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av
Niklas Gustafsson

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The Use of Positioning Systems for Look-Ahead Control in Vehicles

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ABSTRACT

The use of positioning systems in a vehicle is a research intensive field. In the first part of this thesis an increase in new applications is disclosed through a mapping of patent documents on how positioning systems can support adaptive cruise control, gear changing systems and engine control. Many ideas are presented and explained and the ideas are valued. Furthermore, a new method for selective catalytic reduction (SCR) control using a positioning system is introduced. It is concluded that look-ahead control, where the vehicle position in relation to the upcoming road section is utilized could give better fuel efficiency, lower emissions and less brake, transmission and engine wear.

In the second part of this thesis a real time test platform for predictive speed control algorithms has been developed and tested in a real truck. Previously such algorithms could only be simulated. In this thesis an algorithm which utilizes model predictive control (MPC) and dynamic programming (DP) been implemented and evaluated. An initial comparative fuel test shows a reduction in fuel consumption when the MPC algorithm is used.
PREFACE

This Master’s thesis has been performed between September 2005 and January 2006 at Scania CV AB in Södertälje and completes my international studies for a Master of Science degree in Applied Physics and Electrical Engineering.

In some manner my background as a truck driver has helped me in understanding which functions that are necessary and redundant for a truck. Also my engineering background from my education in Linköping has provided me with the necessary curiosity and tools to understand and further develop new technology.

I am grateful for having had the opportunity to work with this interesting subject and my interest in and knowledge of the automotive industry has increased.

Acknowledgement

I express my gratitude to my dedicated supervisors Fredrik Egrelius and Per Sahlholm and all other helpful and friendly colleges at the Patent (UTY) and Concepts (RESC) departments of Scania. Thanks also to my supervisor Lic. Daniel Axehill and my examiner Dr. Rickard Karlsson at the Department of Electrical Engineering, ISY, in Linköping.

Niklas Gustavsson
Linköping, March 2006
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1 Introduction

Many ideas have been presented by various automotive companies over the last few years on new applications utilizing positioning systems as aid for look-ahead control in vehicles. The aim of this work is to map and evaluate such ideas and also to create a working test-platform for look-ahead speed control. With predictive or look-ahead control is meant control based on a probable future event or disturbance. A positioning system provides the means for knowing the future travel path of the vehicle. The thesis is that such knowledge can improve control performance and the purpose is to show that such control is possible today in a real vehicle.

The mapping is limited to the areas within which some of the most beneficial applications can be found; that is adaptive cruise control (ACC), automatic gear change control and engine control. The decision to focus on these areas was a request from the assignee, Scania CV AB, patents department.

Each application in the patent mapping is covered with a section with facts, containing the basic description of the application, and a section with opinions, containing an examination of the technical use of the application and suggestions for improvements. Hence, ideas are not only mapped, but also examined and in some cases further developed.

The mapping reveals that one of the most common ideas is to automatically adapt speed to road topography, primarily in order to save fuel. Different methods have proven successful in simulations, yet an implementation for tests in a real vehicle was not previously available. Therefore the second part of this work has been dedicated to creating a test platform for predictive speed control algorithms in real trucks and try to verify simulation results.

To perform this task it has been necessary to apply knowledge of real-time systems, automatic control, control theory, optimization theory, modeling and simulation, vehicular systems and programming. With the aid of existing controller area network (CAN) hardware and CAN software drivers a real-time test platform has been built up in Matlab/Simulink, with a graphical user interface (GUI) which communicates with the test engineer. The GUI is also the interface to a Simulink control loop structure, where a predictive speed controller has been implemented.

![Figure 1: Test platform for predictive speed control.](image)
The result is a solution where a test engineer simply can bring a laptop computer with the test platform installed, plug-in the CAN hardware interface and start driving. Such a solution was not previously available, but is unique for this work.

The chosen control method is called *model predictive control* (MPC) with the solution method *dynamic programming* (DP). MPC and DP are discussed, applied to the problem and the control performance is evaluated.

The two main parts in this Master’s thesis can be read either independently or as a whole. A reader with interest only in predictive speed control can read and understand Chapter 4 without previously reading Chapter 3. Likewise a reader who intends to get the bigger picture on how positioning systems can be used as control aid in vehicles is recommended to focus on Chapter 3. The division into two main parts follows from work at two different departments at Scania CV AB and the writing of two internal reports for the respective departments.

1.1 Purpose
The purpose of this thesis is to determine how a positioning system can support control in different vehicular systems and to create a test platform for real-time tests of predictive speed control algorithms.

1.2 Restrictions
Systems investigated are restricted to *adaptive cruise control* (ACC), automatic transmission control and engine control. The practical implementation is restricted to one optimization algorithm for predictive speed control.

1.3 Procedure
In the first part of this Master’s thesis an extensive patent mapping within this field of science has been performed using patent and article databases such as Delphion and SAE in order to find the state of the art today and to find any trends in patent filings and/or publications. The next step has been an attempt to value and improve strategies for engine, transmission and adaptive cruise control, possibly opening up for future patent applications or prophylactic publication.

In the second part of this Master’s thesis, a practical task has been performed, implementing an interface for a cruise controller where fuel consumption is optimized for a predetermined route using an optimization algorithm. This part shows that look-ahead control is possible in a real vehicle and concretizes the ideas from the first part.

First functions for the collection of road grade data from road data files were created. Next, parameters of a known optimization algorithm were adjusted for the purpose of real-time execution and a program utilizing this algorithm was programmed on a PC. Thereafter, a graphical user interface was created where road data files can be chosen and several algorithm and vehicle parameters can be set. The program was also adjusted to interface the vehicle CAN network. Finally, the created system was tested and evaluated through a comparative fuel test.

1.4 Outline
In Chapter 2 a brief introduction to different positioning systems are given and pros and cons of each system are discussed. In Chapter 3 the result of the patent mapping of support from
positioning system to ACC systems, gear changing systems and engine control systems is available. In chapter 4 the real time implementation of the predictive speed controller is described thoroughly. Chapter 5 contains general conclusions and suggestions for future work. Since this thesis contains a lot of footnotes, the footnotes have been collected in a reference list at the end of the thesis in order to make it easier to read.

1.5 Abbreviations

The following abbreviations are used throughout this Master’s thesis:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ABS</td>
<td>Anti-lock Braking System</td>
</tr>
<tr>
<td>ACC</td>
<td>Adaptive Cruise control, also referred to in literature as ICC or AICC for intelligent/adaptive intelligent cruise control</td>
</tr>
<tr>
<td>A/T</td>
<td>Automatic transmission</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>CC</td>
<td>Cruise Control</td>
</tr>
<tr>
<td>CSMA/CR</td>
<td>Carrier Sense Multiple Access/Collision Resolution</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential GPS</td>
</tr>
<tr>
<td>DP</td>
<td>Dynamic Programming</td>
</tr>
<tr>
<td>ECU</td>
<td>Electronic Control Unit</td>
</tr>
<tr>
<td>EGNOS</td>
<td>Euro Geostationary Navigation Overlay Service</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
</tr>
<tr>
<td>FCW</td>
<td>Forward Collision Warning</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GM</td>
<td>General Motors</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
</tr>
<tr>
<td>LOS</td>
<td>Level Of Service</td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
</tr>
<tr>
<td>MSAS</td>
<td>Multi functional Satellite Augmentation Service</td>
</tr>
<tr>
<td>PCC</td>
<td>Predictive Cruise Control</td>
</tr>
<tr>
<td>POI</td>
<td>Point Of Interest</td>
</tr>
<tr>
<td>RDS</td>
<td>Radio Data System</td>
</tr>
<tr>
<td>RT</td>
<td>Real Time</td>
</tr>
<tr>
<td>S/A</td>
<td>Selective Availability</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>SHTL</td>
<td>Scania Heavy Truck Library</td>
</tr>
<tr>
<td>TCS</td>
<td>Traction Control System</td>
</tr>
<tr>
<td>TMC</td>
<td>Traffic Message Channel</td>
</tr>
<tr>
<td>WAAS</td>
<td>Wida Area Augmentation System</td>
</tr>
</tbody>
</table>
2 Positioning Systems

This chapter contains a short description of the most common positioning systems and their respective advantages.

2.1 Dead-Reckoning Systems and Odometry

Methods where a travel path is extrapolated from a known starting position using different sensors to measure turning directions and travelled distance are often referred to as dead-reckoning methods. There are several methods to perform the dead-reckoning, but all have in common that they suffer from error growth with time. Hence, the use of a Kalman filter to reduce estimation errors is common. One advantage with dead-reckoning methods, however, is that they can be used everywhere and that they do not rely on external systems to work.

One known method is based on the terrestrial magnetic field. In such a system the position is calculated based on travelled distance at a certain angle through the terrestrial magnetic field. The travelled path is made discrete and the position can then be calculated as

\[
\begin{align*}
\Delta D_x &= D \cos(d), \\
\Delta D_y &= D \sin(d),
\end{align*}
\]

where \(D\) is the travelled distance and \(d\) is the angle through the earth’s magnetic field. When each discrete part of the travelled path is small enough this approximation turns out to be quite accurate.

A common system is an inertial navigation system (INS), where accelerometers and rate gyros are used to determine position and attitude by integrating accelerometers twice and rate gyros once. The primary advantage is that such systems are very fast and can be used for real-time control purposes. However, because of the integrations, errors from the sensors accumulate with time, causing a drift. Therefore inertial navigation systems are often integrated with a GPS system in order to calibrate the position from the GPS.

In yet another system the difference between different wheel speeds of a vehicle is used to model the change in position. This is also referred to as odometry and has been subject to a Master’s thesis at Scania CV [1].

2.2 Beacon Based Positioning System

Another common method is a stationary beacon positioning system where beacons are spread along a road and in-vehicle beacon sensors receive positioning information from the beacons. This has the drawback that beacons must be placed on every road that the vehicle travels. The advantage though is an accurate positioning and there is no error growth with time.

2.3 Global Navigation Satellite Systems (GNSS)

2.3.1 Satellite Positioning – Advantages and Problems

The global positioning system (GPS), is a positioning system where the current position, altitude, direction and velocity can be calculated from satellite signals. The GPS system is currently based on 24 satellites orbiting the earth. There are two currently available public GPS (GNSS) systems: NAVSTAR, owned by the US Department of defence and GLONASS,
owned by the Russian federation. However, NAVSTAR is the most commonly spread system and is often what is meant when GPS is mentioned. Also, it should be mentioned that a European global positioning system, called Galileo is planned to be operative in 2008. The Galileo system will be interoperable with GPS/NAVSTAR and GLONASS and all systems will benefit from more available satellites. The Galileo system is also planned to offer a more robust and continuous signal, making it more suitable for control purposes (than conventional GPS). Also, it is claimed to give accurate positions in tunnels and inside buildings [2]. However, the rest of this chapter refers to GPS in its currently existing form.

The advantage of GPS systems is that they do not suffer from error growth with time and that all necessary equipment is the receiver. The transmitting infrastructure (satellites) already exists and is operational.

To provide accurate positioning in three dimensions, signals from four satellites are needed to find the correct 3D position and time. If signals from less than four satellites can reach the GPS receiver, or if the signal quality is poor, the positioning may be inaccurate or even impossible. For road vehicles the problem typically arises in tunnels. Another problem with GPS systems is the low update frequency (non-continuous signal), which make them difficult to use for control purposes in vehicles as a stand-alone system. The method to solve the problem is often to use a dead-reckoning or odometry method (2.1) as a complement.

Another known problem with GPS-positioning is that the estimated altitude is a less accurate estimate compared to the estimated horizontal position [3]. This primarily depends on the geometric configuration of the satellites in relation to the receiver. In the ideal case it would be desirable to also have a set of satellites “under” the receiver. In general, the altitude error is 1.5 times bigger than the error in horizontal position. Also, one should realize that the displayed altitude is not altitude over sea level, $A$, but altitude over the ellipsoid, $a$. The reference surface for the altitude is simplified, so it differs from altitude over sea level with 20 to 40 metres in Sweden. To get better altitude measurements, so called geoid corrections, $N$ are required. This is illustrated in Figure 2. The measurements can also be improved by barometrical corrections. Additionally an IP.COM publication [4] describes a method where the road topography (altitude profile) is extrapolated from an estimated road inclination based on vehicle weight and total resistance.

