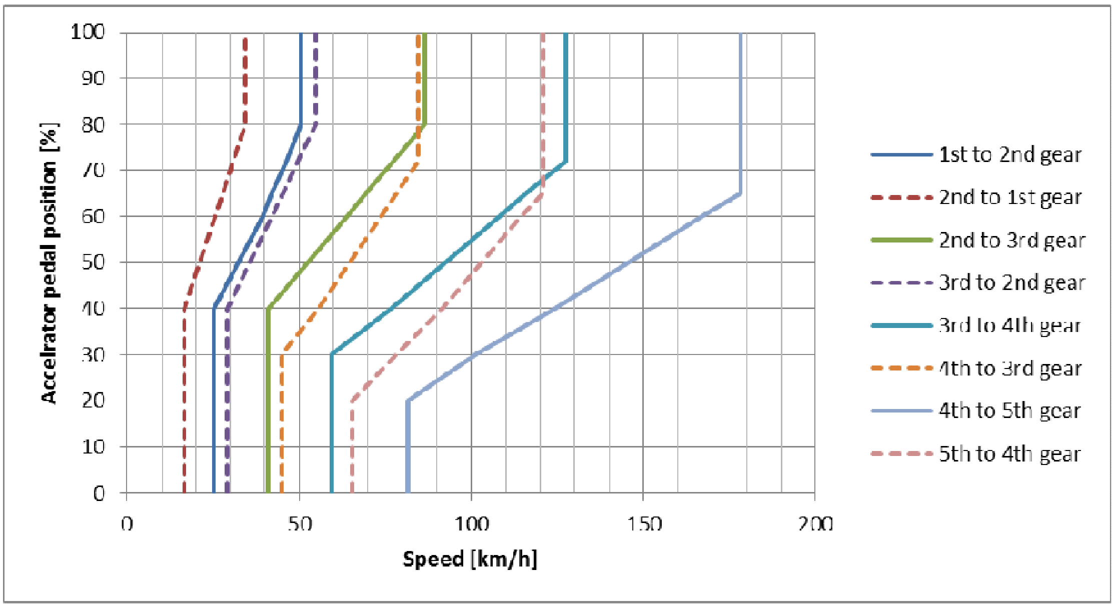

Figure 8 – Typical gear shift schedule for a passenger car

3.1.1 NEDC strategy

The NEDC strategy is probably the most common shift strategy for passenger cars. The gear shifting is performed at fix vehicle speeds in order to meet emissions regulations, or in other words to get low fuel consumption as possible. The gear shifting points are equal for all cars, which are tested in the NEDC (Lacour, Vidon, Perret, Tassel & Joumard, 2011a). The advantage of this is that you can compare the emissions and fuel consumption between different cars due to the fact that you shift at the exactly same vehicle speeds. A major disadvantage with this strategy is the number of gear changes, which is quite high in the new European driving cycle. This does of course not correspond to the reality (Lacour, et al. 2011a).

3.1.2 Engine speed strategy

This gear shifting strategy is a little bit different compared to the previous one, the NEDC strategy. The engine speed strategy shifts when 75 % of the engine speed of where the maximum power is reached and shifts down when the engine speed goes below 1500 rpm (Lacour, et al. 2011b). Due to the fact that every car has its maximum power at different rpm's, the shifting points are different for each vehicle (Lacour, et al. 2011b).

3.1.3 Artemis strategy

The Artemis strategy consists of 4 different predefined shift schedules and each group represents a category of cars (Lacour, et al. 2011). The advantage of this shift strategy is that equally powered cars are using the same shifting points. The drawback of this shift strategy is though that the chosen shift strategy (shifting points) for cars having a high standard deviation from its category is not perfectly matched compared to a vehicle which is closed to the predefined vehicle for its category (Lacour, et al. 2011).

3.2 Heavy duty vehicles

The shift strategy for heavy duty vehicles, i.e. trucks, is different compared to light duty vehicles (passenger cars) because they are, most of the time, travelling at a constant speed. For trucks for instance, there exist driving cycles and nowadays two driving cycles are used frequently, the WHSC and the WHTC (Dieselnet, 2012a,b). The difference between these driving cycles compared to the driving cycles for light duty vehicles are that in these heavy duty driving cycles, engine dynamometers are used as load drivers (Dieselnet, 2012a,b). For the NEDC cycles though, the complete vehicle is tested on a chassis dynamometer (Dieselnet, 2012c). Of course there exist other driving cycles for different countries but the WHTC and WHSC are used worldwide.

3.2.1 Time-based method

For a given road inclination, this shift strategy method chooses its gear shifting points is such a way, to improve the travelled time compared to a standard automatic transmission (Ivarsson, Åslund & Nielsen, 2010a). For road gradient of 6 %, the improvement in fuel consumption and time was 0.1% respectively 0.5% compared to a conventional automatic transmission, according to Ivarsson, et al. (2010).

3.2.2 Fuel-based method

As the name already suggests, the fuel-based method reduces the fuel consumption for a given road inclination compared to a conventional automatic transmission (Ivarsson, Åslund & Nielsen, 2010b). According to Ivarsson, et al., the fuel consumption could be improved by 0.4% while going 0.2% slower.

3.2.3 Instantaneous gear shift

The instantaneous gear shift strategy is a further optimized version of the fuel-based method. Gear shifts are now done in single steps compared to multiple steps before and therefore the fuel consumption could be improved by 1.2% while going 2.2%

slower, compared to a conventional automatic transmission, according to Ivarsson, et al. (2010).

3.2.4 GPS-based gear shifting

Mercedes, Scania and Volvo are using GPS/road data in order to optimize the gear shifting process for emissions and fuel saving. Each of their technologies is bottom line using, as mentioned before, the same technology but it is done in different ways.

3.2.5 Mercedes: Predictive Powertrain control

Mercedes Predictive Powertrain Control gear shifting strategy uses GPS data in order to determine the topography of the road. The control algorithm adjusts then the speed, braking or gear shifting in order to drive in the most efficient way, The Verge (2012). Mercedes Predictive Powertrain control is based on their cruise control system which was introduced some years ago. According to Daimler (2012), fuel savings up to 3% are possible with this strategy.

3.2.6 Scania: Active Prediction

Scania's active prediction system is similar to the one Mercedes is using. The difference though is that Scania's system stores the data in their Scania communicator, Scania (2012). Scanias stored road data covers about 95 % of the roads in western and central Europe. When a vehicle then is travelling on a road that is covered, the vehicle speed is controlled so that fuel savings up to 3 % are possible, according to Scania (2012).

3.2.7 Volvo: I-see

Volvos so called *I-See* system is combined together with their transmission system *I-Shift,* Volvo I-Shift (2012), Volvo Trucks Deutschland (2012). The first time a Volvo Truck climbs a hill the system stores that information. The system can then "learn" the topography of the road and uses this information in order to save fuel for the next times. The system is saving the actual slope the vehicle drove on and according to Volvo Trucks Deutschland (2012) the actual slopes a vehicle passed are more accurate than for instance traffic maps. Volvos *I-See* system combined with their *I-Shift* is capable to save up to 5 % fuel, Volvo Trucks Deutschland (2012).

3.3 Control Algorithm

The three gear shift strategies mentioned for the heavy duty vehicles are based on a given road inclination (Ivarsson, et al. 2010c). If the road inclination is not given a model predictive control strategy that uses dynamic programming, could be applied (Fu & Bortolin, 2012a). This control algorithm uses a control horizon and a prediction horizon, which can be seen in figure 2.

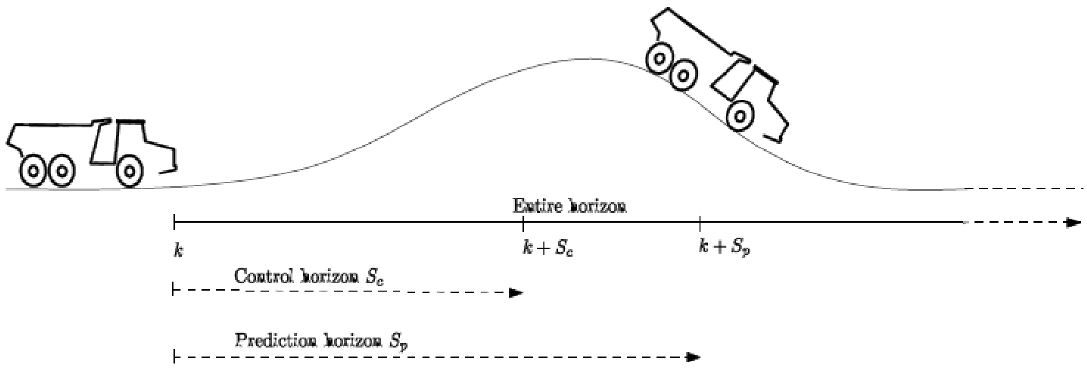

Figure 9 - Control and prediction model (according to Fu & Bortolin, 2012, p.4)

Depending on the length of the horizons, it affects the model predictive control algorithm and therefore the results. Longer prediction horizons will normally give better results but the disadvantage is longer computational time (Fu & Bortolin, 2012b). According to Fu & Bortolin a shorter horizon results in less fuel consumption compared to a longer horizon, but the longer horizon values results in a shorter travel time compared to the shorter horizon values.

3.4 Critical driving situations

The main problem the articulated haulers are having is to handle enormous vehicle inertias. Together with automatic transmission with relatively slow gear changes of up to 800 ms (mainly due to hydraulic delay during clutch filling), there exist certain situations which are critical for the haulers, where you for instance want to avoid start-ups at relatively high uphill slopes. These critical driving situations will be described more in detail below.

- *Startup at a relatively high slope:* The articulated hauler should start up directly at very high slope in order to investigate and optimize the lock up control. It is also possible to test the maximum climbing performance in this situation.

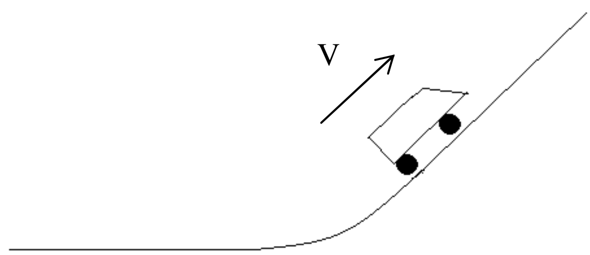

Figure 10 – Start-up at a high slope

- *Horizontal road followed by an uphill slope:* The articulated hauler should start or being driving on a horizontal road followed by an uphill slope with a high gradient. In this case the downshift of the automatic transmission can be investigated and later on optimized.

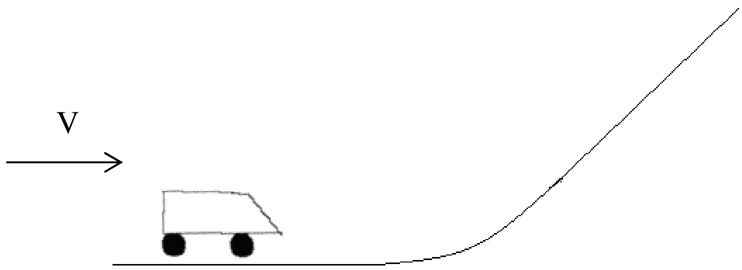

Figure 11 - Horizontal road followed by an uphill

- *Downhill slope followed by an uphill slope:* The articulated hauler should drive on a downhill slope which is then followed by an equally uphill slope. In this driving situation lock up control and downshift can be analyzed and later on be optimized.

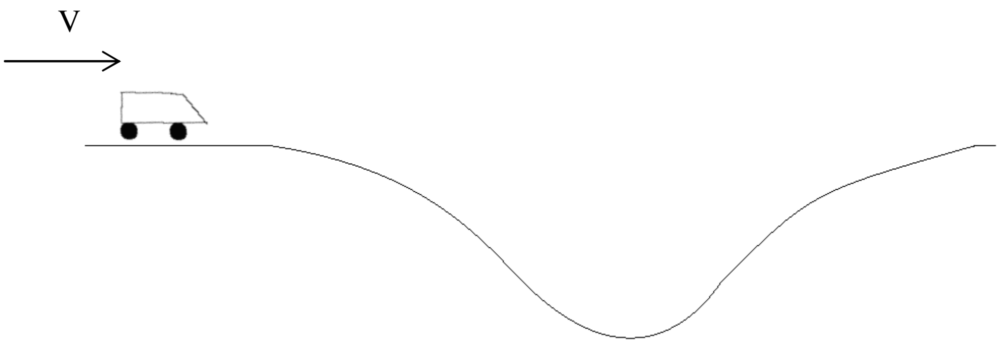

Figure 12 - Downhill slope followed by uphill slope

- *Several minor uphill/downhill slopes after each other:* The articulated hauler should drive on these several smaller uphill and downhill slopes with higher gradients. This critical driving situation n could for instance simulate going in mud.

Figure 13 - Several uphill and downhill slopes after each other

- *Startup in reverse gear at a relatively high slope:* This critical driving situation is similar to the first one. The only difference here is the hauler is driving in reverse gear.

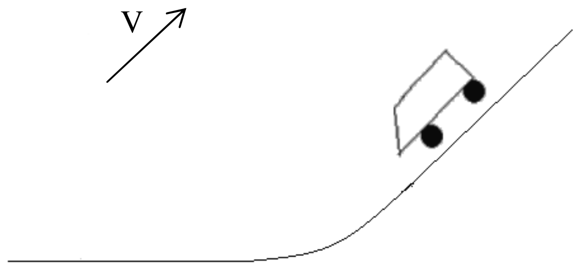

Figure 14 – Start-up in reverse gear

- *Driving with reverse gear into an uphill slope:* This critical driving situation is similar to the second case. The difference here is that the hauler is driving in reverse gear.