![Figure 2: Problems determining altitude with GPS.](image)

Today GPS receivers in vehicles are primarily used for route guidance and fleet management in combination with a two dimensional road map.
2.3.2 Civil GPS Modernization

Before the year 2000 an intentional degradation, also referred to as a selective availability (S/A) was added to the GPS signal. The purpose was to keep the civil accuracy level of positioning down. The S/A was typically a noise altering the time signal causing positional errors of 0-70 metres.

On 2 May 2000 the intentional degradation of the civil GPS signal was set to zero, allowing civil accuracy levels of about 4 meters. This was the first step in the GPS modernization program.

Next step was the addition of yet another signal, the L2 Civil, or L2C, which provided civil GPS users with a more robust signal reception on places with previously poor reception. The first satellite carrying this signal was launched in 2003.

In 2006 satellites transmitting yet another signal, L5 Civil, are planned for launch. This signal will be specifically suited for precision navigation and is the third step in the modernization program.

The final step in the modernization program is the GPS III Program, which includes a complete review of the entire GPS system.

2.3.3 Differential Global Positioning System (DGPS)

Differential GPS, or DGPS, is a system where data from a receiver at a known, geostationary location is used to correct data from a receiver at an unknown location. DGPS offers a significantly more correct positioning than standard GPS. An accuracy of one metre or less is possible.

This opens up for lane level navigation and several automotive applications. DGPS is available as a feature in most high quality GPS-receivers and was first developed to overcome the problems with Selective Availability.

There are also a few other systems for differential corrections which account for satellite orbit, clock drift and signal delays caused by the atmosphere and ionosphere. In the United States there is a system called WAAS (Wide Area Augmentation System), in Europe the system is called EGNOS (Euro Geostationary Navigation Overlay Service) and in Asia there is a Japanese system called MSAS (Multi functional Satellite Augmentation Service). These systems are claimed to provide extended coverage as well inland as offshore, compared to conventional DGPS systems.
3 Patent Mapping of Positioning Systems for Control Aid

To find today’s state of the art a mapping of patent documents have been performed. The purpose of this mapping has been to create a work of reference for concerned departments of Scania within the area of look-ahead control, where map data coupled to the vehicle position is used to create a more driver-like control. The mapping is restricted to the use of positioning systems for ACC, gear changing systems and engine control.

The patent mapping has been performed primarily using the patent database Delphion. The Delphion search comprises a full text search of the most common patent collections, including US, EP, DE and WO patents and patent applications. Also INPADOC and Patent Abstracts of Japan have been included in the search. However, smaller patent collections, such as Swedish were not included in the search. The presented statistics are based on the tools for patent research available in Delphion and the text ‘number of hits’ in the captions, refers to the number of hits when using a specific search string searching the Delphion database.

In some cases, searches have also been performed using thesis databases such as SAE, and in many cases simple web searches have been performed in order to gain a deeper understanding of a specific technique. A detailed description of the procedure and search strings is available in the Scania internal report [5].

It is important to realize that this procedure does not give a complete picture, but a very good overview of available techniques of using positioning systems to support different vehicular systems.

3.1 Using a Positioning System to Support an ACC System

The adaptive cruise control (ACC) system is an enhancement to the conventional constant speed cruise control (CC) system where a vehicle is kept at a constant speed determined by the driver. Other common abbreviations for (practically) the same system are AiCC and ICC.

In a General Motors patent [6], the basics of ACC are described. A vehicle equipped with ACC can follow a preceding vehicle at a predetermined headway distance using a distance measuring instrument such as radar or lidar. ACC is commercially available today in different embodiments and is mostly used in top class vehicles. Many manufacturers of commercial as well as personal vehicles offer some kind of ACC function in their top of the line series.

![Control loop for conventional constant speed cruise control (CC).](image-url)
Examples of feedback control loop structures for CC and ACC are illustrated in Figure 3 and Figure 4 respectively. These control loops, however, should only be considered as simplified illustrations of the classical approach to cruise control and adaptive cruise control respectively. The actual control loop structures may differ from system to system and may be more complex. Each company have their own solution.

Typically both controllers are PI or PID-controllers, because of their simple and well-known structure. Feedback signals are current velocity for CC and distance and/or relative velocity to the target vehicle for ACC. However, more advanced controllers have also been tested and evaluated [7].

An examination of the available techniques reveals several shortcomings to the traditional ACC function forcing the driver to disengage ACC in certain situations. Several patents and patent applications have been filed, where solutions to these problems are given, based on the use of a positioning system (means for positioning such as GPS and/or Dead reckoning coupled to a map database, possibly equipped with information about the travel path environment). A mapping of these methods follows in this chapter.

### 3.1.1 Limitations to ACC

The conventional adaptive cruise control system has many advantages but also several drawbacks which will be presented below.

Conventional ACC systems lack a lot of information that could be an aid for driving. The system makes its decision based mainly on a front radar system. No consideration is taken to ascents, descents, road curvature, side walls or ramps. ACC is solely a system designed to keep the vehicle at a predetermined distance to an obstacle or vehicle in front of it. Hence, ACC actions can contend driver intuition in many situations. Some of the following examples could be used to illustrate this:

![Figure 4: Control loop for adaptive cruise control (ACC).](image-url)
While exiting a highway the standard ACC action would be to accelerate to the preset speed if the road is clear. The preferred driver action, however, might be to decelerate to clear an upcoming turn and/or adapt to new speed limits. This is further on referred to as the ramp problem.

While approaching the end of a descent followed by an ascent the standard ACC action would be to keep the distance to the preceding vehicle at all costs. Meanwhile, the driver can accept a slight increase in velocity and a slight decrease in vehicle distance to get up the next hill and drive more fuel efficient. Also, for fuel efficient drive, an increase in vehicle distance and a decrease in velocity could be desired when approaching the top of a hill. This is further on referred to as the slope problem.

In a sharp curve or roundabout a heavy commercial vehicle has the centrifugal force to take into account in order to prevent a rollover situation and to not cause discomfort for the driver. Assume the preceding vehicle is a smaller personal vehicle, the curve cannot generally be cleared with the same speed and hence the headway distance must increase. However, that is not allowed by the ACC system which will enter the curve at a far too high speed. This is further on referred to as the curve problem.

In all of these situations (and others) the driver probably would feel forced to disengage the ACC system. Solutions for automatically setting a desired velocity and/or distance for an upcoming road segment, such that manual disengagement is unnecessary, are given in the following chapters. The prerequisite of all solutions is that the current vehicle position in relation to the upcoming terrain is known.

After having disengaged the ACC system the driver needs to manually engage the system again and adapt it to the new circumstances. This could cause driver irritation and takes focus off the driving. Since the ACC is disengaged at any manual brake or clutch actions or in some systems when accelerating hard, this is a situation that potentially occurs every time the vehicle overtakes another vehicle or when a gear shift is performed in a manual gearbox. In a lot of these situations ACC disengagement is not desired.

Conventional ACC systems have no information about road geometry and/or connecting or parallel roads, which could cause difficulties in choosing the vehicle to follow. Usually vehicles travelling in the other direction can be excluded from the set of vehicles to choose from, because their velocity is negative. However, vehicles travelling in the same direction are not easily separated, without knowledge of road geometry. This could cause the ACC system to act against driver intention, following the wrong vehicle.

These and other problems that the ACC suffers from, given a desired velocity and/or distance, are also addressed in the following chapters.
3.1.2 Predictive Speed Control

Facts
Several methods for utilizing the vehicle position to optimize fuel efficiency exist. One of these methods is described in a Daimler Chrysler publication [8]. A patent application [9] has also been filed in the United States.

The basic idea is to define a vehicle operating cost function based on environmental parameters, vehicle parameters, vehicle operating parameters and route parameters. As the vehicle travels, an onboard computer iteratively calculates and stores vehicle control parameters that optimize the vehicle operating cost function for a predetermined prediction horizon (distance) along the route ahead of and behind the vehicle.

The operating cost function, $J$, in [9] paragraph 126 is:

$$ J = J_{\text{final-state}} + J_{\text{time}} + J_{\text{fuel}} + J_{\text{velocity}} + J_{\text{lateral-accel}} + J_{\text{penalty}}. \quad (3.1) $$

With this method each of the separate cost functions can be weighed individually to focus on minimizing final state error ($J_{\text{final-state}}$), travel time ($J_{\text{time}}$), fuel consumption ($J_{\text{fuel}}$), drift from preset velocity ($J_{\text{velocity}}$), rollover risk ($J_{\text{lateral-accel}}$) or penalty velocity risk ($J_{\text{penalty}}$). Each of these separate cost functions are described thoroughly in paragraphs 95-126 in [8].

In the SAE publication [8], no consideration is taken to the lateral acceleration, which is of great importance to commercial vehicles. This has, however, been changed in the patent application [9].

The parameters are updated and replaced as the vehicle proceeds. Vehicle speed control is then based on the optimized control parameters from the memory, corresponding to the current position of the vehicle. Figure 5 shows the predictive cruise control loop.

![Figure 5: Predictive cruise control (PCC).](image)

A Siemens AG patent application [10] has also been filed regarding a route selector based on an optimized fuel consumption and travel time. One embodiment of the invention allows the driver to select from a set of possible routes, where fuel consumption and travel time are displayed. After selection of a route, the calculated velocity at the current position can be used as a desired velocity in the ACC controller. According to the route selector a maximum travel
time is an input parameter, which must not be surpassed when the list of routes is decided. The optimization algorithm is not described in the patent application.

Another method for predictive speed control is thoroughly described and tested in Chapter 4.

**Opinions**

The outcome of the predictive speed control optimization algorithm is a desired velocity which could be used in a CC system or ACC system. It is, however, of great importance to realize that a desired velocity cannot always be held in a real traffic situation (due to preceding vehicles and road obstacles), hence this result is only interesting as means of choosing a desired velocity while the actual vehicle velocity has to be based on the road environment.

An assumption is that an optimization of a whole route [10] can never be as good as the optimization of a real-time updated prediction horizon [9].

As illustrated in Daimler-Chrysler's SAE publication [8], Figure 14, the predicted and recorded fuel consumption complies well. Unfortunately, no fuel consumption compliance diagram has been published for the Siemens method. A comparison between both methods would be interesting.

### 3.1.3 Limiting Speed in a Constant-Radius Curve

**Facts**

In a conventional ACC system, no differentiation is done between straight and curved roads, forcing the driver to disengage ACC in order to safely and comfortably pass the curve. Earlier patent applications suggest different kinds of solutions to this problem, wherein a positioning system is used in combination with a digital roadmap to extract information on the present and upcoming road section. In these solutions an allowed top speed for the actual road section is stored, with no consideration to individual parameters such as vehicle type, weight, height and possibly the current weather situation. As mentioned above lateral acceleration can be critical for commercial vehicles and the critical level can be very different from case to case.

In a Mazda Motor Corp. patent [11] one further step is taken. The idea of the described system is to store information about the curve (at least curve radius) and let an onboard computer calculate a safe and comfortable passing speed based on road curvature and friction.

The safe passing speed is calculated as follows [11, paragraph 0032]:

$$v_{safe} = \sqrt{g \cdot R \cdot F_d}$$ (3.2)

where

- $F_d$ is the road friction based on road temperature and moisture (see also Appendix A),
- $R$ is the curve radius, and
- $g$ is the gravitational acceleration.

When the positioning system indicates a curve ahead, information is gathered about actual vehicle speed, curve radius, road temperature, surface and moisture. Then a look-up table is used to find the actual road friction, $F_d$, based on road temperature, moisture and surface (from the map database). After that, a safe passing speed, $v_{safe}$, can be calculated using the
formula above. If the difference between actual and safe passing speed does not exceed a certain threshold value a reduction of speed can be achieved by adjusting engine throttle. If the difference does exceed that threshold value, brakes are applied in order to reduce speed in time before the curve.