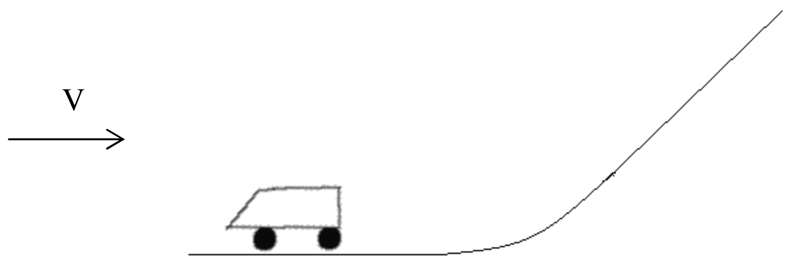

Figure 15 - Driving in reverse gear followed by an uphill slope

4 Measurements on a vehicle

To get a deeper understanding of how the gear shifting process works, measurements on a Saab 9-5 were conducted.

Table 3 - Technical data of the Saab 9-5 Aero

Model	Saab 9-5 Aero, Model year 2001
Displacement	2.3 Liter
Horsepower	230 bhp (169 kW) at 5500 rpm
Torque	350 Nm at 1900 rpm
0-100 km/h acceleration	7,3 seconds
Gearbox	4-speed planetary automatic transmission with torque converter and lockup clutch

The Saab 9-5 Aero is equipped with a 4-speed automatic gearbox with a torque converter and lockup clutch. In order to analyze signals, a CANcaseXL box was installed in the vehicle which is connected to the low- and high-speed CAN bus of the vehicle. The software Vector CANalyzer communicates with the CANcaseXL box and a minor database file was established, which defines and names the signals in the right way in order to allow the software to identify the signals correctly.

If a measurement is traced in the CANalyzer software, the trace of a measurement is shown in ***Figure 16***.

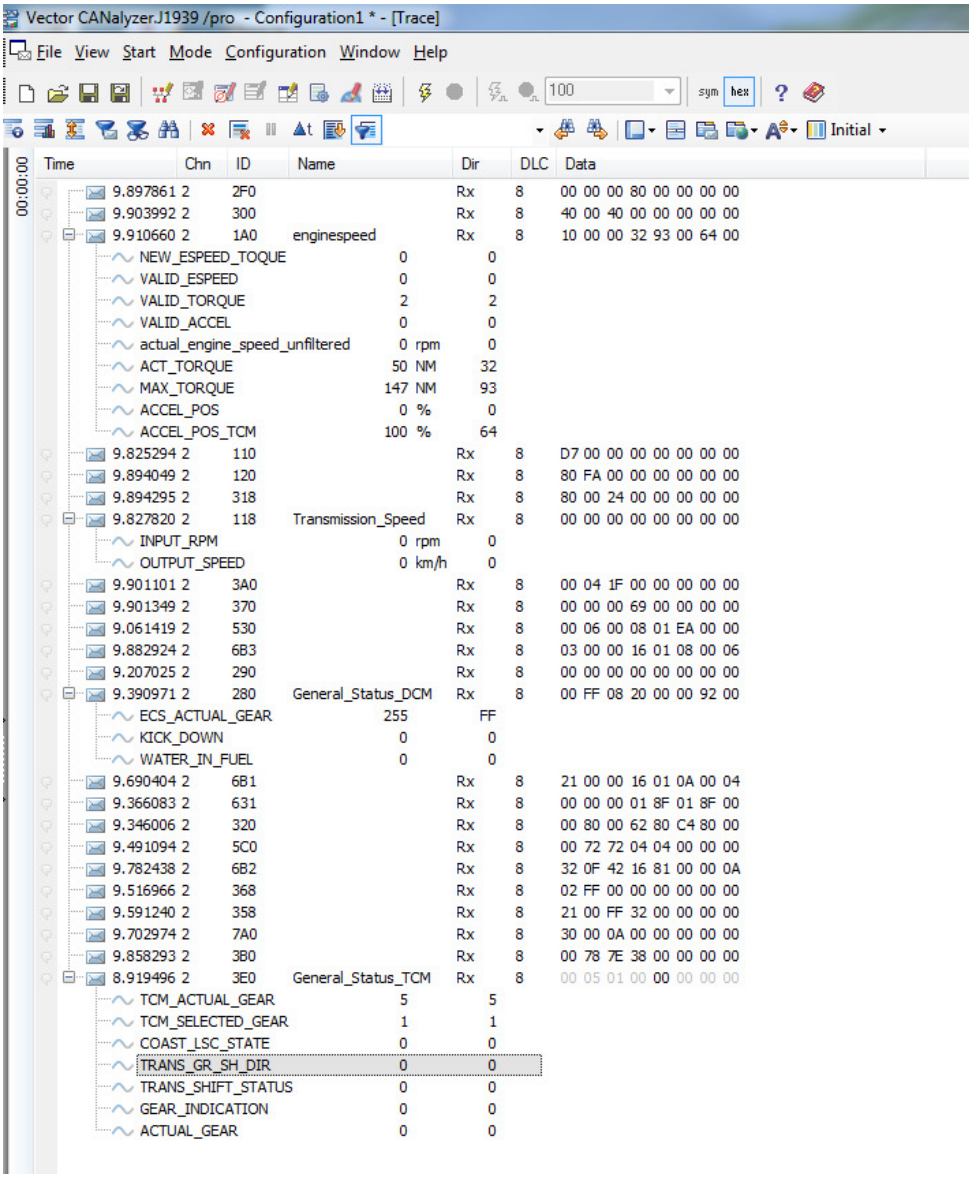

Figure 16 - Trace of a measurement

In the figure above, under each frame, i.e. *General_Status_TCM*, all the signal which belong to this frame can be seen here.

The objective of this thesis is to develop gear shift algorithms that support the driver in critical driving situations for articulated haulers. The purpose of the establishing and analyzing the measurements is to get a deeper understanding of the behavior of gear shift schedules for passenger vehicles looks like and even to get a deeper understanding of the gearbox and shift process.

4.1 Results and discussion

In order to create a gear shift schedule the vehicle was accelerated with different accelerator positions, i.e. 0%, 10%, 20%, …, 100%. To be able to get downshift points, the vehicle was slowed down, i.e. driven on a steep uphill road with different accelerator pedal positions. Due to the lack of a steep uphill it was only possible to conduct measurements for downshifts up to an accelerator position of 20 %. The gear shift schedule for the Saab 9-5, is shown in ***Figure 17***.

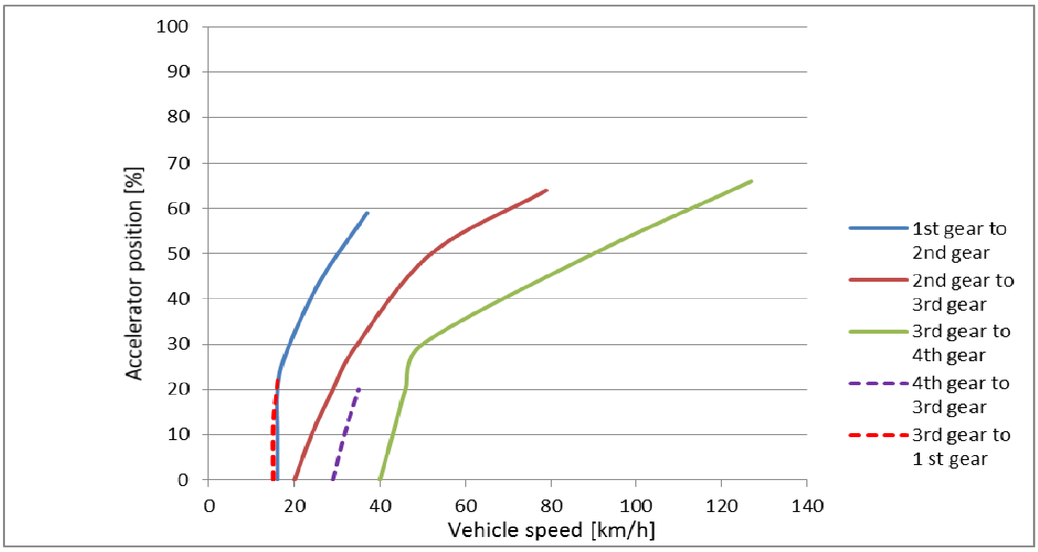

Figure 17 - Gear shift schedule for a Saab 9-5 2.3t

As one can notice, the Saab in general never during the test shifted down from the 3rd to the 2nd gear. Only in the case of deceleration with an accelerator pedal position of 20% the Saab shifted down from 3rd to the 2nd gear once. An explanation for that could either be that the Saab engineers at that time, when the gearbox and shift strategy was developed, decided because of small gear ratio steps to downshift from 3rd to the 1st gear as often as possible. Another explanation could be because of the age and mileage of the vehicle, something could be damaged in the gearbox and that is why the gearbox almost always shifts down from 3rd to the 1st gear. A last explanation could also be that the driving resistance force is so low that the 3rd gear has sufficient torque at low loads and therefore there is no need to downshift from 3rd to the 2nd gear. Regarding the lock-up strategy, as the 4 speed automatic transmission it already indicates, the Saab 9-5 is an older vehicle from 2001. For vehicles nowadays it is beneficial to drive with lock-up quite early (low speed or low accelerator pedal positions) in order to minimize the fuel consumption. A typical lock-up strategy for a modern vehicle is shown in ***Figure 18***.

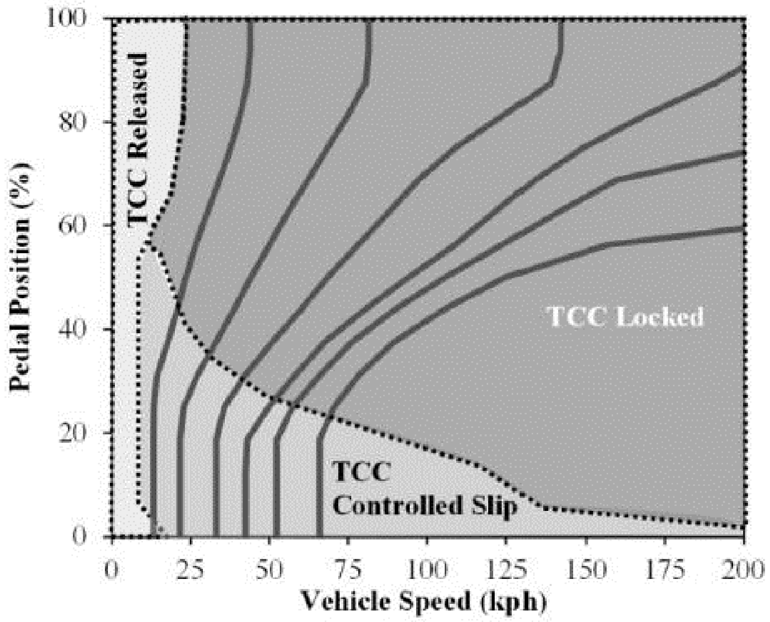

Figure 18 - Modern lock-up strategy (A Dual Clutch Torque converter for Dual Input Shaft Transmissions)

In the case of the Saab 9-5, only two times the Saab drove with lock-up, this was in the case with an accelerator pedal position of 70% for the 3rd gear. In ***Figure 19*** where TCM_ACTUAL GEAR is equal to 11, the 3rd gear was driven with lock up (red arrow).

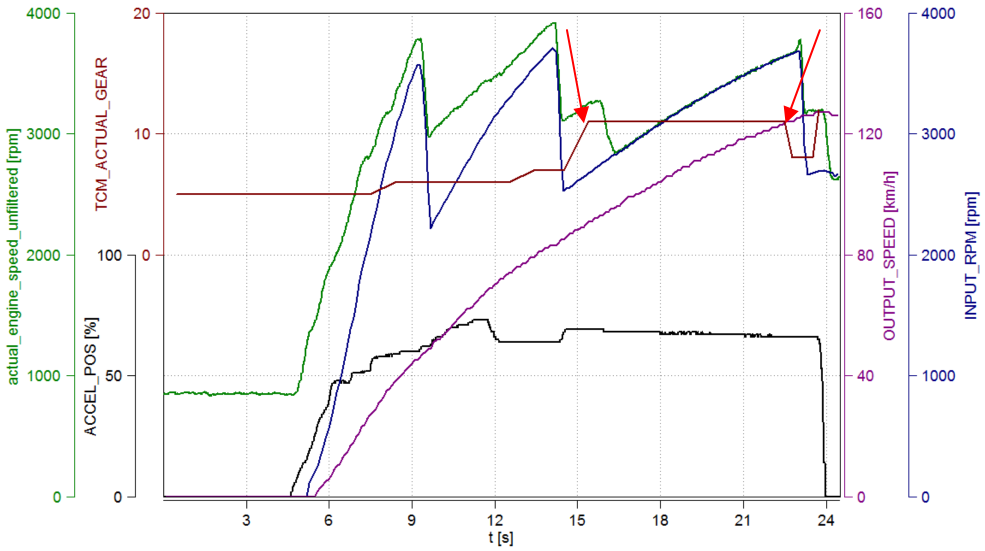

Figure 19 – Example of a measurement with an accelerator position of 70%

In the second case, with an accelerator pedal position of 50% the 4th gear is driven with lock-up (where TCM_ACTUAL_GEAR is equal to 12) from about 100 km/h (red arrow), which can be seen in ***Figure 20***.

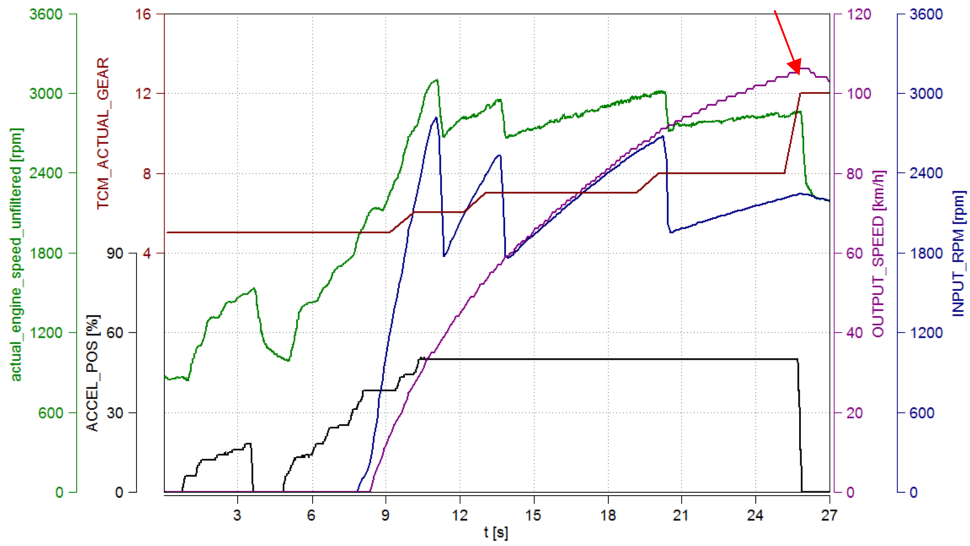

Figure 20 – Example of a measurement with an accelerator position of 50%

If you compare the lock-up strategy of modern passenger vehicles, which was shown in ***Figure 18*** compared to the 2 cases where the Saab drove with lock-up one can notice that the Saab only drives on lock-up at higher vehicle speeds and accelerator pedal positions. One reason for that could be that the automatic transmission only consists of 4 gears, so if you would drive on lock-up at lower vehicle speeds or lower accelerator pedal positions, there could be Noise, Vibration and Harshness (NVH) problems, which is a comfort and quality issue and could give the driver a negative feeling. A second explanation why the Saab only drives on lock-up at higher speeds or accelerator pedal positions could be that the vehicle and driveline was developed in the mid-1990s and at that time the focus wasn't put on fuel efficient vehicles like it is done today. Legislations weren't that sharp at that time compared to nowadays. If you take a look on all measured accelerator pedal positions for upshifts (see Appendix B), almost always when the accelerator pedal position was kept constant, the shifting was almost always performed at the same turbine speed (INPUT_RPM). Modern automatic gearboxes today are mostly equipped with at least 6 forward gears but there exists for instance also gear boxes which are equipped with 9 gears, i.e. the Range Rover Evoque (Green Car Congress 2012).

4.2 Kick-down

Almost all automatic transmissions are having a kick-down function, which means that the driver can force the transmission, within certain boundaries to shift down. This is normally done via pressing full throttle or there is a sort of switch at 80-90 % of pressing the full throttle, so by passing that limit the transmission shifts down. The control unit of the gearbox then gets a signal to shift down to the lowest possible gear.

Of course a certain pedal rate is also required, a slowly increase of the pedal to 80-90% of full throttle won't result in a kick down.

4.3 Different gear shifting maps

Most of the modern automatic transmissions are equipped with different gear shifting maps or gear shifting programs the driver can choose between. The 3 most common are Eco-mode, Winter-mode and Sport-mode. In the first one, the Eco-mode, the gearbox shifts up earlier in order to save fuel. The Sport-mode though works in the opposite way compared to the Eco-mode. Here the gear shifting points are chosen for maximum acceleration. The Winter-mode chooses gears with higher gear ratios, which means it choses for instance the 2^{nd} gear for a start off. While using the 2^{nd} for a start off the output shaft speed of the transmission is kept down for a longer time which prevents tires from slipping on snowy and icy road conditions.

4.4 Manual mode

Nowadays automatic transmissions also can be shifted "manually" by the driver. Sport car brands for instance also offer their customers to shift the gears via paddles on the steering wheel, like you are doing it in the formula 1.

5 Modeling and simulation

This section describes the how gear shift schedule algorithms have been designed.

5.1 "Original" gearshift

The "original" gearshift schedule from the beginning in the model of the AVL Cruise software is only a simple rpm controlled gear shift schedule, with no gear shift times at all. This means when the control algorithm reaches the rpm to shift, the gear shift is done immediately with no time delay. Because of that gears are shifted all the time especially when the hauler is driving at critical point where it shifts down and then accelerates again and immediately shifts again etc. so to say infinite gear shifts are possible. Even though it sounds "perfect" with no gear shift times at all, it is not realistic and a gear shift process with gear shift times needs to be implemented.

5.2 Inclination shift strategy

The approach of this gear shift schedule is to vary the gear shifting point depending on the actual road inclination the articulated hauler is driving on, which is similar to the system Volvo uses on their trucks. This gear shift schedule algorithm uses an inclination sensor as an input to the gear shift schedule algorithm.

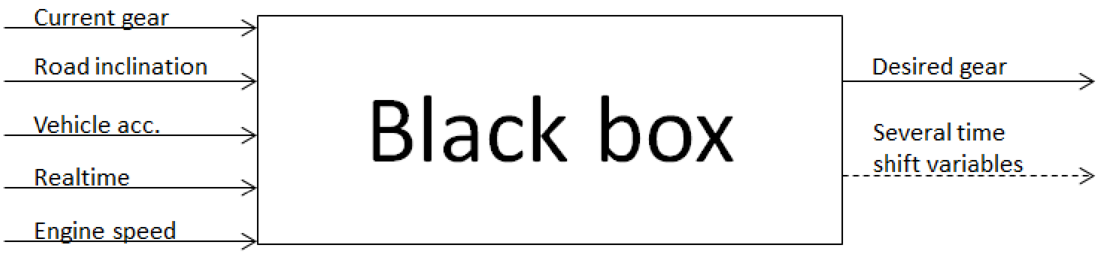

Figure 21 - Black box inclination shift

This gear shift schedule algorithm uses the following parameters as an input:

- Current gear [-]
- Real time [s]
- Vehicle acceleration [m/s^2]
- Road inclination [%]
- Output speed of the gearbox [rpm]

With these five input variables the gear shift schedule algorithm varies the shifting points depending on the actual road inclination of the articulated hauler. The output variables are therefore:

- Desired gear [-]

- Several time shift variables.

The output *Several time shift variables* is only being used for programming purposes, in order to make the gear shift process more realistic, so technically they aren't real outputs.

5.3 Gear shifting "area" (Base shift schedule)

If you take a closer look at ***Figure 22*** below, you can notice that the vehicle has its maximum Torque of 2525 NM at 1050 rpm and its maximum power at 1800 rpm, which was already mentioned in section 1.3.

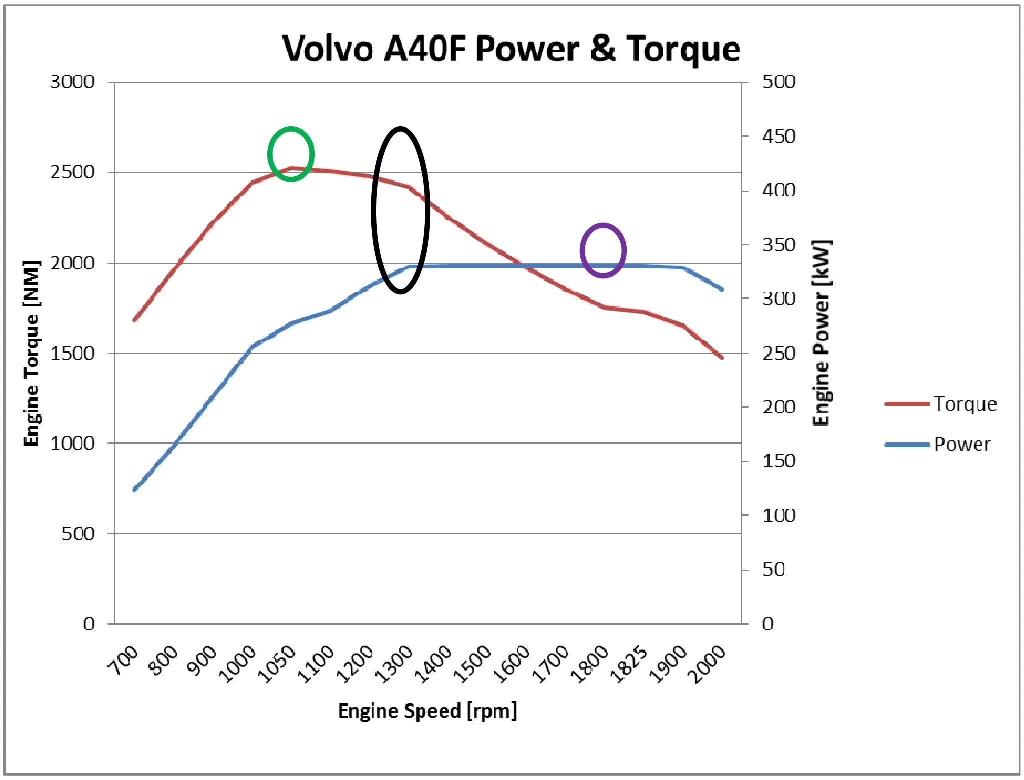

Figure 22 - Gear shift areas

In order to, for instance, avoid startups from standstill at high road inclinations one way could be to take as much speed with you up the hill as possible. From the literature study it is known that the *Engine speed shift strategy* shift at very high engine speed and therefore one strategy could be to choose gear shifting point at or close to maximum engine power (purple circle). A second strategy could be, in order to save fuel, to choose gear shifting points at or close to the maximum torque (green circle). Another interesting thing, the engine almost has its maximum power at 1300 rpm where at the same time the engine still is having around 95 % of its maximum torque (black circle). Summarized there are also 3 base gear shift schedules, an area with high torque, relatively high torque and high power and only an area with high power. Instead of just looking at the power and torque graph it also could be interesting to look at the specific fuel consumption to see where the engine is running with the highest efficiency.

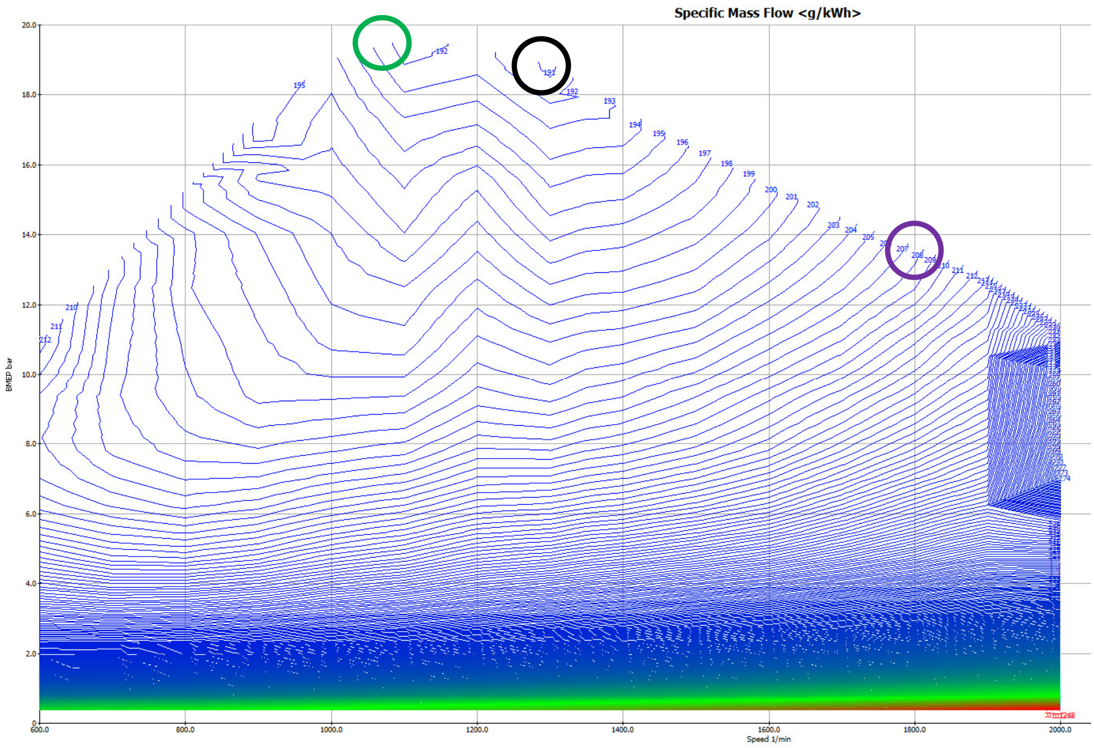

Figure 23 - Specific fuel consumption of the Volvo D16 engine for the articulated hauler

For the green area, where the engine is producing the maximum torque, the specific mass flow of fuel is 193 g/kWh. The black area, where the engine still is producing 95 % of its maximum torque and almost maximum power the specific mass flow of fuel is 191 g/kWh. For the purple area where the engine produces the maximum power of 350 kW at 1800 rpm the specific mass flow is 208 g/kWh. By looking at the specific mass flow values it would be beneficial in terms of fuel consumption, to be in the black area where the specific mass flow is at its lowest.