In the Scania CV patent application [12] another method to decide and set a desired speed for an ACC-system in a curve is described. A positioning system could be used to determine the vehicle position and thereby also the distance to a known curve. The geometry of a curve can be determined from a camera or another optical system, which also can be used for a lane departure warning system or other purposes. Another possibility is to use measurements from in-vehicle sensors and/or accelerometers which can provide an image of the currently travelled curve and which speed that is appropriate for that curve. It is mentioned that the curve speed limit should depend on at least one of the following parameters: weather conditions, road conditions, time of day, vehicle weight, curve geometry and an accepted lateral acceleration for the driver. It is, however, not mentioned exactly how the desired speed shall be calculated.

Finally, in a Toyota patent specification [13], a navigation device is described, where a more accurate estimation of an upcoming curve is made, from which a safe passing speed could be calculated. In this document the transverse slope (bank angle) of the road is also considered and the following expression for the lateral acceleration: \( a_l = \frac{v^2}{R} - g \cdot \sin(\theta) \) is used, where \( v \) is the vehicle speed, \( R \) is the curve radius and \( \theta \) is the transverse slope at any position. The curvature \( (1/R) \) and transverse slope, as well as the lengthwise slope are stored for every node on a road in the digital map. The patent relates not only to the actual controller, but also to the storing of road shape data comprising location, curvature, transverse and lengthwise slope for each node.

**Opinions**

Patent documents describing different speed limiting devices in curves are numerous. Most of them, however, are based mainly on lateral acceleration influence in the actual curve. In those systems, for example, a warning might be displayed to the driver if a threshold lateral acceleration is imminent. However, then it might already be too late. Systems where information about the curve is known in advance, and an ACC desired velocity is chosen accordingly beforehand, appear to be quite rare.

The gain of the Mazda method [11] is that a vehicle can clear a sharp curve, with respect to road slippage, without disengaging the ACC system. After the curve the ACC resumes its function with follow mode or conventional cruise control. The drawback of the solution is that no lateral acceleration allowance is set. Hence, there is still a potential risk of a rollover situation, which could be eliminated with the previous solutions [12] or [13].

Based on this knowledge, a solution is suggested where the safe passing speed with respect to road slippage is added to the vehicle operating cost function mentioned in Section 3.1.2. That could be achieved by adding an extra cost function \( J_{\text{road-slippage}} \) as described in Figure 6, (3.3) and (3.4).
Figure 6: Cost function graph considering road slippage.

\[
J_{\text{road-slippage}} = \begin{cases} 
\infty & \text{if } (v_{\text{safe}} - v_{\text{desired}}) < 0 \\
M \frac{1}{x} & \text{if } (v_{\text{safe}} - v_{\text{desired}}) \geq 0
\end{cases}
\]  

In (3.3) and (3.4) above \(v_{\text{safe}}\) is the calculated safe speed (as mentioned above), \(v_{\text{desired}}\) is the desired speed used in the ACC system, and \(M\) is a weight factor used to choose how much consideration that should be taken to the road slippage in the total vehicle operating cost function.

Since the safe curve speed with regard to road slippage under no circumstances is allowed to be exceeded, an infinite cost is applied if it does and a function that exponentially increases close to zero is applied for desired velocities below the threshold value \(v_{\text{safe}}\). The second function could be altered to fit the needs for a specific vehicle, even though the exponential behaviour close to zero is necessary.

From this we can derive the following cost function:

\[
J = J_{\text{final-state}} + J_{\text{time}} + J_{\text{fuel}} + J_{\text{velocity}} + J_{\text{lateral-accel}} + J_{\text{penalty}} + J_{\text{road-slippage}}
\]  

None of the investigated patent applications or patents combines the non-slip and lateral-acceleration factors for limiting curve speed. Therefore the solution could contribute to an improved ACC function.

Although the radius of a curve can be calculated from location data, the transverse slope of the road is not available in a map database today. In Appendix A the effects of road bank information on the recommended desired speed is clarified. The calculated radius may also be quite inaccurate if node spacing is wide. Hence, a more detailed map database with road shape data should be prepared, possibly as suggested in [13].

### 3.1.4 Speed Adaptation to Road Type and General Curvature of Road

**Facts**

The method to adapt speed to a curve, mentioned above, assumes knowledge of curve radius. However, not all curves are of constant radius. Examples are clothoid or transition curves, where the curvature increases linearly with the distance along the spiral, or a winding road in general. Hence, a method for adapting speed to the general curvature of a road, based on total road angular change for a prediction horizon ahead of and behind the vehicle, has been developed by the BMW Group. The method is described in an SAE publication [14].
In the BMW publication, the emphasis is on adaptation to anticipated vehicle speed (dynamic expectation) in different situations. Distinctions are made between highways (high dynamic expectation), rural roads (middle dynamic expectation) or streets/exits (low dynamic expectation). Also, on a winding road the dynamic expectation is lower than on a straight road, as well as the dynamic expectation at an exit is lower than it is on the highway. This is illustrated in Figure 7 and Figure 8.

![Figure 7: Anticipated vehicle dynamics based on total road angular change. Picture from Fig. 10 in [14]. Reprinted with permission from SAE Paper 2004-01-1744 © 2004 SAE International.](image1)

Figure 8: Anticipated vehicle dynamics at an exit. Picture from Fig. 3 in [14]. Reprinted with permission from SAE Paper 2004-01-1744 © 2004 SAE International.

The distinction between different dynamic expectations can be used to alter the search field of the front radar to fit the current road. When travelling a road of high dynamic expectation the search field can be narrowed to fit a highway lane and decrease the risk of nuisance errors from neighbouring lanes. When travelling a road of middle dynamic expectation, like a rural road, the system operates in standard mode, with no limit to the radar search field. Finally, when travelling a road of low dynamic expectation other settings can be made. One example, which is mentioned in the publication, is to alter the resume behaviour on an exit ramp.

Furthermore, in an Aisin patent application [15] an apparatus for predicting road shape and a method of calculating a clothoid curve and fitting it to a corner in a digital map, utilizing GPS positioning data, is described. It is suggested that the predicted road shape can be utilized to control the vehicle, but how is not described in the patent application.

**Opinions**
The method described in [14] takes no consideration of road gradient and hence it provides no solution to the slope problem. The document does contain some information about means for ramp identification, of which most are the same as the method described in Section 3.1.7.
What it also provides is a means for choosing a desired velocity for the ACC system. All driver action needed is to set a preferred velocity and then the speed is adapted to the current road situation. The most interesting part of this publication is the idea to adapt speed to total road curvature of the current road segment a distance ahead and a distance behind the vehicle to meet driver expectations.

No patent application has been found regarding this system.

3.1.5 Speed Adaptation in a Slope

Facts
In a MAN patent [16], a vehicle positioning system is used to control slope speed adaptation. The idea is that ACC disengagement in an ascent or descent for a commercial vehicle should be unnecessary.

Usually, a driver knows how to brake and accelerate to pass an ascent or descent in a safe and fuel efficient manner. This means that the driver allows the speed to increase slightly towards the end of a descent (allowing distance to the preceding vehicle to decrease). The patent also mentions a possible extension where speed is allowed to drop (and distance to increase) towards the end of an ascent. Conventional ACC-systems do not have that kind of dynamic control. Instead they attempt to keep the preset distance and velocity at all costs.

In the MAN solution, the problem is solved with four separate controllers: A velocity controller for the throttle, a velocity controller for the brake force, a distance controller for the throttle and a distance controller for the brake force. Then the largest value from the brake pressure controller and the distance brake controller is sent as a desired value to the brake actuator. The minimum value from the velocity controller and the engine distance controller is then selected as a desired value for the throttle actuator. The system needs data such as road topology and a set allowance for the difference between desired values for distance and velocity and actual values.

The brake controller uses the exhaust brakes, retarder and/or service brakes depending on needed brake power.

Opinions
The invention is highly applicable to commercial vehicles and the only patent which fully integrates predictive speed control with ACC.

3.1.6 Distance Adaptation using Shared Vehicle Network Data

Facts
In a Ford Global Technologies Inc. patent [17] an ACC system is described where information is passed between vehicles in a vehicle network to get a better idea of an acceptable desired distance between vehicles.

Of course, the prerequisite of using this system is that not only the own vehicle is equipped with a communication device, but also other vehicles. Naturally, this limits the use of the invention.

Primarily, it is the ability to brake the own vehicle as well as the preceding vehicle’s braking ability that are used to determine a safe distance, in order to avoid a collision. Braking ability
can depend on the state of the road, tyre pressure, tyre temperature, vehicle load and driver attention.

The Ford patent describes two ways to determine the shape of the road. One is to use radar to measure the surface of the road and the other is to use the functions that already exist in anti-lock braking systems (ABS). If one wheel accelerates more than another, that indicates a loss of friction. This combined with the road temperature is said to give a relatively good idea of the shape of the road.

The attention of the driver can be judged through numerous distraction factors, such as touching the climate control, car stereo or the use of a cellular phone. Studies have also been made on eye movement to check driver alertness.

All of these factors are measured and sent between the vehicles. The received information is then processed and the braking ability of both vehicles can be determined and distance automatically adjusted to a safe distance. The driver can also be displayed the above mentioned information or be acoustically alerted. He/she could with the aid of that information be alerted of worse road conditions ahead, a distracted driver in the vehicle ahead or any other useful information that can be of use.

**Opinions**

The idea of the Ford patent is also described in the SAE paper [18], describing the GPS modernization program, as an upstream warning function. Naturally, an upstream warning is useless without a positioning system. If the direction of the hazardous situation in relation to the own vehicle cannot be determined the information is useless.

Several other patents and patent applications relate to the problem of choosing a desired distance between vehicles in an ACC system. One example is the Daimler-Chrysler patent application WO05061265A1.

### 3.1.7 Ramp Identification in Adaptive Cruise Control

**Facts**

The conventional ACC system cannot separate a ramp from a road. This could cause the speed controller to increase speed at an exit ramp if no vehicles are present in front of the own vehicle. In a Ford Global Technologies Inc. patent application [19] an ACC system is described that can make that differentiation and hence adapts speed to the ramp, without contending driver intuition.

In order to identify an upcoming ramp the system utilizes a navigation system with a GPS receiver and a map database. The ramps are classified in the map database with special ramp classes or numbers. The ramp class could provide information about position and type of ramp (exit, on, off, high/low speed connector ramp) from a look-up table. Using this approach a gathering of the needed information should be relatively straight-forward. Unfortunately, the estimation of the vehicle position relative to the ramp can contain errors which may cause major consequences for the ACC function. One of the major concerns is that the intersection position, which is mapped in the map database, does not always agree to the actual point where the vehicle should turn off, causing an uncertainty in vehicle positioning relative to the ramp. The problem is most serious when several ramps are almost in the same position, as in a traffic interchange or where service roads go parallel to a ramp.
Longitudinal positioning errors can cause the ramp to be indicated too late while lateral errors can place the vehicle on a parallel road. Hence, not only a GPS system is used in this method, but also a yaw rate sensor and a lane change sensor to gather more information about turns, directions and curvature.

When the navigation system indicates a ramp nearby, all of these sensors and the GPS system give a number of possible candidate positions where the vehicle could be. Each position is assigned a probability. The most probable candidate represents the predicted vehicle position. If any of the candidates lie on a ramp on the digital road map, a ramp is near.

With the aid of the above mentioned sensors separation of a specific ramp can be made and hence the speed can be adjusted accordingly. The positioning system is used primarily to indicate a nearby ramp, while the lane change and/or yaw rate sensor is used to indicate that the vehicle has turned on or off a road and separate a specific ramp from a set of possible ramps.

In this system the auto-resume function of an ACC system could be inhibited without driver intervention, for example if the ramp is a low-speed exit ramp. If the ramp is a high-speed connector ramp, the system could automatically auto resume with an adaptation to new speed limits on the connected road.

In an earlier BMW patent [20] a similar system is presented. The idea of that patent is only to prevent acceleration if the vehicle is determined to be at an exit and the vehicle in front no longer is visible (to the ACC radar system). It is determined that a vehicle is on an exit if an exit probability is higher than a certain threshold value. The exit probability is based on a base probability function, which is maximal close to the theoretical exit and smaller or zero before and after the decision field. Also, other vehicle conditions may increase the exit probability. One mentioned example is an active winker.