5.4 Algorithm for new gear shift points

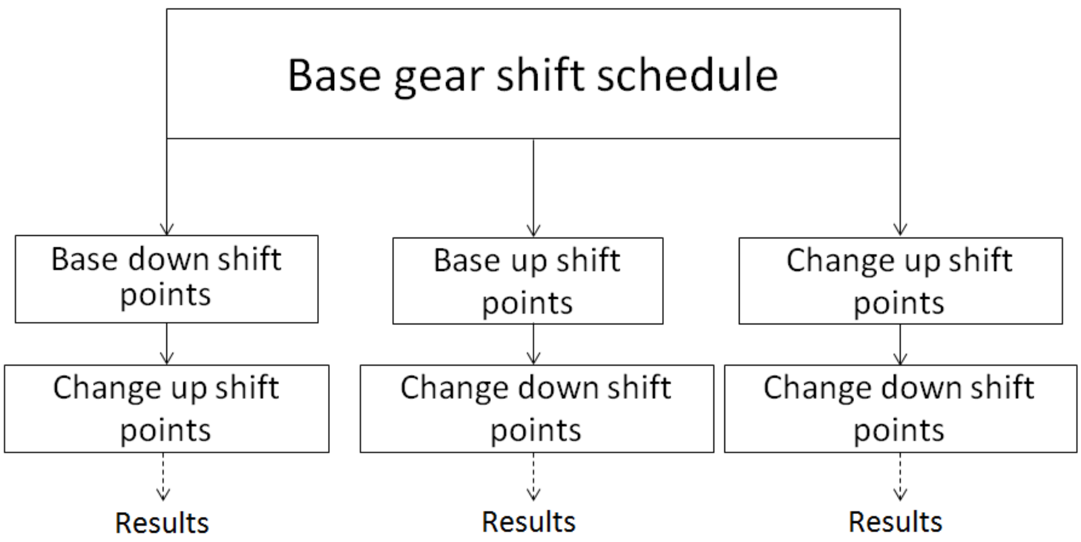

Figure 24 - Algorithm for choosing new gear shift points

With the matrix simulation the software Cruise offers, it is possible to enter multiple gear shifting points and the run the simulation for each variation separately. The next step is then to analyze all results in terms of total travelling time versus the fuel consumption.

5.5 Inclination criteria

Regarding the critical inclination points, where the gear shifting points will vary, the downshift inclinations are more important than the upshift, because no critical driving scenarios are downhill. Due to the fact that the articulated hauler is heavily loaded, more than 60 tons, the vehicle won't be able to accelerate at for instance at an inclination of 15 %. For upshifts negative inclinations (downhill roads) are rather important. For downshift of course, positive inclinations are important because the vehicle probably won't shift down while accelerating downhill.

6 Results

This chapter describes all the results which have been established with the inclination shift strategy. More detailed results (graphs etc.) are attached in the appendices section.

6.1 Inclination Shift

With the algorithm, described in section 5.4 and the base shift schedule described in 5.3 and by running several matrix simulations, 8 new shift schedules were established.

6.1.1 Inclination Criteria

For the inclination gear shift schedule, varying the gear shifting point at different road inclinations is very important. By looking at the different tracks and their inclinations (see Appendix D), there are quite a lot of inclinations around 7% to 11%. Simulations have shown that the difference at low inclination, around 4-11 %, doesn't need different gear shift points. The difference in inclination from 8-14 % does affect the shifting performance as well as the fuel consumption and travelling time. Therefore the first gear shifting criteria inclination was chosen via data driven decision to an inclination of 12 %. For high inclinations, the critical inclination was set via data driven decisions, to 35 %.

6.1.2 Analysis of Simulations

For the base shift schedule (figure 21, green area) it is not possible to have shifting points at maximum toque at 1050 rpm. If the vehicle would shift at 1050 rpm the engine rpm for the next gear would be so low that the vehicle would drive without lockup which results in bad fuel consumption as well as travelling time. So for the base shift schedule *High torque* the shifting points are over 1050 rpm.

These 8 gear shift schedules can be assigned to the 3 base gear shift schedules:

- High rpm (purple area): Here downshift and upshift points are kept in such a way that shifting is done at or close to the maximum power, like the *Engine Speed Shift Strategy* is doing it (*h-rpm1, h-rpm2, h-rpm3, h-rpm4)*

- Smooth area: In this area the engine power is still high while the torque available is sufficient enough compared to the *High rpm* case above (*s-Trpm1, s-Trpm2*).

- High Torque: This case is similar to the *Smooth area*, the difference is that the gear shifting point are lower which results in more torque available compared to the *Smooth area* (*h-T1, h-T2).*

In order to evaluate the 8 different gear shift schedules, they have been tested on 9 different tracks. A short description of the tracks can be seen in ***Table 4***. A more detailed description of the tracks can be seen in Appendix E.

Table 4 - Short description of the tracks

Name	Length [m]	Max. Inclination [%]	Min. Inclination [%]
Test track	1620	40	-40
Målajord Provbana 2x Vänstervarv	2493.8	19.047	-20.63
Målajord Provbana Vänstervarv	1168.8	24.19	-17.74
Målajord Provbana 2x Högervarv	2493.8	20.63	-19.04
Målajord Provbana 3 Vänstervarv	2150	20.63	-22.22
Målajord Provbana 45 upp	681.3	20.63	-16.5
Målajord Provbana 45 ner	681.3	16.66	-20.79
Målajord Provbana 67 upp	1200	19.04	-11.11
Målajord Provbana 89 Öster	262.5	6.45	-11.11

For the first track the results, travelling time versus fuel consumption can be seen in ***Figure 26***.

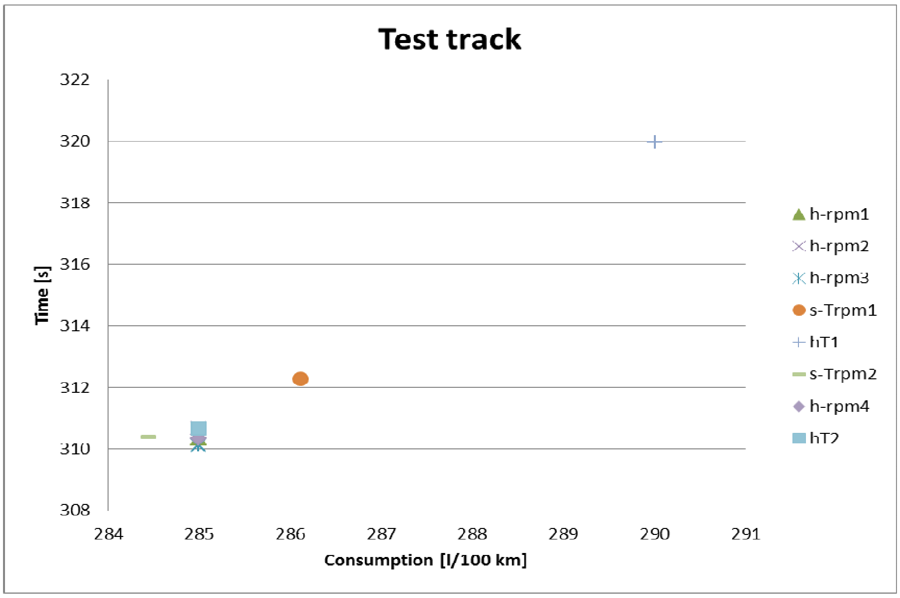

Figure 25 - Test track results

On the *Test track* the gear shift schedule s-Trpm2 consumes the least amount of fuel but on the other hand, the gear shift schedule h-rpm3 is the fastest one.

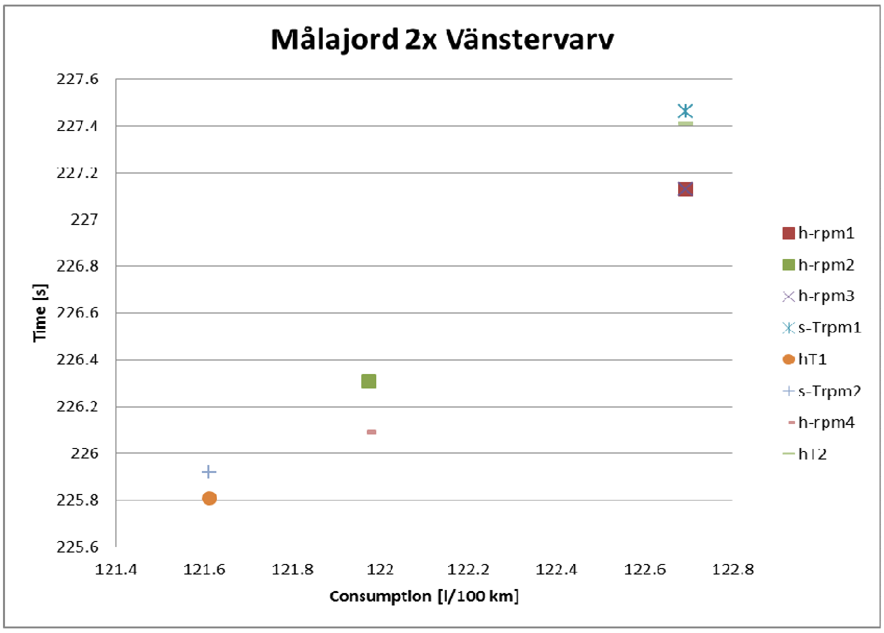

Figure 26 - Målajord Provbana 2x Vänstervarv results

On the second track the gear shift schedule hT1 is the fastest one and together with s-Trpm1 they consume the least amount of fuel.

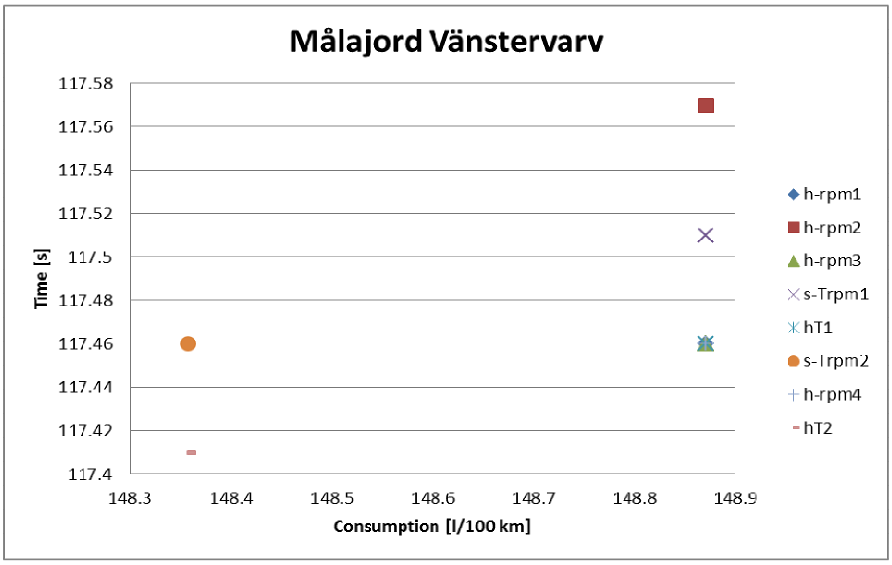

Figure 27 - Målajord Provbana Vänstervav results

At the *Målajord Vänstervarv* track hT2 is clearly the fastest and consumes the least amount of fuel. The gear shift schedule s-Trpm2 consumes the same amount of fuel as hT2 but is a little bit slower.

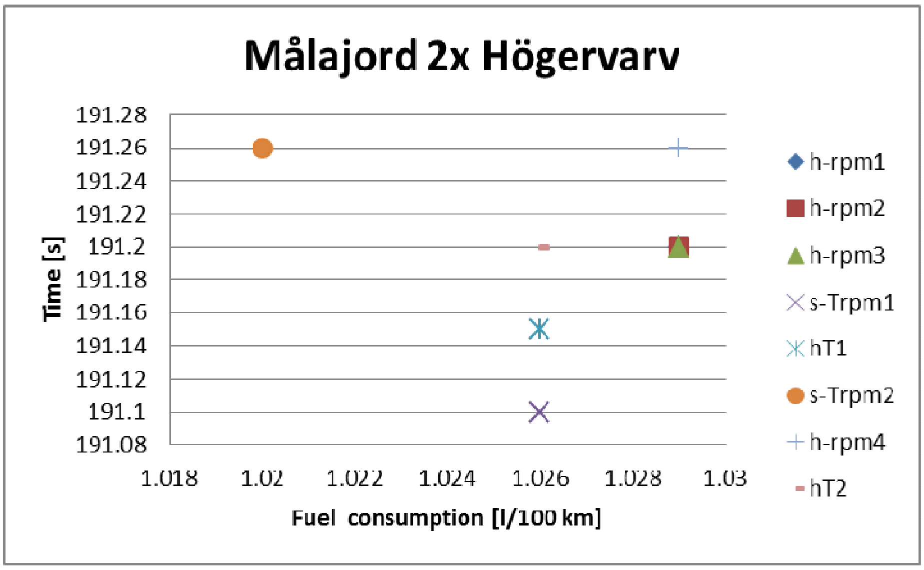

Figure 28 - Målajord 2x Högervarv results

For the *Målajord 2x Högervarv* track s-Trpm2 consumes the least amount of fuel again, but the fastest gear shift schedule is s-Trpm1.

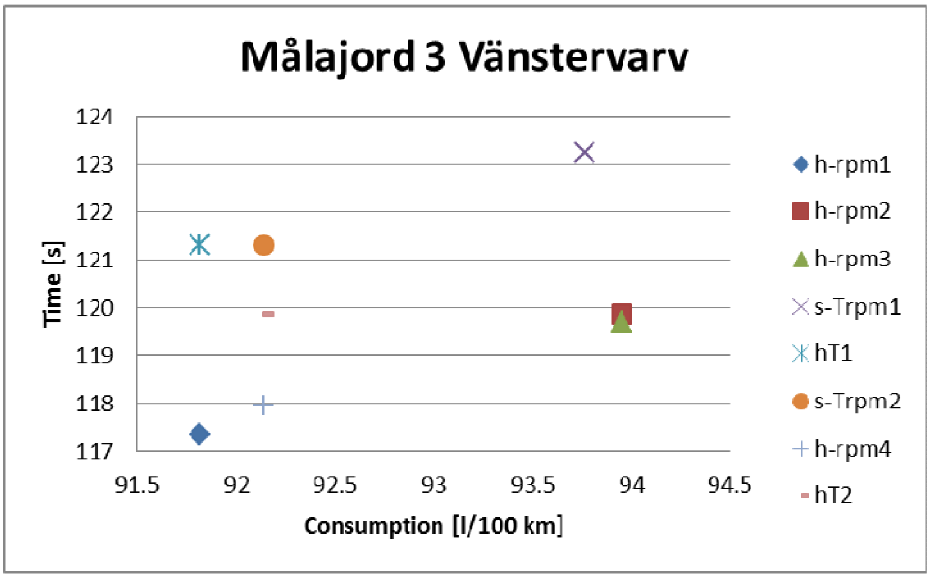

Figure 29 - Målajord 3 Vänstervarv results

For the *Målajord 3 Vänstervarv* track the travelling's times differs quite a lot like on the *test track*t. The gearshift schedule h-rpm1, which shifts at high rpm (maximum power) is clearly the fastest one and surprisingly consumes together with hT1 the least amount of fuel.

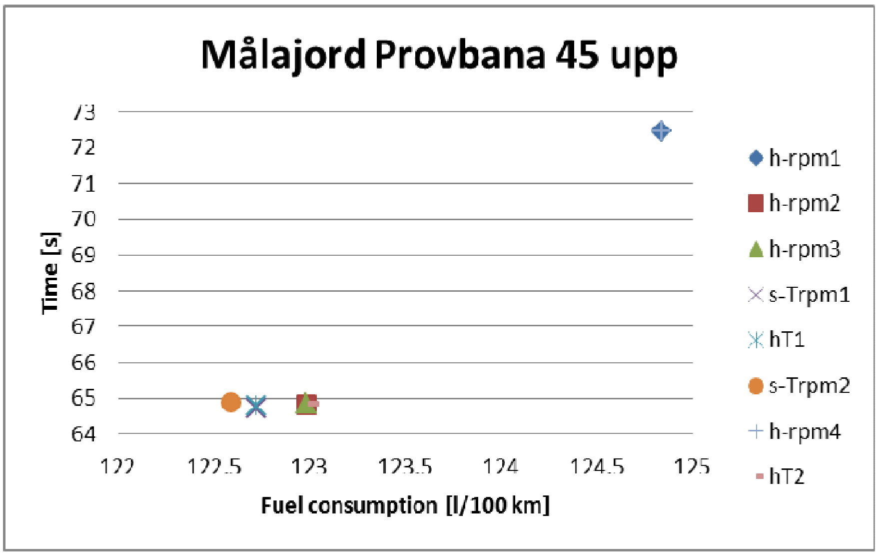

Figure 30 - Målajord Provbana 45 upp results

At the *Målajord Provbana 45 upp* s-Trpm2 consumes the least amount of fuel and is almost as fast hT1.

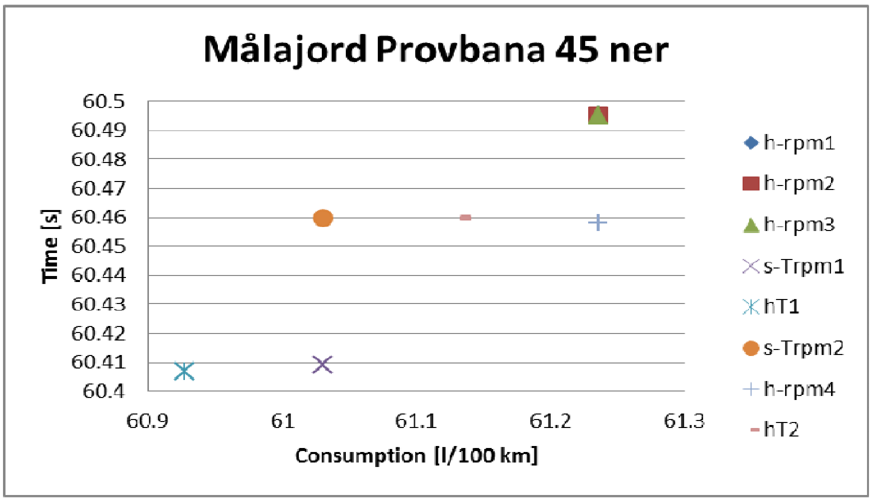

Figure 31 - Målajord Provbana 45 ner results

On the same track again but going downhill instead, hT1 is best gear shift schedule because it consumes the least amount of fuel and is the fastest one.

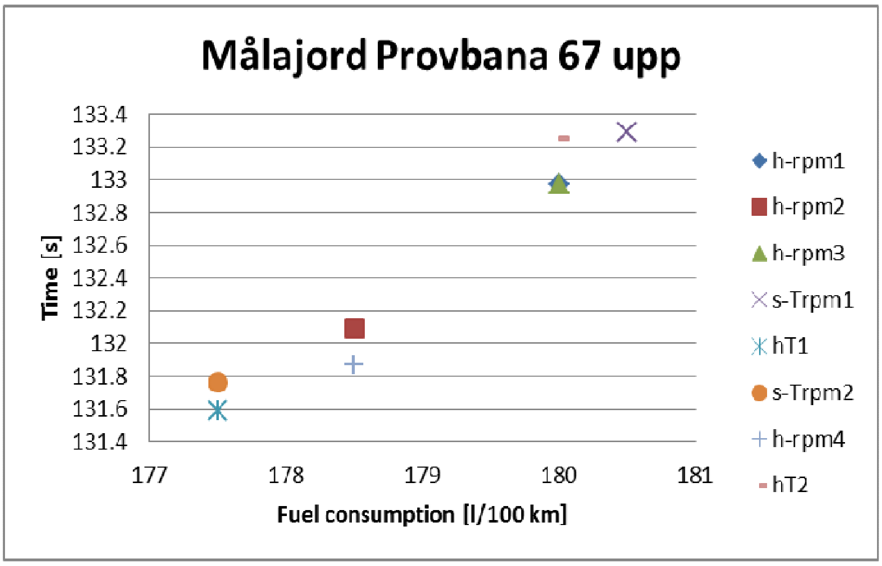

Figure 32 - Målajord Provbana 67 upp results

At the *Målajord Provbana 67* hT1 and s-Trpm2 consumes together the least amount of fuel but hT1 is a little bit faster than s-Trpm2.

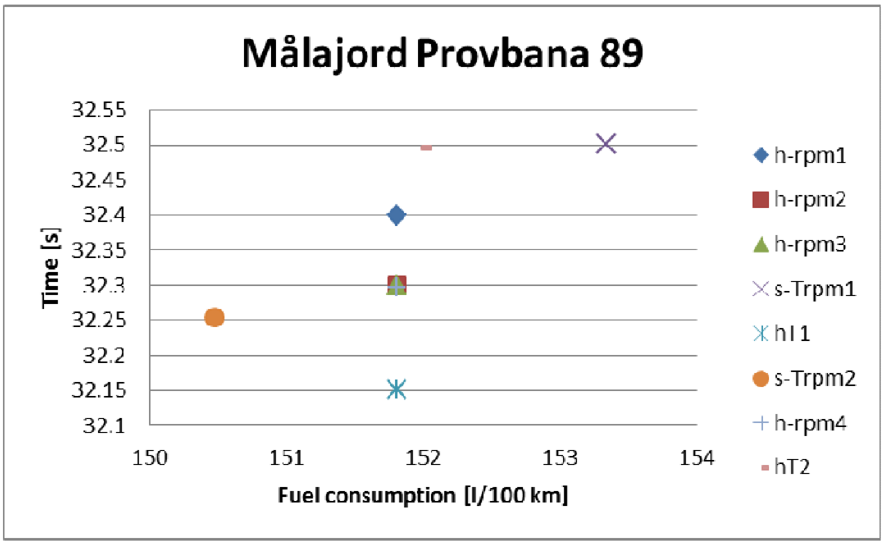

Figure 33 - Målajord Provbana 89 results

At the last track *Målajord Provbana 89* s-Trpm2 consumes the least amount of fuel but on the other hand hT1 is a little bit faster than s-Trpm2.

6.1.3 Evaluation

From the results in the section above, the gear shift schedule hT1 and s-Trmp2 were mentioned several times. In order to evaluate them and find the "best" one all gear shift schedule have been analyzed against each other in terms of travelling time and fuel consumption. Green marked values represent the lowest fuel consumption or fastest travelling time. Red marked values represent the highest fuel consumption or highest travelling time.

Table 5 - Fuel consumption results

Fuelconsumption (l/100 km)								
Track/Name	h-rpm1	h-rpm2	h-rpm3	s-Trpm1	hT1	s-Trpm2	h-rpm3	hT2
Testbana	285	285	285	286.11	290	284.44	285	285
Målajord - Provbana 2x Vänstervarv	122.69	121.97	122.69	122.69	121.61	121.61	121.97	122.69
Målajord - Provbana Vänstervarv	148.8706	148.8706	148.8706	148.8706	148.8706	148.3573	148.8706	148.3573
Målajord - Provbana 2x Högervarv	88.03901	88.03901	88.03901	87.78234	87.78234	87.26899	88.03901	87.78234
Målajord - Provbana 3 - Vänstervarv	91.81395	93.95349	93.95349	93.76744	91.81395	92.13953	92.13953	92.13953
Målajord - Provana 45 Upp	124.8349	122.9855	122.9855	122.7213	122.7213	122.5892	124.8349	123.0001
Målajord - Provana 45 Ned	61.23587	61.23587	61.23587	61.03038	60.92764	61.03038	61.23587	61.13313
Målajord - Provana 67 Upp	180	178.5	180	180.5	177.5	177.5	178.5	180
Målajord - Provana 89 Öster	151.8095	151.8095	151.8095	153.3333	151.8095	150.4762	151.8095	152
Mean consumption	156.7867	156.5455	156.823	157.1007	156.6294	155.6764	156.5499	156.5128
Placement	6	3	6	8	5	1	3	2
Median consumption	124.8349	122.9855	122.9855	122.7213	122.7213	122.5892	124.8349	123.0001
Placement	7	4	4	2	2	1	7	6

Just by looking at the numbers it can be noticed that *s-Trpm2* consumes at 6 tracks the least amount fuel. The gear shift schedule hT1 consumes least amount of fuel at 3 tracks. The big disadvantage the gear shift schedule hT1 has though is that it is the worst gear shift schedule in terms of fuel consumption at the test track, with high road inclination.

Table 6 - Fuel consumption results in rankings

Fuel consumption (l/100 km)								
Track/Name	h-rpm1	h-rpm2	h-rpm3	s-Trpm1	hT1	s-Trpm2	h-rpm3	hT2
Testbana	2	2	2	7	8	1	2	2
Målajord - Provbana 2x Vänstervarv	5	3	5	5	1	1	3	5
Målajord - Provbana Vänstervarv	3	3	3	3	3	1	3	1
Målajord - Provbana 2x Högervarv	5	5	5	2	2	1	5	2
Målajord - Provbana 3 - Vänstervarv	1	7	7	6	1	3	3	3
Målajord - Provana 45 Upp	7	4	4	2	2	1	7	6
Målajord - Provana 45 Ned	6	6	6	2	1	2	5	4
Målajord - Provana 67 Upp	5	3	5	8	1	1	3	5
Målajord - Provana 89 Öster	2	2	2	8	2	1	2	7
Mean placement	4.5	4.375	4.875	5.375	2.625	1.5	4.125	4.375
Placement	6	4	7	8	2	1	3	4

Even though h-rpm3 seem to rank as third it consumes the most fuel at 3 tracks. If you now take a look at the travelling time, which can be seen in ***Table 7*** & ***Table 8*** below, s-Trpm2 has a good mean travelling time which makes this gear shift schedule the second fastest although it is not the fastest on any track.