Opinions

The Ford application [19] is the more comprehensive of the two documents. It is described in detail how ramps shall be identified and how different actions shall be taken on different kinds of ramps.

However, the BMW patent [20] was the earlier of the two and comprises a simple, but working solution to the ramp problem referred to in Section 3.1.1.

Both solutions are applicable to commercial vehicles, but the effort is large compared to the problem which is solved, i.e. that the ACC system automatically disengages at an exit. Few heavy duty vehicle drivers would rely on an ACC system while exiting a highway. However, if the information was available anyway for other applications, systems like the ones mentioned above could advantageously be subject for implementation.

3.1.8 Predicting Driving Path

Facts

Most ACC systems use an angle-triggered multi-ray-radar to determine distance. The polar coordinates can easily be transformed to a Cartesian coordinate system where the x-axis runs in the vehicle travel path direction and the y-axis perpendicular to that as illustrated in Figure 9. One method is to let the area to be searched for possible target vehicles be a limited band in the y-coordinate as shown in Figure 10. With this method no regard is taken to road geometry,
which could cause nuisance errors in certain situations. The question is how the search area or band should be formed to eliminate those nuisance errors.

In a Robert Bosch GmbH patent application [22] a method for determining the driving path with the aid of a navigation system is presented. The idea is to gather information about road geometry such as road width, number of lanes in each direction, connecting roads, ramps, curvature and parallel roads for a predetermined prediction horizon and use this information to predict the driving path.

It is relatively straight-forward to separate vehicles travelling in the different direction from vehicles travelling in the same direction because of their negative velocity. However, vehicles on side lanes can in certain situations easily be mistaken for vehicles travelling in the own lane, which would cause ACC to adapt the speed after them. In the method presented in [22] this problem is solved by predicting the driving path on the basis of the above mentioned information. This is illustrated in Figure 11. In the upper situation the band is allowed to be wider because there are no side lanes in the same direction. The predicted driving path is also adapted to an upcoming curve. In the lower situation, an exit is detected on the right side as well as a side lane travelling the same direction on the left side. Hence, the predicted driving path is adjusted to the situation eliminating nuisance errors.
Opinions
The use of the system is obvious. Without knowing the road geometry a band can only be selected with a standard width, which may or may not be applicable to the current traffic situation. The more information that can be gathered about the road geometry, the better the prediction of the driving path gets. Therefore it would also be a possibility to use a camera to track centre, side and/or lane dividing lines either as a complement to the above mentioned systems or as a stand alone system.

The above mentioned system is highly applicable to commercial vehicles.

3.1.9 System and Method for Controlling an Object Detection System of a Vehicle

Facts
A Ford Global Technologies, Inc. patent application [23] describes a method for controlling an object detection system with a limited range. With the aid of a positioning system and a digital roadmap, road geometry ahead can be obtained. The primary information is the horizontal and vertical curvature of the road.

The system gathers information from the map database, the positioning signal and vehicle motion sensors to create an attention plan, comprising primarily which area that is interesting for the object detection means.

For an adaptive cruise control system (ACC), this could be used to “bend” the laser search field around a corner, to get a more relevant search field for distance adaptation and/or forward collision warning. Another example that is given is that knowledge of road geometry may help in extracting interesting pieces of information from a picture (if a camera is used as an object detection means), saving image processing time.
A similar idea is used in Section 3.1.8 where a driving path is predicted. In the previously mentioned Scania CV application [12] it is mentioned that the radar antenna could be turnable during curving or when travelling uphill or downhill. Finally, in Section 3.1.11 a system is described, where a positioning system aids an ACC system in correctly classifying real obstacles in the predicted vehicle path.

**Opinions**
The system [23] is very similar to BMW’s adaptive light control system, only the same principle has been applied to an object detection means.

Even though it is specifically claimed in the application that the mentioned examples are not to be considered limiting, it may still be worth mentioning that the system could be used to discover a congestion ahead quicker than a conventional front radar could. That specific example is not mentioned in the application.

### 3.1.10 Auto Resume Apparatus for Adaptive Cruise Control

**Facts**
An ACC system is disengaged at certain driver operations such as braking, clutching and in some cases acceleration. This is a safety measure designed to keep the driver in control of the vehicle at all times. However, in a lot of situations the driver intends to resume the ACC immediately after the intervention and the disengagement becomes an annoyance.

In a Hitachi Ltd. patent application [24] a method for automatically resuming ACC function after driver intervention is described. Which speed and distance between vehicles that should be used is decided from a large number of criteria regarding the driving environment and driver action. A navigation system is used mainly to recognize the travelling environment (area) such as for example highway, street and suburb.

Other means for detecting the environment and traffic situations could be: vehicle velocity, communication systems, gear shifts and wipers. Combined, these means provide an image of the traffic situation including: which kind of road the vehicle is at, if a traffic jam situation is forming ahead and how the weather is. The driver intention is predicted from his/her actions, causing the disengagement, for example, how hard the driver has braked.

In paragraphs 30 and 35 a clear description of system action based on different brake pressures and accelerations is given. It is claimed that a heavy pressure on the brake pedal generally means that the driver intends to disengage the ACC system, and then this is also done. A lighter brake hydraulic pressure, on the other hand, is claimed only to be intended to reduce speed, but not to disengage ACC.

**Opinions**
Basically the invention is a set of logical schemes to analyze a preferred ACC resume pattern. A lot of the used sensors already exist in a vehicle which provides a cheap and relatively simple solution, regarding more control logic than actual hardware.

Yet another aid that the navigation system could provide, is the driving plan. That could provide an even better decision making basis. For example, if it is known that the driver intends to turn off at the next exit, maybe ACC auto resume is not desired. However, this is not explicitly mentioned in the patent application.
3.1.11 Stopped Object Detection in ACC

Facts

In a Ford Global Technologies Inc. patent application [25] an invention is presented that unlike conventional ACC systems can classify stopped objects to the degree necessary to actively cause a vehicle to brake in the presence of stopped objects (paragraph 7 in [25]).

The main object of the system is to inhibit the auto resume mode, and actively brake if needed in the presence of stopped traffic. The inhibit resume mode is activated if an object is detected, found not to be a valid moving target and the object is in the future vehicle path. Hence, a positioning system is necessary to enable stopped object detection, without causing nuisance errors to the ACC systems.

If stopped objects were to be detected without creating a future path profile, such would be detected at all times (for example signs, bridges and guardrails) and the ACC system would not be very useful, having to brake all the time. Therefore stopped objects and objects travelling in the different direction are not detected by conventional ACC systems. Knowledge of the future road path, however, enables the ACC system to disregard those obstacles that are not in the future path and only pay attention to true obstacles.

The system comprises a vehicle controller, which in response to an object profile, vehicle yaw rate, vehicle speed and a navigation signal determines an operating mode. That could be the follow or cruise modes as in conventional ACC, or the auto resume or inhibit resume modes.

Opinions

In auto resume mode the vehicle slowly accelerates to the preset speed, when the road is clear. However, nothing is mentioned in the patent application about different auto resume patterns on different roads. The idea behind speed adaptation due to anticipated vehicle dynamics, as described in Section 3.1.4 could be useful to enhance this system if some kind of road classification would be available in the navigation signal.

The invention [25] also presents a solution to unintended auto resume in a curve, utilizing curvature information from the navigation signal and/or the yaw rate sensor.

3.1.12 Partial Summary 1 - ACC

It is clear that positioning systems can be of great use to supply ACC with valuable information. In particular three main problems with conventional ACC have been identified; slope, curve and ramp. Solutions have been given to all three problems.

None of the investigated patents or patent applications offers a solution to all ACC problems. The main reason for that probably lies in the patent application procedure. When applying for a patent it is common that each function is applied for separately. In doing so, the applicant will not have to risk losing patentability of the entire invention if a single application is rejected.

It is also not necessarily so, that a multifunction, optimization based solution is the best method to solve each individual problem, especially not if the available processor time allocated for different calculations shall be considered.
In the theory, however, an optimization based solution, where partial cost functions are weighed after significance, appears to be a good solution to the problem of choosing a desired velocity at a certain road segment.

In a commercial vehicle, safety and fuel consumption should be given priority above driving style adaptation to each individual driver. It is crucial that the vehicle enters a curve at a safe and comfortable speed and it is crucial that speed is adjusted in a slope to minimize fuel consumption.

Even though optimization based predictive speed control systems exist, no complete ACC improvement system, fully applicable to commercial vehicles is disclosed. More cost functions could be added to improve the ACC desired velocity setting, as suggested in Section 3.1.3. No method comprising a speed limiting device that takes both the lateral acceleration factor and the loss of friction factor into account has been found.

The investigated ACC functional improvements relate to very different problems such as identifying ramps, predicting the driving path, providing a better auto resume pattern, enabling stop-and-go ACC and properly detect and classify stopped object in the vehicle path. All methods, however, utilize data of the present position in relation to the environment.

The map database that is coupled to the positioning system should contain more information than it does today. The most important pieces of information are (except vehicle position):

- Information about road curvature (given as a radius or angular change)
- Information about the transverse slope (bank angle)
- Information about road topography (data should be available in three dimensions)
- Road classification (highway, rural road etc.)
- Number of lanes in each direction
- Road width and/or lane width
- Ramp class

Figure 12 and Figure 13 shows the main actors and the trend of publication within this field of science. As we can see, the three main actors are Ford, Bosch and Hitachi. The trend of publication is remarkable, with no hits before the year 2000 and a vast increase in publications in 2003. Considering the 18 months delay between patent filing and publication there may be a connection between the S/A removal on 2 May 2000 (see Section 2.3.2) and the increasing trend of publication between 2000 and 2003. Another possible explanation is the entrance within this field, of two large, not previously active players: Ford and Hitachi.
Figure 12: Main actors within this field of science (number of total hits).

Figure 13: Publication year within this field of science (number of total hits).
3.2 Using a Positioning System to Support a Gear Changing System

3.2.1 Background

An automatic gearbox is designed to assist the driver by shifting gears automatically. Most common is a sequential gear shift pattern, based primarily on the accelerator opening degree and vehicle speed. However, the thought has risen to use the own vehicle position in relation to the environment and primarily the road inclination ahead, to provide a better gear shift pattern. The reason is primarily to optimize the gear changing strategy with respect to a set of control parameters, such as average speed, fuel consumption, emission rates and comfort.

In many Scania vehicles, a standard automatic transmission, developed by Allison is used. The Allison system has proven reliable and functions for eliminating shocks within the powertrain is included. A disadvantage, however, is the increased fuel consumption, compared to a manual gearbox.

In Scania’s own semi-automatic gear changing system, OptiCruise, gear changes can be made either manually or automatically. The clutch pedal is kept for low-speed manoeuvring to maintain control of the vehicle at all times. This is a preferred solution among many drivers, since they get all advantages of an automatic gearbox combined with the sensitivity of clutch operations at low speed ranging. OptiCruise has a hill mode, where the driver operates a switch to tell the system that an ascent is starting. In the hill mode, gear changing is initiated at higher engine speeds than in the standard mode.

3.2.2 Limitations to Conventional Automatic Gear Shifting Strategies

Lots of drivers prefer an automatic gearbox over a manual gearbox. The main reason for that is that an automatic gearbox takes some of the difficulties away from driving. It simply gets easier and less exhausting to drive a vehicle, when the driver does not have to control cluthcing and shifting gears.

However, there are also several drawbacks with an automatic gearbox, especially when it comes to commercial vehicles. The conventional automatic gearbox can be held responsible for the following:

- Worse fuel-efficiency
- Worse emission-rates
- Worse comfort (powertrain shocks)
- Unintended gear shifts
- Not shifting gears when the driver intends to
- Not adapting gear shifts to the running road to prevent the above

Hence, several improvements can and have been made to the automatic gearbox. The investigated improvements regard gear shifting strategies, taking road data of the future path, related to the present position of the vehicle into account. These strategies will be described in the next chapters.
3.2.3 Optimization Based Strategies and Predictive Gear Change Control

Facts

In a Volvo Lastvagnar patent [26] a system is described where an ECU continually performs computer simulations for the future vehicle path, based on at least anticipated road inclination and throttle position, for a set of different gear shift strategies (gear change rpm, gear regions, shift patterns). The ECU then chooses a gear shift strategy that optimizes a driver chosen control parameter, such as emission rates, average speed or fuel consumption. These parameters can be weighted individually.