Table 7 - Travelling time results

Time (seconds)								
Track/Name	h-rpm1	h-rpm2	h-rpm3	s-Trpm1	hT1	s-Trpm2	h-rpm3	hT2
Testbana	310.34	310.67	310.12	312.27	319.97	310.4	310.34	310.67
Målajord - Provbana 2x Vänstervarv	227.13	226.31	227.13	227.46	225.81	225.92	226.09	227.41
Målajord - Provbana Vänstervarv	117.46	117.57	117.46	117.51	117.46	117.46	117.46	117.41
Målajord - Provbana 2x Högervarv	191.2	191.2	191.2	191.1	191.15	191.26	191.26	191.2
Målajord - Provbana 3 - Vänstervarv	117.35	119.88	119.71	123.23	121.31	121.31	117.95	119.88
Målajord - Provana 45 Upp	72.47	64.83	64.836	64.72	64.787	64.89	72.471	64.844
Målajord - Provana 45 Ned	60.495	60.495	60.495	60.409	60.407	60.46	60.458	60.46
Målajord - Provana 67 Upp	132.97	132.09	132.97	133.29	131.59	131.76	131.87	133.25
Målajord - Provana 89 Öster	32.4	32.3	32.3	32.501	32.151	32.254	32.296	32.496
Mean time	157.7269	156.9181	157.0276	157.8113	158.0794	156.9643	157.5244	157.2025
Placement	6	1	3	7	8	2	5	4
Median	117.46	119.88	119.71	123.23	121.31	121.31	117.95	119.88
Placement	1	4	3	8	6	6	2	4

The gear shift schedule hT1 is the fastest gear shift schedule at 3 tracks, but still has the disadvantage to be really slow at the test track with high road inclinations. If you now take a look at the rankings, ht1 is the fastest one, but still the slowest one the test track.

Table 8 - Travelling time rankings

Time (seconds)								
Track/Name	h-rpm1	h-rpm2	h-rpm3	s-Trpm1	hT1	s-Trpm2	h-rpm3	hT2
Testbana	5	5	1	7	8	4	2	5
Målajord - Provbana 2x Vänstervarv	5	4	5	8	1	2	3	7
Målajord - Provbana Vänstervarv	2	8	2	7	2	2	2	1
Målajord - Provbana 2x Högervarv	3	3	3	1	2	7	7	3
Målajord - Provbana 3 - Vänstervarv	1	4	3	8	6	6	2	4
Målajord - Provana 45 Upp	7	3	4	1	2	6	8	5
Målajord - Provana 45 Ned	6	6	6	2	1	4	3	4
Målajord - Provana 67 Upp	4	4	4	8	1	2	3	7
Målajord - Provana 89 Öster	4	4	4	8	1	2	3	7
Mean placement	4.625	5.125	4	6.25	3	4.375	4.125	5.375
Placement	5	7	2	8	1	4	3	6

The two gear shift schedules hT1 and s-Trpm2 seems to be the most promising ones. In order to make a conclusion which one of these two is the "best" one, they will be compared to each other in a Pugh matrix. Although the gear shift schedule h-rpm3 seems to be a good one as well, this gear shift schedule has not been taken to account because it is slowest on 2 tracks and consumes the most amount of fuel at 3 tracks.

Table 9 - Criteria

Criterias / respect to	Time (s)	Fuel consumption (l/100 km)
---	over 5 seconds	over 5 l/100 km
--	over 0.5 and below 5 secons d	over 1 and below 5 l/100 km
-	below 0.5 seconds	under 1 l/100 km
+++	over 5 seconds	over 5 l/100 km
++	over 0.5 and below 5 seconsd	over 1 and below 5 l/100 km
+	below 0.5 seconds	under 1 l/100 km
0	Same	Same

The criteria's for the Pugh matrix can be seen in ***Table 9***.

Table 10 - Pugh matrix, s-Trpm2 as reference with respect to traveling time

Time (seconds)		
Track/Name	s-Trpm2	hT1
Testbana	R	---
Målajord - Provbana 2x Vänstervarv	E	+
Målajord - Provbana Vänstervarv	F	0
Målajord - Provbana 2x Högervarv	E	+
Målajord - Provbana 3 - Vänstervarv	R	0
Målajord - Provana 45 Upp	E	+
Målajord - Provana 45 Ned	N	+
Målajord - Provana 67 Upp	C	+
Målajord - Provana 89 Öster	E	+
Sum		3x "+"

If the gear shift schedule s-Trpm2 is used as reference compared to the gear shift schedule hT1 with respect to traveling time, hT1 is better. The disadvantage hT1 has, which has been mentioned before, is still that hT1 is the slowest gear shift schedule at the test track which contains high road inclination.

Table 11 - Pugh matrix, s-Trpm2 as reference with respect to fuel consumption

Fuel concumption (l/100 km)		
Track/Name	s-Trpm2	hT1
Testbana	R	---
Målajord - Provbana 2x Vänstervarv	E	0
Målajord - Provbana Vänstervarv	F	-
Målajord - Provbana 2x Högervarv	E	-
Målajord - Provbana 3 - Vänstervarv	R	+
Målajord - Provana 45 Upp	E	-
Målajord - Provana 45 Ned	N	+
Målajord - Provana 67 Upp	C	-
Målajord - Provana 89 Öster	E	--
Sum		7x "-"

7 Discussion and recommendation

This last chapter will discuss the results obtained, discuss about the inclination shift in general as well as give some recommendations.

7.1 Discussion of Results

From Table 5 and Table 6 it is already know that the gear shift schedule s-Trpm2 consumes the least amount fuel, so there no surprise that the gear shift schedule hT1 is the worse compared to s-Trpm2 in terms of fuel consumption.

Due to the fact that only 2 gear shift schedules are compared to each other, putting the gear shift schedule hT1 as reference, would just give the opposite results. From the Pugh matrix it is now known that the gear shift schedule s-Trpm2 is much better in terms of fuel consumption and that hT1 is a little bit faster with respect to traveling time. The gear shift schedule hT1 though has the huge disadvantage of being slowest at the test track with high road inclinations as well as having pretty high fuel consumption at that test track as well. If one would ignore the results of the test track, the gear shift schedule hT1 would then have a mean travelling time of 118.0831 seconds compared to 118.1643 seconds for the s-Trpm2 shift schedule. For the fuel consumption, hT1 is having a mean consumption of 120.3794 liter/100 km compared to 120.1214 liter/100 km for the s-Trpm2 shift schedule. As one can see the differences are quite small.

As the purpose of this master thesis is to work out a gear shifting strategy that support the driver in critical driving situations (for instance described in section 2.2) which the test track does and because the gear shift schedule ht1 doesn't perform well on the *test track*, both in terms of fuel consumption and traveling time compared the gear shift schedule s-Trpm2 which has the best fuel consumption on most of the tracks, therefore the best solution for a gear shift strategy which supports the driver in critical driving situations is the s-Trpm2 gear shift schedule. Although the gear shift schedule ht1 is faster, just by looking at the numbers, s-Trpm2 is only at a maximum around 0.3 seconds slower.

The gear shift times, which have been measured to 800 ms for downshifts and 600 ms for upshifts by AVL are somehow a little problem together with the extremely fast changes in driving resistance for the articulated hauler. To shorten the gear shift time is not that simple due to the fact that the mechanical design of the transmission is rather fixed. A "pure" software solution is therefore normally easier to introduce from this aspect.

In order to handle the "slow" gear shift times, a better prediction of the road topography or deceleration/acceleration ahead could be an alternative to for instance enable to skip more gears, i.e. to downshift from the 7th gear to the 4th gear. Of course one should think about were the boundaries of the engine rpms for a smooth ride are in terms of Noise, vibrations and harshness (NVH), because NVH could give the driver a negative feeling.

7.2 Influence of weight

The inclination gear shift strategy which has been developed and been analyzed in section 3, is as mentioned before rpm controlled. As the weight of the articulated hauler with the best gear shift strategy *s-Trpm2* was set to 62 tons, a test-simulation with 42 tons and the same gear shift point showed a clear improvement of both travelling time and fuel consumption. By analyzing at which rpm's shifting was performed in the end, shifting was done in the region of 1400 to 1750 rpm which is clearly not in the region where shifting was performed before with the weight of 62 tons. A further development could be to use the vehicle weight as an input variable to the blackbox, presented in section 2.3.2. In reality it could be possible to measure the weight via the suspension of the vehicle and use it as an input, while the vehicle is standing still. Due to the limitation of the software CRUSIE it was not possible to use the weight as an input variable to the gear shift strategy, and therefore the simulations were performed with the same weight. Of course the loaded weight on the articulated hauler differs in reality so it is almost a requirement to change the gear shifting points depending on the actual weight loaded.

7.3 Future Recommendation

This subchapter discusses future work regarding improvements that can be done with the inclination shift. Furthermore a recommendation regarding predictive shift is given.

7.3.1 Gear shift strategy with pedal position

The inclination shift strategy developed in this thesis is rpm controlled, which means gears will always be changed at the same rpms (of course be change depending on the actual inclination) no matter what the throttle angle is. So in order to optimize the gear shift strategy a possible way could be to change gears depending on the actual throttle position, road inclination and vehicle speed. This would mean a 3D gear shift schedule graph which is represented in ***Figure 34***. A typical gear shift schedule for a passenger car is controlled by the actual throttle position, which can be seen in ***Figure 17***.

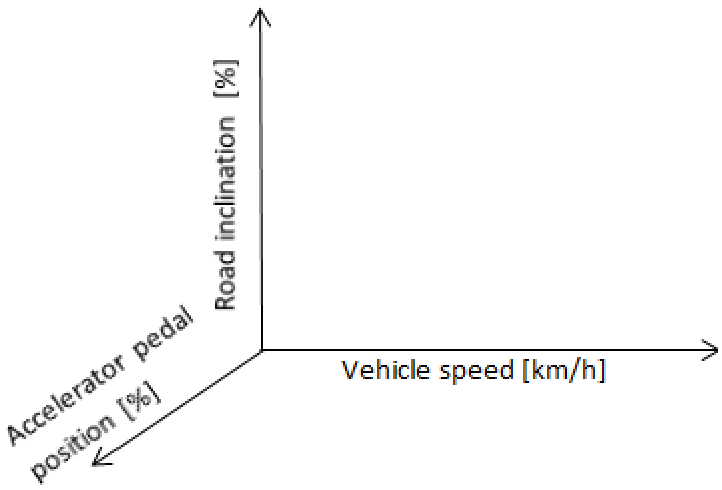

Figure 34 - 3D gear shift schedule

As the articulated hauler has only been simulated with full throttle position, the second control parameter *Accelerator pedal position [%]* would enable even more and better results in terms of fuel consumption and travelling time for cruising speeds. Of course the programming code would be more complicated, a better model of the driver is required and the simulations probably would need more time but computer performance isn't a problem nowadays.

7.3.2 Predictive shift

A further development of the inclination shift strategy could be to implement a sort of predictive gear shift. This could be done in two different ways.

7.3.2.1 Predictive shift via approximation of inclination

The predictive shift strategy via approximation could be a further development of the inclination shift strategy. The idea with this strategy is to predict the road inclination via the road inclination the vehicle has passed, i.e. via a Taylor approximation.

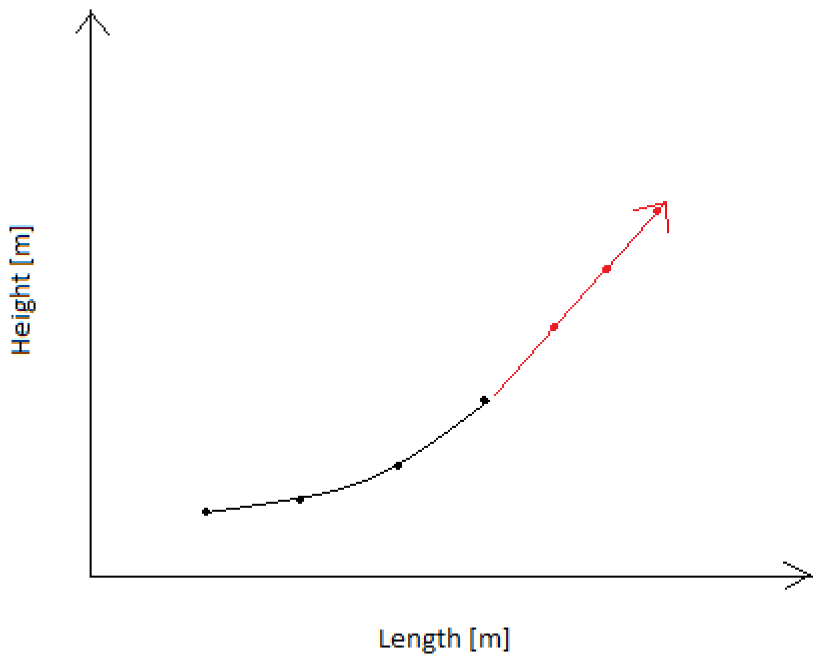

Figure 35 – Predictive shift via inclination

The figure above is showing the black road the vehicle has passed. As one can notice the inclination of the road is increasing. Via approximation one could assume that the road inclination will increase ahead (red line). As a breaking point for a complete new approximation, one could use the change in positive or negative inclination (uphill or downhill). So for instance if the vehicle is driving on an uphill road with a constant gradient the prediction would probably say that the road will follow that inclination. If the road inclination "suddenly" would change from uphill to downhill, a new prediction could start in that point were the downhill point starts, which can be seen in ***Figure 36***.

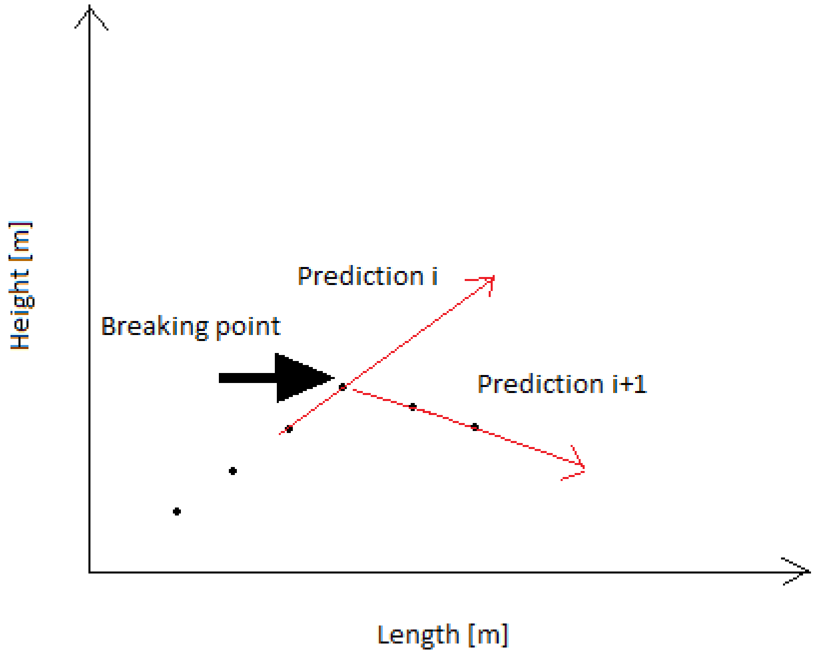

Figure 36 - Predictive shift with breaking condition

The advantage with this predictive gear shift strategy compared to the inclination shift strategy is that this strategy can "look ahead", the inclination shift strategy only changes gear for the actual position, which could mean a slower response in gear shift due to a rapidly change in driving resistance. The predictive gear shift strategy though could assume an increase or decrease in road inclination and change gear earlier compared to the inclination shift.

7.3.2.2 Predictive shift via a known track

The idea with this strategy is to load a known track the articulated hauler will drive on into a program which then determines the gear shift points in terms of either best fuel consumption, fastest travelling time or a combination of fuel consumption versus travelling time. The advantage with this strategy is of course that you will get the "best" gear shift point in terms of your criteria. A major disadvantage though is, how you handle off-track position of the vehicle, i.e. what happens if the vehicle doesn't drive on the route which the gear shift are determined for. Another disadvantage is, before the vehicle is even able to drive on the construction zone, all possible routes will have to be captured and stored somehow and every time the driver wants to drive to a certain destination, the driver need load the track into the software which than creates the gear shifting points.

Due to lack of project time and the fact that the C-programming interface in AVL's software CRUISE is so limited and only simpler commands can be written, it was unfortunately not possible to develop the predictive gear shifts via approximation of inclination or the predictive gear shift via a known track further. It would certainly have been possible to do this using Matlab as an interface to Cruise but given the time frame it was not possible sort out the licensing issues.

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Lacour, Vidon, Perret, Tassel & Joumard, 2001c *Impact of the Gearshift strategy on emission measurement*, Institut National de recherche sur les transport et leur sécurité, 9

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(AVL 2013b) *AVL Cruise – Vehicle System and Driveline Analysis,* Available at the Internet: https://www.avl.com/c/document_library/get_file?uuid=e3198e0c-3a41-4ed4-acde-d844f447d34f&groupId=297166

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8.3 Pictures

[Figure 1] Volvo Construction Equipment, *A52F Specifications,* Available at the internet: http://www.volvoce.com/dealers/en-gb/vcegb/products/articulatedhaulers/A25F_A30F/Pages/A25F_specifications.aspx

[Figure 9] Juali Fu & Gianantonio Bortolin, 2012a, *Gear Shift Optimization for Off-road Construction Vehicles*, KTH Royal Institute of Technology, Stockholm Sweden & Volvo Construction Equipment, Eskilstuna Swden, page: 4

[Figure 12] Darrell Robinette & Ted Skrzycke, *A Dual Clutch Torque converter for Dual Input Shaft Transmissions,* General Motors Company, page: 3

Appendix A – List of Signals

Signal name	Functional name	Data type	Unit	Range
ACTUAL ENGINE SPEED UNFILTERED	UNFILT_ESPEED	VALUE	rpm	0/7000
ACTUAL TORQUE	ACT_TORQUE	VALUE	Nm	-100/400
ACCELERATOR POS	ACCEL_POS	VALUE	%	0/100
ACCELERATOR POS TCM	ACCEL_POS_TCM	VALUE	%	0/100
ACTUAL GEARBOX	ACTUAL_GEARBOX	BOOLEAN	-	-
ACTUAL GEAR	ECS_ACTUAL_GEAR	BINARY	-	-
KICK DOWN	KICK_DOWN	BOOLEAN	-	-
ACTUAL GEAR	TCM_ACTUAL_GEAR	BINARY	-	-
SELECTED GEAR	TCM_SELECTED_GEAR	ENCODED	-	-
TRANSMISSION SHIFT PATTERN STATUS	TRANS_SHIFT_STATUS	ENCODED	-	-
INPUT RPM	INPUT_RPM	VALUE	rpm	0/7000
OUTPUT RPM	OUTPUT_RPM	VALUE	km/h	0/255

TCM_ACTUAL_GEAR (description of values)

$02 = R (Reverse gear)
$03 = N (Neutral gear)
$05 = 1 (First gear)
$06 = 2 (Second gear)
$07 = 3 (Third gear)
$08 = 4 (Fourth gear)
$10 = 2+lock-up
$11 = 3+lock-up
$12 = 4+lock-up

TCM_SELECTED_ GEAR (description of values)

1 = P (Park)
2 = R (Reverse gear)
3 = N (Neutral gear)
4 = D (Drive)
5 = 1 (First gear)
6 = 2 (Second gear)
7 = 3 (Third gear)
8 = 4 (Fourth gear)
11 = M (Manual)
12 = L (Low)