A positioning system with a GPS receiver and/or an extrapolation navigation system (2.1) and a digital roadmap is used to determine the vehicle position and to predict the future path and future road inclination. Also several in-vehicle sensors are used to provide information about instantaneous vehicle speed, engine speed, throttle valve position and acceleration, vehicle weight, road inclination, driving resistance and more. Engine, turbo and transmission characteristics are also considered in the simulation.

The purpose of this system is to provide a better gear shifting strategy, considering the future path, optimizing one or more driver selected control parameters. Not only sequential shifting patterns are possible. Gears can be skipped, if such patterns turn out to be optimal with respect to the chosen control parameters.

In an older Nissan Motor Co. patent [27], a system for controlling the vehicular driving force in anticipation of the road topography ahead is described. The actual driving force at the current position is measured and then the required driving force at a future position is measured by taking into account the vehicle weight and road slope.

The engine and/or transmission is controlled in such a way that the required vehicular driving force, corresponding to the road inclination ahead, at an estimated position, is provided, but also such that fuel consumption is kept as low as possible. The controlling means are air/fuel mixture ratio, gear range shifting characteristics and torque converter characteristics ([27] column 22, rows 19 through 24). Three gear change characteristics maps are available: lower-, normal- or higher-geared and the appropriate map is selected by a comparison of the estimated required driving force and the generated driving force.

Another patent regarding predictive gear shift strategies is an Aisin Patent [28]. There a shift map which minimizes the fuel consumption is determined by comparing the estimated engine power requirement for the planned route with a prestored mileage map.

The controller described in the Aisin Patent can also control the operating status of vehicle accessories that may increase the engine load while in operation. Typical such accessories are air-conditioner, fan and defogger. Hence, these accessories can be switched off in an ascent in order to get as much driving power as possible, without consuming more fuel. Facts and opinions on this feature can be found in Section 3.3.12.

The Aisin controller calculates the constant running load horsepower, $F$, as

$$ F = k \cdot X \cdot \frac{v}{75} \ [\text{ps}], $$  

(3.6)

where $k$ is a constant, $X$ is the vehicle weight and $v$ is the vehicle speed.
Next, that value is corrected with respect to the newly received road information as:

\[ F = k(X + x) \cdot SP / 75 + f \text{ [ps]}, \]  

(3.7)

where \( f \) is the correction factor for the excess load of the accessories and \( x \) is a conversion factor, converting road inclination to an excess weight.

Next, the required engine torque is calculated as:

\[ T_e = F \cdot r / G \cdot D \text{ [kgf m]}, \]  

(3.8)

where \( r \) is the effective diameter of the driving wheels, \( G \) is the gear ratio and \( D \) is the differential ratio.

Next a constant fuel consumption rate \( F_1 \) for the constant running load horsepower \( F \) and the engine torque, \( T_e \), and an engine RPM, \( N_e \), is determined from a mileage map.

Finally, the fuel consumption rate, \( F_L \), is calculated as:

\[ F_L = F_1 \cdot N_e \cdot T \text{ [g rpm/ps]}, \]  

(3.9)

where \( T \) is the running time in hours on the section ahead. A section is characterized by having the same conditions, i.e. requiring the same driving force.

From \( F_L \) the different gears are evaluated, with respect to fuel efficiency. The gear which proves to be most fuel efficient for the current section is chosen. However, a shift is not performed if a shift back is necessary within 500 metres. In that case, the total fuel efficiency of the route benefits from keeping the current gear, even if a better fuel efficiency on that current section could be achieved than if the gear was changed.

Essentially the same technique is described in the Aisin patent EP 0 752 548 B1.

**Opinions**

The Volvo patent optimization algorithm is not described in detail, but from its description it seems rather similar to the one described in Section 3.1.2. However, [26] was written earlier than the predictive cruise control patent application [9]. The main difference is that the Volvo patent focuses on gear shift strategies, while the Daimler-Chrysler patent application [9], focuses on choosing a desired velocity. However, the means to achieve those goals are basically the same in both methods and it is reasonable to believe that a real implementation would comprise as well predictive speed control as predictive gear changing strategies.

In the Nissan patent [27], a simple solution for estimating a required driving force at an estimated future position, based on the slope between the current and future position is described. Next, one out of three gear maps are chosen, such as to produce enough driving force, yet keeping fuel consumption as low as possible. The idea is simple, but very useful in numerous applications.
The Aisin patent [28] is unique in its sense for optimizing shift schedules after a desired vehicle speed. In other words, the controller does not let the speed be a variable. Instead gear choices are variables, which results in a specific engine speed, engine torque and fuel consumption rate to provide the vehicle with enough driving force for the upcoming section.

It is important to clarify that the fuel efficiency could be optimized more than in this patent, but not if the desired velocity is to be kept. Hence, this is probably a preferred solution for vehicle drivers, ahead of a solution where speed is allowed to drop. Haulage contractors on the other hand would probably prefer a solution where overall fuel consumption is reduced more.

It is not mentioned, in the Aisin patent, how the conversion of road data to excess vehicle weight is performed. Neither is it mentioned what road data that is necessary to store. It can be assumed, however, that only information on road topology is necessary.

The optimization algorithm is fairly simple, compared to other optimization strategies, since it does not work with cost functions. Instead it works with logical schemes and simply chooses the gear that consumes the least amount of fuel from a mileage map.

### 3.2.4 Selecting a Gear Shift Map Based on Road Grade

**Facts**

In the control system described in a Honda application [29], a road grade parameter is determined from the difference between actual and predicted acceleration of the vehicle, where the predicted acceleration is the acceleration the vehicle would have on level ground in third gear. That gives an estimate of the road grade. That estimated road grade is then corrected with respect to road information from a navigation system and an estimated vehicle weight.

The navigation system is used only to determine on which type of road the vehicle is travelling and which kind of territory the vehicle is in (for example a mountainous down-grade road).

The navigation system is continuously evaluated for errors. A temporary error in the navigation system would simply cause the correction factor for the estimated road grade to fall out. That means an estimate could still be made, even if the navigation data was temporarily erroneous. In that case the gear ratio determination would not be affected by navigation data. Navigation data is mainly utilized to avoid shifts in very short slopes, where they might not be necessary.

The vehicle weight is also estimated and utilized to correct the grade parameter, eliminating the need for including road grade in the navigation information. Figure 14 illustrates the gravity force that changes with vehicle weight, while for example the air drag is the same (for a vehicle travelling with the same speed). Since the acceleration is the sum of all forces acting on the vehicle, divided by vehicle mass, it stands clear that vehicle weight must be considered to determine the road grade from vehicle acceleration.
Figure 14: Grade parameters must be corrected for vehicle weight.

Knowing the road grade and vehicle load an appropriate gear shift map can be selected where the gear shifts are functions of vehicle velocity and throttle opening. There are five possible gear shift maps: steep-upgrade, slight-upgrade, level-road, slight-downgrade and the steep-downgrade map. A typical example of how a gear shift map can look is given in Figure 15.

![Figure 15: Example of a gear shift map.](image)

Very briefly it is mentioned that the steep-downgrade map could be used also if it is known that a corner is ahead of the vehicle. However, how to choose an appropriate speed based on radius of curvature is not mentioned.

**Opinions**

Utilizing vehicle weight to correct the road grade is a good idea. However, it is not described in the application how the vehicle load exceeding a standard vehicle load is determined. One method could be to measure fuel efficiency at a level road and compare it to a reference fuel efficiency, which appears to be a simple solution if the vehicle weight cannot be determined.
by other means. Several other methods to determine vehicle load are known (one example is disclosed in the Scania CV patent application WO 03/044471 A2).

It appears that the system described is only partially aided by the navigation system and it is not predictive. In the first claim it is claimed that road information at the determined instantaneous position should be put out. That would mean that it can only be determined if the vehicle is in a slope, not if a slope is to be reached. In paragraph 167 it is claimed that road grade information does not need to be stored. Instead it is sufficient with information on which type of road the vehicle is running, such as a mountainous down-grade road or a city street. The advantage of this compared with calculating road grade from nodes with altitude data is that the volume of calculation decreases. However, a drawback is that the system does not utilize the full potential of predictive road information.

The illustration in Figure 16 can be used to describe the need for road classification from the navigation system in this patent, even if road grade data is not stored. If the controller knows that the vehicle is on a mountainous up-grade road, an unnecessary up-shift can be prevented in the short down-slope in sector B in the figure. Without the navigation system, other vehicle sensors would have noticed a downslope and might have performed an up-shift. That is presumably the reason for the correction factor from the navigation system.

![Figure 16: Mountainous up-grade road.](image)

Essentially the same technique is described in US 6, 275, 760 B1.

### 3.2.5 Automatic Transmission with Learn Mode

**Facts**

In the IBM patent application [30] a system is described where a Global Positioning System and a monitoring device for the automatic transmission is utilized to determine if the performance of the transmission can be improved at a certain position.

The system continuously monitors the transmission performance (for example all gear shifts, time in each gear and engine speed), general vehicle performance (primarily fuel efficiency) and the current position.

The performance data of the transmission is logged and coupled to a specific position or road segment. When the vehicle approaches a certain position for the first time or when vehicle
conditions differ a lot from the previous approach, the event is stored as a one-time event and the factory threshold values for the transmission is used. All unnecessary shifts and/or inappropriate shifting positions using previously set threshold values are logged and new, more appropriate threshold values are set for the next approach. An unnecessary shift is characterized by an up-shift followed by a down-shift within a short, predefined time interval (or opposite). Hence, the system is learning from its previous mistakes.

If the vehicle arrives at a position that previously has been visited, it is not certain that the new threshold values which are coupled to that position can be used. If the vehicle load is very different from the last approach, the new approach is characterized as a one-time event and factory threshold values are set.

Opinions
This is a fairly simple method and system that, surprisingly, seems unique in its sense. The threshold values are updated after an evaluation of previous behaviour at a certain position. If the unnecessary shift was a down-shift, the new threshold should be lower. On the other hand, if the unnecessary shift was a shift to a higher gear, the new threshold values should be higher. A few different suggestions to the implementation of such a system in the vehicle are displayed in the figures 8, 9A and 9B in [30].

Due to its nature, the system does not improve transmission performance on a road that has not previously been visited by the vehicle. Naturally, that is a large drawback. However, the system does not need an expert driver; instead it evaluates its own performance continuously, to determine if better threshold values can be set. It is also, as mentioned above, a simple solution, basically comprising just monitoring devices for fuel efficiency and gear shifts, a memory to log shifts and positions and a set of logical schemes.

Possibly, if this method [30] is combined with another method the factory settings could be improved such that it also performs a relatively good gear shift when the vehicle approaches a situation for the first time. That could include the use of in-vehicle sensors and/or map data from a positioning system.

A similar idea was presented in the Aisin patent application, [31], which was published already 1996. Also in [31], a gear shift pattern is coupled to a position and used when the vehicle approaches the same position next time under similar conditions. However, in the Aisin application, the system cannot recognize and/or learn from unnecessary gear changes. Instead the purpose of that system is to determine a gear map based on driver activity and then shift to that gear map automatically, when the vehicle approaches the same location under similar conditions. That is if the driver indicates that he/she is not satisfied with the choice of gear map the system learns to use another gear map next time. There are only two available gear maps: Power and Economy mode. The system is probably not designed for commercial vehicles in slopes, but simply to automatically learn the driver’s preferred gear shift characteristics at specific locations and times.