Appendix B – Gear shift schedule

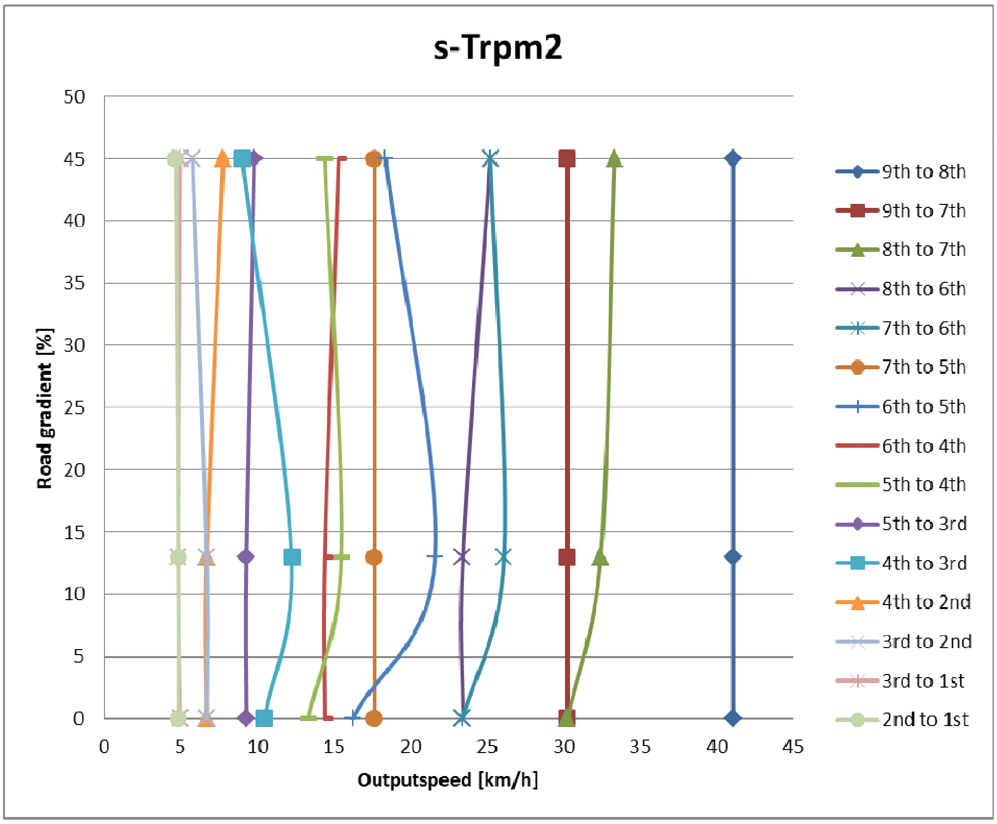

Figure 37 - Gear shift schedule for s-Trpm2

Appendix C – Track information

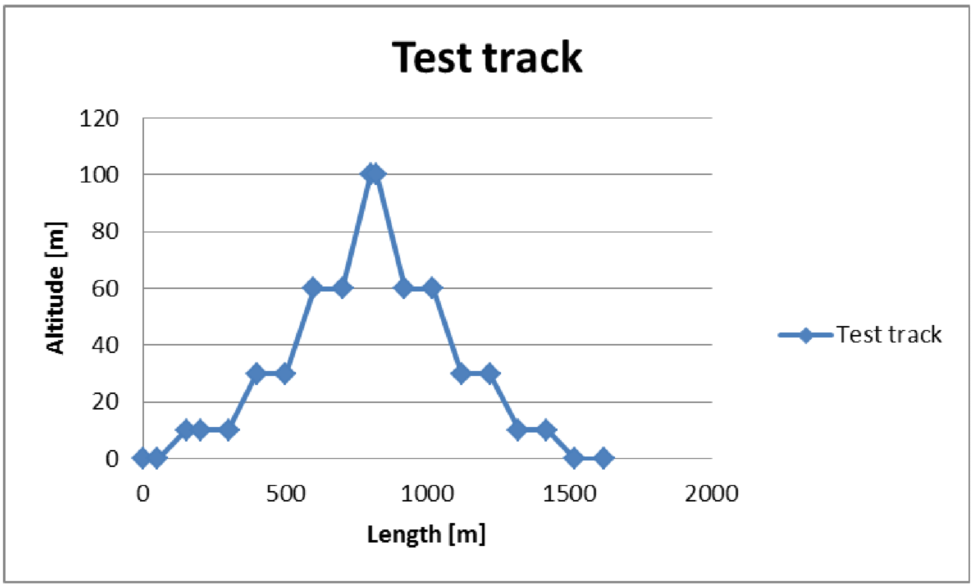

Figure 38 - Test track layout

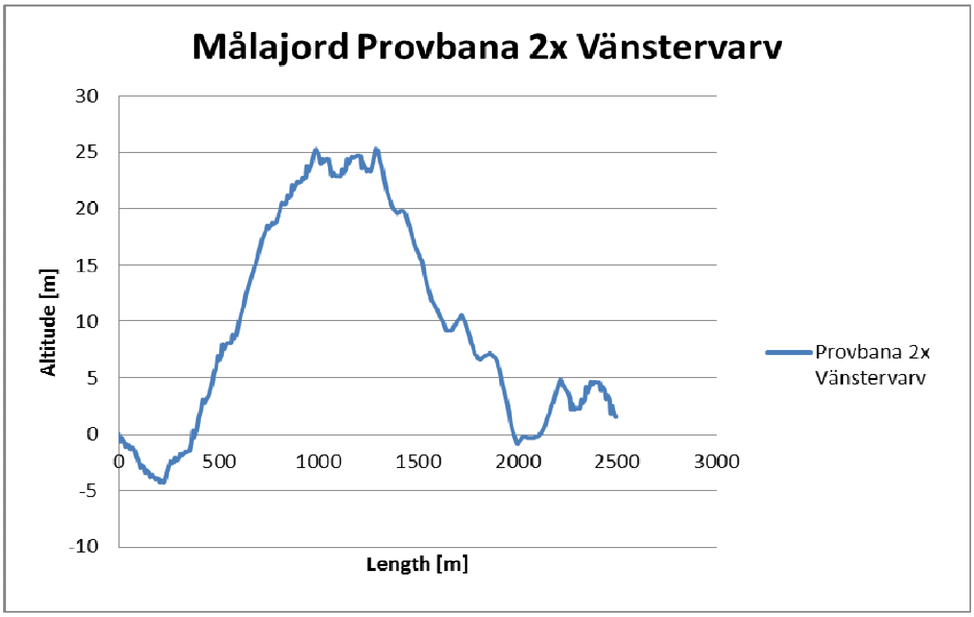

Figure 39 - Målajord Provbana 2x Vänstervarv

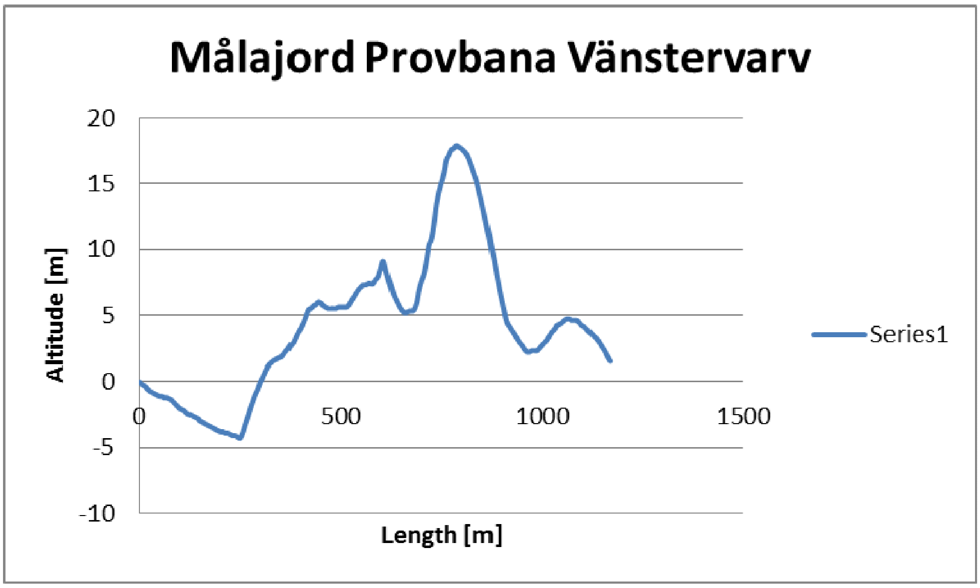

Figure 40 - Målajord Provbana Vänstervarv layout

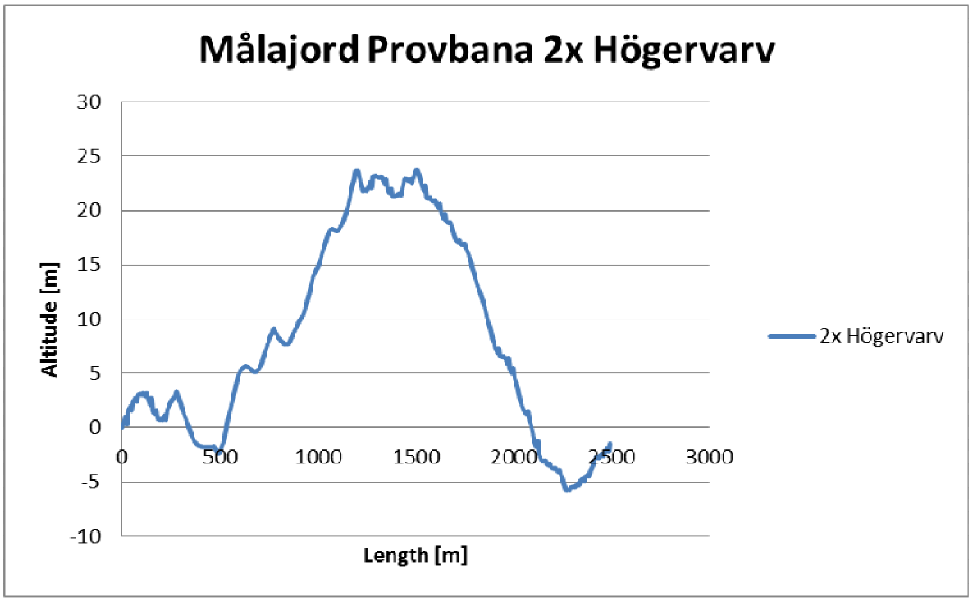

Figure 41 - Målajord Provbana 2x Högervarv layout

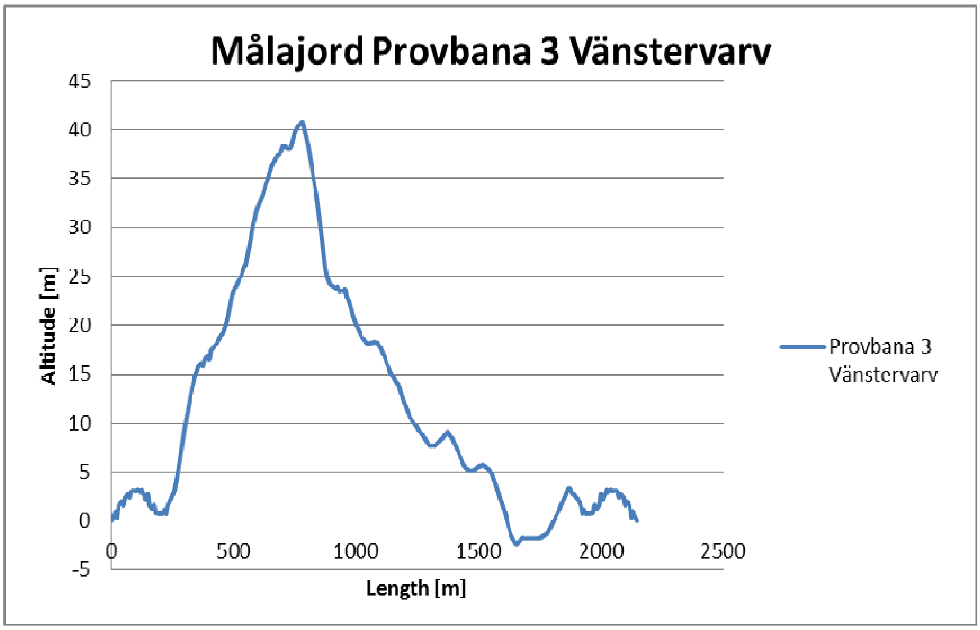

Figure 42 - Målajord Provbana 3 Vänstervarv layout

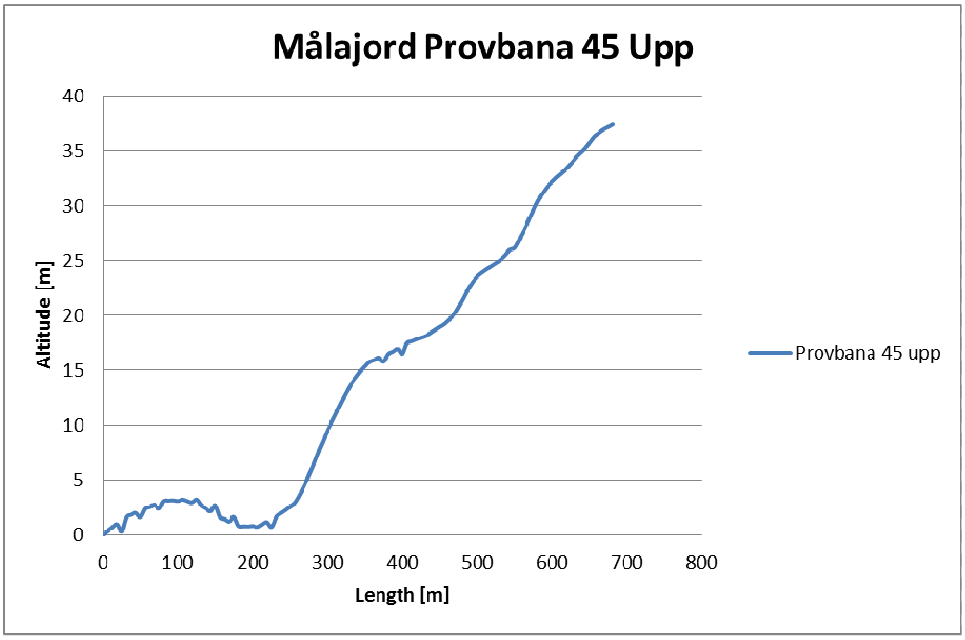

Figure 43 - Målajord Provbana 45 Upp layout

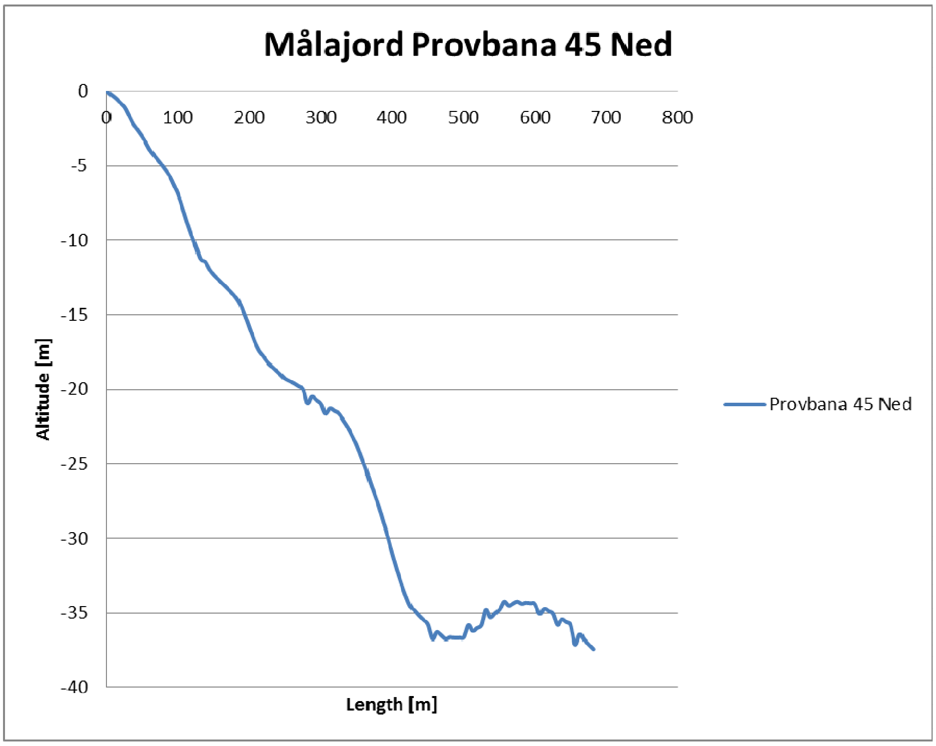

Figure 44 - Målajord Provbana 45 Ned layout

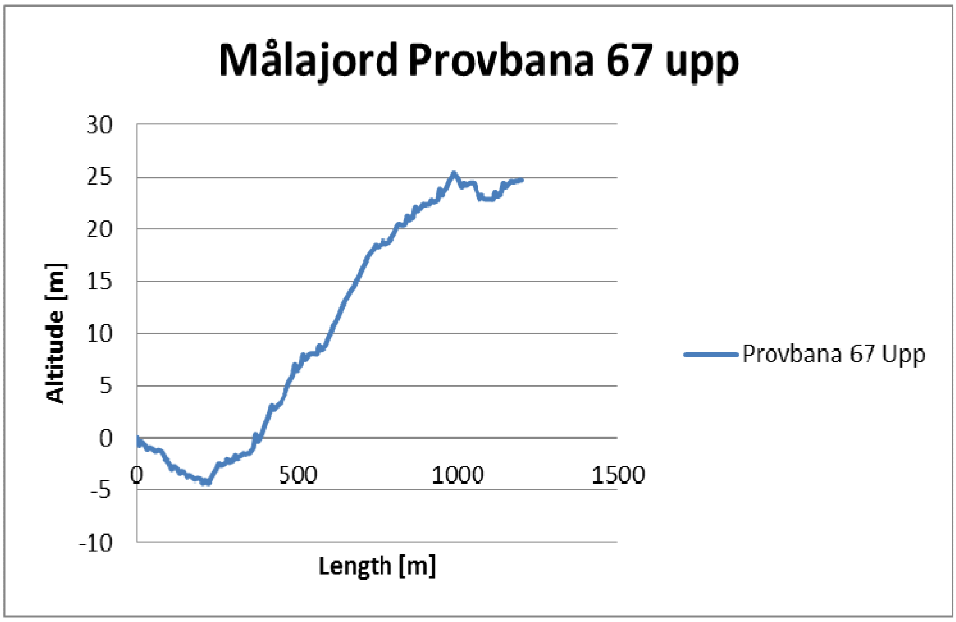

Figure 45 - Målajord Provbana 67 upp layout

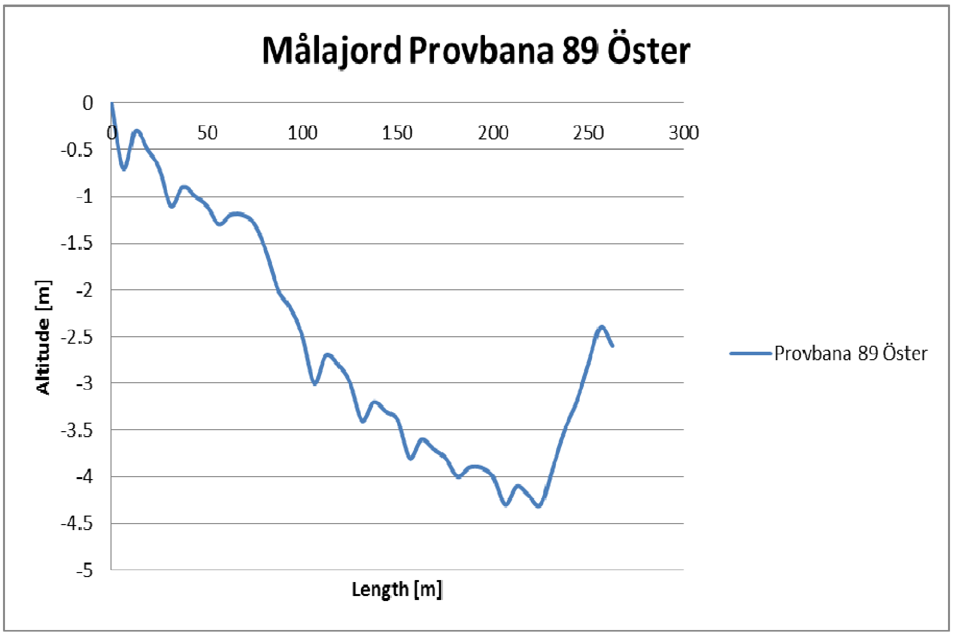

Figure 46 - Målajord Provbana 89 Öster layout