3.2.6 Inhibit Unnecessary Gear Changes in Corners
Facts
Conventional automatic gearboxes could suffer from the problem of a frequent shifting when approaching a curve, due to driver intervention (such as pressing the brake or accelerator pedal). The problem is called busy-shifting. That is an unnecessary upshift or a downshift caused by only a small change in driving conditions. Busy-shifting can lead to increased fuel
consumption, higher emission rates and driver annoyance. If the curve was to be detected earlier, unnecessary downshift/upshift operations could be inhibited and a better shift pattern for the curve could be set.

This is done in a Toyota patent [32] by allowing a gear stage region having a high gear ratio to be wide if a curved road is detected. In other words, if the vehicle is travelling a curved road, the gear stage regions for the lower gears are wider than normal. Hence, even if the accelerator pedal is depressed or released, the frequent gear shifts that usually follow from such behaviour do not occur. Instead the vehicle stays in a higher gear ratio, so that a sufficient driving force can be retained. As a result of this, drivability and comfort are said to be improved.

The Toyota patent [32] also provides several other solutions for transmission control based on road data. For example, gear stage regions having a low gear ratio are widened in residential areas in order to lower the engine speed and hence improve the vehicle’s fuel economy and sound level. Another example is that the control system makes the shift pattern liable to set a relatively higher gear ratio in downslopes, in order to inhibit up-shifts and increase engine brake torque.

Recognition of residential regions and road geometry is made from a positioning system coupled to a digital three-dimensional road map.

Another solution to the busy-shifting problem is described in the Toyota patent US 6,740,006 B2. However, in that patent, information about the upcoming road section is not utilized.

Opinions
In Section 3.1.3 a number of methods to control speed in a curve are described. In most of those patent documents a massive description of how to calculate a safe speed in the curve is given. Few of the investigated documents on transmissions contain such detailed descriptions. Instead a safe speed for the specific curve is already given and a deceleration curve is calculated accordingly.

The Toyota patent [32] is probably the most comprehensive patent in transmission control aided from positioning systems. It contains several methods and ideas on how transmission performance can be improved, all having that in common that gear stages having either a higher or a lower gear ratio are widened, so that the shift pattern is liable to set a relatively higher or lower gear ratio depending on the situation.

3.2.7 Utilizing Distance to a Specific Section to Control Gear Change

Facts
In an Equos Research patent [33] a system is described that controls an automatic transmission utilizing a route guidance system (GPS and digital road map), taking anticipated changes in the driving conditions into account. That could be achieved with information about specific positions where a downshift may be necessary, such as intersections, curves, train crossings, ramps, tollgates and places where the width of the road changes. By utilizing the distance between the present position and the specific positions mentioned above, a smooth deceleration and/or downshift can be achieved, eliminating driver uneasiness.

In the Toyota Patent [34], another system that utilizes distance to a position where a downshift may be necessary, such as an intersection, is described. The main concern for this system
is to prevent a shock in the powertrain, caused by sudden working of a one-way clutch, when the vehicle accelerates after a deceleration near or in an intersection. This is done by prohibiting a down shift until the vehicle speed is smaller than a predetermined speed.

**Opinions**

The principle of these patents is highly applicable to commercial vehicles. The knowledge that a curve appears in a specific distance from the current vehicle position allows a smooth deceleration accordingly and allows smooth down-shifts at appropriate times.

However, it is not certain that knowing about an intersection in advance is necessary to perform a smooth down-shift. Ordinary automatic transmissions have gone through a massive development over the last few years, including software to eliminate shocks in the powertrain. That is the case in the Allison A/T systems used in a lot of Scania vehicles. Hence, it would be interesting to see if the powertrain shocks actually are more frequent in A/T systems that do not use navigation data (as claimed in patent [34]), or if that statement is based on early A/T systems only.

In a previous Equos Research patent [35] a more detailed description of how the proper vehicle speeds and gears should be chosen in different situations is given. Apart from certain differences patents [35] and [33] are similar. It appears the US patent [33] is a stripped down version of the European patent [35].

The patent [34] appears to be even less detailed than [33]. Nothing is mentioned about the radius of a corner. The only information that can be read out is position of intersections relative to the vehicle, whether an intersection is near, whether a road is curved, sloped or not. The type or road can also be read out. However, given that information, it is hard to see how a correct deceleration can be calculated.

The system described in [35] contains up to six means for determining the current position. Probably the idea is that only the GPS and maybe one dead-reckoning method shall be used. In the patent, however, the inventors may want to be sure to cover all possibilities.

The patent [35] also contains means for calculating road slope to a specific position ahead where a shift of gears may be necessary, but this information appears to be used mainly to determine deceleration curves, for example before a turn.

The above mentioned patents, all aim to select an appropriate shift pattern to follow a calculated deceleration curve. The individual differences are small and generally the differences relate to detail of information of the road situation ahead.

### 3.2.8 Driving Force Control Apparatus for a Continuously Variable Transmission

**Facts**

In an Aisin and Toyota patent [36], a driving force control apparatus is described, in which a continuously variable transmission is used. The target input number of shaft rotations, of the variable transmission, is a function of necessary deceleration and the accelerator opening. These functions are stored in the onboard memory.

The navigation system and digital map is used primarily to aid a driving force control apparatus in corners. Road gradient is also estimated, but only from current driving
conditions, and with the aim to correct the target input number of shaft rotations required for handling the vehicle in a curve.

The road data is based on nodes. Curves ahead are classified into three categories: gentle, moderate or sharp corners depending on the turning angle, $\theta$, between tangents going through nodes at a specified distance ahead of and behind a node, $i$, on the curve.

From the turning angle and the distance of the arc a curve radius can be calculated. Given that radius and a maximal accepted lateral acceleration, at that position, a maximal allowed velocity can be calculated. From that velocity a recommended deceleration can be calculated. These deceleration curves are then used as input to select a desired number of shaft rotations of the continuously variable transmission for the upcoming road section. Please note that the following expressions describe the method in the patent [36]. In other methods different expressions for calculating a deceleration curve may be used.

Accepted lateral acceleration: $a_L = \frac{v_{ni}^2}{r}$

Recommended deceleration: $G_i = \frac{v_0^2 - v_{ni}^2}{2 \cdot L_i}$, where

$v_0$ is the present velocity,
$v_{ni}$ is the recommended velocity at the node, $i$,
$r$ is the estimated radius of curvature at the node $i$, and
$L_i$ is the distance to the node, $i$.

**Opinions**

None of Scania’s vehicles are equipped with a continuously variable transmission. However, the concept is interesting and presents a fairly simple solution that in its simplest embodiment also could be applied as a regular gear shifting strategy. A recommended deceleration in a curve is calculated from node data, the deceleration curve is corrected for missed road data using an extrapolation navigation system and then the deceleration curve can be used to determine when to perform a gear shift.

The same strategy could easily be applied to vertical curves (slopes). What is missed here is the road bank angle which is usually applied to sharp corners. Knowing the road bank would give a better recommendation to the recommended safe speed in a curve. For an evaluation of road bank angle information, see Appendix A.

### 3.2.9 Method for Controlling Automatic Gear Change

**Facts**

In a Toyota patent application [37] a system is described, where a gear change controller changes gears as a function of vehicle speed and throttle valve opening degree (as usual), when travelling on a straight, flat road and as a function of road curvature and/or road inclination when travelling in a curve and/or slope.

Here a node system is also used to determine a turning angle and a radius of curvature, as described in Section 3.2.8. Curves are classified as gentle, middle or hairpin curves. Road inclination is determined on the basis of previously stored reference acceleration and the current vehicle acceleration.
The extracted information (on upcoming curves and/or slopes) is used to determine up-shift and down-shift patterns. Different actions are performed based on curve class and road inclination.

The deceleration curves here are different from those calculated in chapter 3.2.8. Here, the desired deceleration is constant (ramp), starting from a certain distance before the corner to ensure that the vehicle has reached a safe curve speed before the curve.

The actual vehicle speed is then compared to the calculated deceleration curves and gears are changed accordingly, unless brake or accelerator operations show that the driver intends to inhibit a gear change.

In the Toyota patent application [37] a left/right curve detecting means is also used. Naturally the road curvature differs if the vehicle travels on the right or left side of the road. On a multi-lane road the difference can be significant. The problem is illustrated in Figure 17. The vehicle on the left side of the road travels through a curve with the radius $r_2$, which is a much gentler curve than the vehicle on the right side. Hence, if road node data is given only as the centre of the road, information on whether the curve is a left curve or a right curve must be supplied to get a correct estimation of the road radius of curvature. Supplying lane width or road width and number of lanes is also a necessity to correctly estimate road curvature.

![Figure 17: Same curve, different curvature.](image)

**Opinions**

This patent application classifies curves as gentle, middle or hairpin. The advantage of that is that it provides a fairly simple solution. However, it can also lead to a gear changing strategy that is not as precise as it would be if the exact radius of curvature is used.

The problem with different road curvatures in different lanes in the same curve was first brought to my attention through this application. Considering that this is a large problem, especially on multi-lane highways, it is surprising that this has not been mentioned explicitly earlier. More detailed information and calculations on this matter is available in Appendix A. However, this application only utilizes knowledge of road direction, i.e. if the road turns right or left. Nothing is mentioned about utilizing information on road width, number of lanes or lane width that might be necessary to extract a correct radius of curvature from node data.

Another possible solution would be to have a set of nodes for each lane, i.e. considering each lane to be a different road.

### 3.2.10 Other Gear Shift Strategies

**Facts**

In a Scania CV patent application [38] a method is presented where a gear shift in a semiautomatic or automatic gear changing system is prevented if one or more spinning wheels
are detected by the traction control system, TCS. The derivative of the acceleration, which indicates the difference between the vehicles acceleration and a previously calculated acceleration, is also used to determine if the wheels are spinning.

To estimate the acceleration the formula $a_n = \frac{\Delta v}{\Delta t}$ is used, where $\Delta v$ is the speed difference between the current speed and the speed $\Delta t$ seconds earlier.

A positioning system, such as GPS is mentioned as a possible means to determine the actual vehicle speed. Naturally, the speed indication from the wheel sensors may not be trusted if the wheels are spinning.

Two methods to prevent gear shifts are suggested. One method is to indicate gear shift prevention through an indicator. The other method is to drastically increase engine speed intervals for each gear. The result in both cases is that the vehicle stays in the same gear, keeping maximal gripping power.

3.2.11 Partial Summary 2 – Gear Changing Systems

Different gear shifting strategies have been developed ever since the automatic transmission first appeared on the market and several improvements have been made. However, solutions that utilize a positioning system to develop a gear changing strategy for an upcoming road section are not particularly common. Instead, the most common solution is to choose a gear ratio based on the current vehicle speed and driver action (through the pedals) according to a fixed map. It is also known to base the gear ratio on the current road inclination and other parameters that affect the forces acting on the vehicle.

Undoubtedly, knowledge of road inclination ahead can be useful when choosing whether to perform a shift or to inhibit the shift. An optimization based strategy can be used, where one or more control parameters are weighted and/or unnecessary gear shifts in slopes can be inhibited.

Also, a lot of solutions exist, where information on upcoming corners are utilized to optimize the gear shifts. Even there unnecessary gear shifts can be inhibited and anticipated changes in driving conditions can be utilized to perform a smooth deceleration and shift pattern. However, there are several different suggestions as to how that deceleration should be performed and curves classified. It shall also be mentioned that not only a curved road presents corners, but also turns in the route to be followed (intersections).

It seems that the level of detail on how to extract the shape of a corner is generally lower in these patents and applications, than in those concerning ACC-systems (Section 3.1). As shown in Appendix A, the means for extracting a curve radius matter to the recommended speed in that curve and it is clear that the transverse slope must be considered in order to get a correct recommended speed and thus gear, even if the curvature is known (This is shown in Appendix A).

With some individual differences, the utilized information is: current position, future road inclination, allowed speed, upcoming curves and other specific positions where a downshift may be necessary, such as intersections, curves, train crossings, ramps, tollgates and places where the width of the road changes.
One obvious use for positioning systems in Scania's semi-automatic gear changing system Opticruise is that the slope switch could be eliminated and the corresponding function could be improved, using different shift maps for different slopes, using predictive decision means, instead of decision means based on current vehicle status, as today. In addition, a function for descents could be built in, where upshifts in descents are inhibited.

The gear changing system has much to gain from positioning systems. The key is to use different gear change maps in different situations, and not be locked to one gear map which has been developed to somewhat fit all situations. The proper gear map can be chosen with respect to anticipated required driving force (based on road slope, vehicle weight and/or driver intent) or with respect to a deceleration pattern.

With the aid of navigation data, up-shifts in descents can be inhibited in order to increase engine brake torque, saving both service brakes and fuel. Also, unnecessary gear shifts can be inhibited, saving fuel and decreasing powertrain stress. The systems described in [28] and [30] are also good examples of where the transmission as a stand-alone system can benefit from positioning data.

In Figure 18 and Figure 19 the main actors and trend of publication within this field are displayed. As displayed in the diagram, Toyota and Aisin AW and its research company Equos research are leading this field.

Regarding the publication date, it can be noticed that patent applications have more than doubled in 2001 compared to the previous year. Possibly this is a result of the first step in the GPS modernization, the removal of the intentional degradation of the civil GPS signal on 2 May 2000. More information on this matter can be found in Section 2.3.2.

![Figure 18: Main actors within this field of science (number of total hits).](image)
Figure 19: Publication year within this field of science.
3.3 Using a Positioning System to Support an Engine Controller

3.3.1 Background
An engine can be tuned after the estimated running resistance of a vehicle, utilizing a positioning system. An engine can be controlled in numerous ways, such as amount of fuel injected, opening degree and timing of valves, amount of recirculated exhausts, compression of air and more. However, it is important to realize that the output is not only a specific engine torque or power, but also different levels of emissions and different fuel efficiencies.

Systems that relate to adaptive and/or conventional cruise control systems, i.e. means for choosing a desired speed based on vehicle position are dealt with in Section 3.1.

3.3.2 Limitations to Conventional Engine Control
A combustion engine is a great means to provide power for a vehicle. However, it does suffer from some drawbacks that could be eliminated, or at least improved with the aid of a positioning system. In short it is a matter of three major problems:

- Too much vehicle emissions
- Too much fuel consumption
- Too poor performance adaptation in transient processes

Combustion of hydrocarbon fuels, such as diesel, causes emissions of carbon dioxide (CO$_2$), which is a necessary by-product of a complete combustion and a contributor to global warming, carbon monoxide (CO), which is toxic, and hydrocarbons (HC), which result from incomplete combustion. Nitrogen oxides (NO$_x$) form when the hot, burnt hydrocarbon fuel rapidly cools in the surrounding atmosphere. These solutions are highly applicable considering upcoming environmental standards Euro 4 and Euro 5, where nitrogen oxide exhausts and particulates exhaust must be decreased radically.

Scanias already operable solution for Euro 4 is exhaust gas recirculation (EGR) in order to avoid the need for additives (as in selective catalytic reduction, SCR). EGR can be controlled with the aid of a positioning system as will be described in Section 3.3.3.

Naturally, it is desired that the vehicle consumes as little fuel as possible. Hence this will be discussed through the entire chapter.

An engine is generally designed as a compromise between different desired performances in different driving situations. There are methods to alter the operation of the engine with engine load, but ahead knowledge of changes in engine load is rarely used.

3.3.3 Controlling Exhaust Gas Recirculation (EGR) based on Future Engine Load

Facts
In a Volvo Lastvagnar patent [39] a method for controlling exhaust gas recirculation (EGR) based on the future engine load is described. For a description of the technique to estimate the future engine load, see Section 3.2.3. There a related Volvo Lastvagnar patent [26] is described.
The addressed problem is that an incomplete combustion may occur in combination with gear shifts with EGR in operation. Hence, smoke may appear from the engine exhaust manifold when the engine torque is reduced in a gear shift. The reason for that is that the recirculation valve is closed too late and that therefore some exhausts are left in the intake manifold. When those exhausts are combusted, particle emissions are increased. This may appear as smoke.

With the previously described technique to determine a future engine load and estimate when a gear shift will be performed, the valve can be closed at exactly the right time and no exhausts will be left in the intake manifold. This control is performed with respect to fuel efficiency and vehicle emissions when a change in vehicle conditions occurs.

Other anticipated changes in vehicle conditions (than gear shifts) may be torque reduction at the top of a hill or torque increment after the end of a descent.

Essentially the same technique is described in WO04111415A1.

**Opinions**
The idea to regulate the EGR valve after anticipated changes in engine torque is good. However, it is not certain what there is to gain with closing the EGR-valve completely before a torque reduction.

![Diagram of EGR purposes](image)

**Figure 20: Purpose of EGR.**

The purpose of EGR is primarily to reduce the amount of NO\(_x\) emissions, by recirculating exhausts and use exhausts instead of air to fill up the cylinder in order to lower the rate of combustion.

Since the specific heat capacity of the EGR-gas is much greater than for air, the rate of temperature rise in the cylinder is reduced, such that the combustion takes place at a lower temperature and therefore NO\(_x\) exhausts are reduced.

When more power is needed from the engine, it would be rational to increase the air ratio in order to be able to combust larger amounts of fuel and to feed the turbine with higher temperature gases. Hence, it would be a reasonable measure to close the EGR-valve just in time before an uphill slope (torque increase), not when engine torque is presumed to be reduced, like in a gear-change or just in time before a downhill slope, as suggested in the Volvo patent. The problem with that approach (to close the valve before a torque increase), though, is that it could be difficult to meet exhaust requirements.
The main reason to close the valve before an anticipated gear change, is rather that a boost pressure could be built up during the gear shift than a reduction of visible smoke. This is not mentioned in the Volvo patent.

In the end it is not a matter of performing a discrete control (open or closed valve) but a continuously variable valve control to meet exhaust regulations for as well particle as NO\textsubscript{x} emissions. Volvos solution may decrease the amount of visible smoke (particle emissions); however NO\textsubscript{x} exhausts may actually increase. Clearly, a trade-off is necessary.

It also seems as if the need for using a positioning system to control the EGR valve is very small, since the time horizon from output of a signal to valve actuation is very small. Even without a positioning system gear changes can be anticipated further ahead than the time horizon, by using different in-vehicle sensors.

3.3.4 System and Method to Control Injection of Reducing Agent with the Aid of a Positioning System

Facts
In order to fulfil the reduction of nitrogen oxides in exhausts required in the Euro 4 and especially Euro 5 standards, one idea is to use so called Selective Catalytic Reduction (SCR). SCR is an after-treatment of the exhausts, where a urea-based additive (reducing agent) is injected into the catalyst to react with the nitrogen oxides and form nitrogen and water.

SCR was first developed for industrial stationary applications, such as power plants and gas turbines. Hence, one of the unsolved problems is to develop a strategy, to make SCR efficient also under transient operating conditions. In prior art mobile solutions, SCR is primarily efficient at highway speed with high engine load and high gross weight.

A method and device for controlling the injection of reducing agent is described in the Scania CV application [40]. In that application a computational model is used to estimate the nitrogen oxide conversion level and create a closed-loop control system for the injection of reducing agent.

An investigation [41] performed by the US Department of energy shows that the price for urea based additives may be as high, or higher than the price for diesel.

In a Cleaire Advanced Emission Controls patent application [42] a method of simultaneously monitoring, logging and controlling an industrial process is described. In particular the patent relates to methods for engine exhaust after treatment and SCR in vehicles is mentioned as one of the possible applications. In paragraphs [0062] and [0105] it is mentioned that a GPS-receiver could be used to control the process based on which air quality district that the vehicle currently is driving in (geographical/jurisdictional area).

Opinions
The Scania application [40] provides a good method and device to control the injection using a closed-loop system. However, the problem with determining what levels of conversion that are desirable remains. Considering the price of urea, it is not certain that the same levels of conversion are desired everywhere. The method presented in [42], however gives a solution to that problem.
The method [40] also suffers from the problem of being non-predictive. Hence, it would be desirable to inject different amounts of reducing agent depending on the anticipated future workload of the engine and the entire vehicle. In order to do this a solution where a positioning system is used is suggested:

Anticipated transients such as gear shifts or changes in engine load could be utilized to adjust the injection to the current and/or predicted driving operation mode. A predictive system aided by a positioning system could allow the system to operate at its full potential, without risking so called ammonia slip (when accumulated excess ammonia is released from the catalyst). When a change in driving conditions or a transient is expected the amount of injected reducing agent can be reduced in time. The gain is a better NOx conversion and a better fuel efficiency when operating the system at its full potential and an elimination or at least a reduction of the risk of ammonia slip at sudden changes in driving conditions.

The method comprises the following steps:

1. Load a vertical road profile
2. From the road profile, an inclination, $\alpha$, at every position is given.
3. From $\alpha$ the vehicle is modelled with respect to the longitudinal forces acting on the vehicle. A typical example is given in [43], but other models can be used. Yet another example is the model used in Section 4.1.2.
4. The model is used to determine a desired engine torque at that position, either by utilizing the model in a speed controller optimized with respect to fuel efficiency, whereby the torque is given from an optimization algorithm, or by assuming that a constant speed is held, whereby the desired torque easily can be calculated from the model.
5. The engine speed and other engine specific control parameters necessary to deliver a specific torque are given from look-up tables.
6. The engine specific control parameters are used as input data to a complete engine model where gas flow, temperature and composition is estimated from the input data.
7. The exhaust gas parameters are used to control an exhaust aftertreatment system, such as, but not limited to, a selective catalytic reduction system (SCR), towards optimal performance. That could be for example the injection of reducing agent before the catalyst.

No patent document or article regarding this solution for reducing agent injection control has been found in this mapping.

3.3.5 Adaptive Emission Control Using Fuel Injection

Facts
In an expired United States patent [44] an adaptive emission control method is described where a timing map for fuel injection is chosen on the basis of the geographical and jurisdictional location. For example, an ultra-low emissions, non optimally fuel efficient timing map can be used in a city with strict regulations and very polluted air, while a low emissions, optimally fuel efficient timing map can be used otherwise.

The emissions that is claimed to be lowered with the ultra-low emissions timing map are primarily ozone precursors and other non-$\text{CO}_2$ pollutants. It is also mentioned in the patent that the same principle could be applied to other emission control devices.
Opinions
This patent has certain similarities to the ones described in Section 3.3.6, although this system is focused on emission control. The system is highly applicable to commercial vehicles.

3.3.6 Choosing a Fuel Map for the Engine based on Vehicle Location

Facts
In a Cummins Engine Company patent [45] an engine fuel map is selected based on the current vehicle position. The different maps comprise at least the following modes: A low emissions fueling mode, a fuel economic fueling mode and a high engine output fueling mode for urban, rural and hilly geographical locations respectively.

In other words, if the engine is in an urban area the focus is laid on low emissions, in a rural area or highway the focus is laid on fuel efficiency and finally in hilly conditions, such as a mountainous area the focus is laid on maximum power output (if desired from the driver).

The different geographical areas are recognized by matching the current position, from a GPS-receiver, with a specific region on a digital map. If it is determined that the vehicle is in a specific region, the fuel map is changed accordingly and otherwise a default fuel map is used.

An earlier Cummins patent application, EP 0 581 558 A1, describes a method where a choice can be made between two different fuel delivery curves, where the second fuel delivery curve provides more power than the first one. The choice is based on road grade, and the main idea is that the switch to high power output should be done if the vehicle speed falls a predetermined delta miles per hour below a learned speed of the vehicle. Another embodiment is also shortly described, where a positioning system could be used to determine which fuel delivery curve to be used.

Finally, an International Truck patent [46] describes a somewhat different method of fuel map selection. In [46] a centralized control system is suggested, from which a fuel map depending on the geographical position can be selected. A couple of different fuel maps are stored in look up tables in the vehicle, and the centralized system only selects which one to use. The vehicle is also equipped with a GPS unit to provide the vehicle position. All communication between the centralized control system and the vehicle is performed via a two way wireless communication system. However, it is not mentioned explicitly which one. The main difference between this system and other systems is that in [46] it is not necessary to store a digital road map in the vehicle. Instead a complete GIS system can provide necessary, well updated information from the centralized control system. It is mentioned that this can be particularly useful for military vehicles in hostile areas.

Opinions
The Cummins patent [45] is probably a solution that is preferred among drivers, since power is accessible when needed (such as in a mountainous region). Many solutions, where fuel efficiency is optimized based on road topography do not provide full power in an ascent and speed is allowed to drop to a minimum at the top of the hill. This may be a great feature for the test track, however in a real road environment; all extra power is appreciated by a driver when driving uphill. In the mean time the driver can accept less power when the vehicle is travelling a flat road at constant speed.
Another advantage is the decreased need for down-shifts in an ascent, which may decrease powertrain wear.

Similar solutions exist that are not based on a position system. Then primarily vehicle acceleration is measured and evaluated. A constant stop-and-go pattern would for example indicate that the vehicle is in an urban area. Likewise, no acceleration would indicate a constant speed travel on a rural road or highway.

The recognition of a change of areas does not require the positioning means to be extremely accurate and it does not require recognition of road grade or bank angle at every position. Hence, this is a function that relatively easy could be built into existing navigation systems.

The centralized control method suggested in [46] provides a simpler implementation in a vehicle, at the expense of a communication system and a central control system coupled to a Geographical Information System (GIS). The main advantage of this method is probably its built in ability to quickly update geographical information. However, systems like [45] may only need slight adjustments of the information already available in a route guidance system to accurately select a fuel map. Hence, the centralized method seems unnecessarily complex in most cases. Exceptions are cases where a fast update frequency of the geographical information is necessary, for example as the mentioned example with a vehicle travelling a hostile area or possibly in cities where emissions regulations tend to change often.

3.3.7 Valve Control based on Anticipated Future Changes in Engine Load

Facts

In a Volvo Lastvagnar patent application [47] a method is described where valve timing and/or valve lift height can be adjusted according to anticipated driving conditions while the vehicle is driven. Among the mentioned benefits are: better efficiency, increased component life, less emissions and better power performance.

One advantage with variable valve timing is the ability to operate the engine in different operating modes in different driving conditions. For example, the same engine could operate either according to the Miller cycle (as described in Miller’s patent US 2670595) or the ordinary Diesel cycle and change between the two when conditions change.

The basic idea behind the Miller cycle is that the intake valve is left open longer than it normally would be. As the piston moves back up in what is normally the compression stroke, the charge is being pushed back out the normally closed valve.

Instead the extra, needed charge is delivered from a supercharger. Hence, by allowing the actual compression to start first when the piston has pushed some extra charge out, each stroke is shorter. Yet the same compression is delivered, thanks to the supercharger. A gain with this is improved fuel efficiency, since less work is needed by the engine for the same compression.

The supercharger typically will need to be of the positive displacement kind (due to its ability to produce boost at relatively low RPM) otherwise low-rpm torque will suffer.

The Miller cycle "works" as long as the supercharger can compress the charge for less energy than the piston. In general this is not the case, at higher amounts of compression the piston does a better job. However, the key is that at low amounts of compression the supercharger is
more efficient than the piston. Thus the Miller cycle uses the supercharger for the portion of
the compression where it is best, and the piston for the portion where it is best. To this end
successful production versions of this cycle have typically used variable valve timing to
effectively switch off the Miller cycle when efficiency does not meet expectation.

The gain of using a positioning system is that it can provide a certain look-ahead to avoid
unwanted delays when shifting between operating modes. For example, the change between
Miller and Diesel cycles can be performed before a vehicle starts to climb a hill (and needs
the extra power).

Opinions
There is another advantage with using the Miller cycle at low amounts of compression. By
letting a supercharger or turbocharger compress the air instead of the piston and letting an
intercooler cool the air before it reaches the cylinder, the same compression can be reached at
a lower temperature. Since nitrogen oxides ($\text{NO}_x$) are caused by high combustion
temperatures, such emissions can be lowered.

All this was known in the fifties, when the patent was published by Miller. The idea of the
Volvo patent application [47] is to utilize knowledge of future road topography and transients
(for example gear-shifts and torque reductions) to control valve timing at the right moment.

The application does not mention explicitly why it should be necessary to alter the valve lift
height.

3.3.8 Supercharger Control
Facts
In a Volvo Lastvagnar patent application [48] a method to control a supercharger in a
combustion engine with respect to future transients (for example gear shifts) is described. The
idea is to alter the geometry of the turbine and/or regulate a waste-gate valve, in time before
the extra power is needed. Hence, the turbo delay can be eliminated and changes of boost
pressure can be made in advance.

In situations where a reduction in torque is expected, such as a vehicle approaching the top of
a hill, the geometry is changed so that the boost pressure drops before the expected torque
change. Also, an anticipated increase in torque, such as a vehicle about to start climbing an
ascent, will cause the geometry to change, so that the boost pressure is raised beforehand.

Opinions
This is applicable to all variable geometry superchargers. However, it is questionable if the
time horizon for the turbo delay is so big that a predictive supercharger control is worth the
effort. This could be subject to tests. It is possible that such a prediction could be done
internally, even without the aid of a positioning system.

3.3.9 On Board Diagnostics (OBD) Enhanced with an Electronic Horizon
Facts
In a Ricardo UK Limited patent application [49] a method for enhancing an on-board
diagnostics system of a vehicle with an electronic horizon is described. The electronic horizon
comprises primarily position from a GPS aided navigation system, telematics, traffic info and
weather.
The idea is to determine the optimal conditions to carry out the diagnostics (for example timing and frequency). A number of suggested uses for the electronic horizon is given in the application. For example to minimize intrusive and/or aborted diagnostics. One of the more common diagnostic strategies is to alter engine operation to generate a known response. With the electronic horizon such diagnostics could be performed unaborted, when the vehicle is in a desired state for the diagnostics. Hence, the number of aborted diagnostics could be minimized, fuel could be saved, emissions reduced and component life could be prolonged.

Other advantages are reduced processor loading and memory occupancy of the OBD routines, leaving capacity for other features. It is claimed in the application that as much as 65 % of the ECU is occupied with diagnostic routines. Hence, a lot could be gained from a better scheduling with the aid of environment recognition means.

Opinions
Regarding the decreased processor and memory load, this naturally must be weighed against the increased load by implementing an electronic horizon. On the other hand, as mentioned in the application, these features may still be available for other functions.

The application is low detailed when it comes to how the scheduling actually should be performed. What is described is simply that means for determining traffic situation and road geometry could be used to schedule OBD routines in a better way. However, a person skilled in the art is considered to understand the situations where the respective diagnostics are best performed.

3.3.10 Choosing Boundaries in an Engine Output Characteristics Map based on Vehicle Position

Facts
In a Cummins, Inc. patent [50] a system for controlling a combustion engine is described. The basic idea is to store an engine output characteristics map in a memory, where engine output is displayed as a function of engine speed (RPM). Then certain borders (limitations) are applied to the engine output characteristics map, restricting engine speed if needed to improve fuel efficiency.

Next, the current gear ratio and vehicle speed are determined and the borders are modified accordingly. The means for controlling engine speed is the fueling.

The utilization of a positioning system is only one embodiment of this system. However, some useful ideas on how to adapt the output of the engine to the environment are presented. It is claimed that knowing which kind of area the vehicle travels (rural or urban), region topography characteristics (hilly or level) or jurisdiction (country, state, county, etc.) could be useful, since fuel efficiency goals may be different depending on these factors. A continuation in part (CIP), US 6,957,139 B2 has recently been granted (2005-10-18) but the changes do not concern how the positioning system is used.

Opinions
This patent has actually quite little to do with positioning systems. The use for positioning data from a GPS-system is mentioned as an extra side feature and it is not disclosed that the system aims to be predictive.
Instead, it is the idea of different fuel efficiency goals in different regions (topographical, jurisdictional or geographical) that is interesting here. It is not too far fetched to believe that also accepted emission levels may differ with these regions. Basically the same idea is mentioned in the previously discussed patent [45], even though the means for achieving the performance adaptation are different.

### 3.3.11 Controlling a Combustion Engine of a Vehicle with Automatic Stop/Start Function

**Facts**
In a Ford Global Technologies, LLC patent [51] a method to automatically control start and stop of an engine is described. It is said that if an engine is switched off for more than a threshold period of time, fuel has been gained from the switching off.

Hence, this patent describes a method to determine if the switch on/off feature of the engine should be enabled or not, based on vehicle speed, time, brake monitoring and region. If a stop-and-go situation occurs, like in a slow moving queue, this method suppresses the switch off, in order to avoid uneconomic switching off.

Typical indications of stop-and-go situations are repeated activation of the brake or the vehicle being in an area prone to stop-and-go traffic at a specific time of day. The latter can be determined with the aid of a GPS-receiver and a digital map.

**Opinions**
This is a very simple idea to switch the engine off only when it is relatively more economic than to keep it running. However, very few, if any, commercial vehicles are equipped with an automatic stop/start function today. The reason for this is probably the relatively higher torque required and the life expectancy of the starter in a commercial vehicle.

### 3.3.12 Scheduling and Control of Vehicle Accessories Connected to the Engine

**Facts**
It is mentioned in the Aisin patent [28] that the operation mode of vehicle accessories that may affect the fuel consumption (A/C, fan, defogger), can be scheduled with respect to road data. The idea is basically to switch accessories off in a situation where high power output is required, such as in an uphill slope, and switch accessories back on when the higher power output no longer is required. This control can be either non-predictive using sensors or predictive using a positioning system. The Aisin patent has previously been discussed in Section 3.2.3 and primarily relates to transmission control.

In a Scania CV related publication [52] an optimal control method for the cooling system of a vehicle is presented. The idea is to minimize fuel consumption when driving the generator, keeping the temperature of the cooling system within certain limits. Hence, a simulation model is developed and an optimal control strategy is presented for a prediction horizon (known road grade). A positioning system can provide the algorithm with altitude data.

**Opinions**
The problem is that auxiliary systems today are mostly mechanically connected to the engine. Since these systems must function properly in all situations a surplus capacity in the most
common driving situations are built in. If, however, these systems could be electrically driven they could be controlled according to the above mentioned optimal strategy.

Therefore, the idea to control vehicle accessories is good, due to their unfortunate abilities to increase fuel consumption and emissions. Primarily the air conditioning system can vastly increase fuel consumption and emissions. According to a US Department of energy publication [53], the use of a vehicle air conditioning system can (worst-case scenario) increase NO\textsubscript{x} emissions with as much as 80\% and CO emissions by as much as 70\%. Fuel consumption can increase with as much as 22\%.

Hence, it could be worth the effort to try to improve the performance of vehicle accessories. Some climate control systems already contain an economic mode, but it may also be possible to increase performance by improved scheduling, as mentioned in the Aisin patent. However, in the case of a climate control system there is really no delay. Hence, a predictive scheduling may be redundant if sensors for current engine load or road grade exist. A decision based on the current situation is enough.

On the other hand, if the information would be available anyway (primarily for other applications) it would be desirable to use it.

In the publication [52] a good strategy for cooling system control is presented. However, one should realize that the prerequisite may be an improved electrical system. Better generators and/or power storage devices may be required. Hence, as mentioned in the publication, the strategy cannot be considered for immediate implementation.

3.3.13 Partial Summary 3 – Engine Control
The engine controller could most certainly benefit from a positioning system. The primary benefits are an improved fuel efficiency, less emissions and a quicker response under transient conditions.

With more strict environmental regulations, with respect to particle emissions and NO\textsubscript{x} exhaust, coming up, methods to control the engine with respect to these emissions are needed. The two primary methods used to achieve Euro 4 and Euro 5, EGR and SCR, can both be aided by positioning systems, as mentioned in 3.3.3 and 3.3.4. A new method for SCR control is suggested in Section 3.3.4.

With constantly increasing fuel prices, improved fuel efficiency is also desired. Such benefits could be obtained within cruise control (see Section 3.1) or direct engine performance adaptation.

Factors for performance adaptation could be which kind of area the vehicle travels (rural or urban), region topography characteristics (hilly or level) or jurisdiction (country, state, county, etc.). It is not certain that the same fuel efficiency goals or desired emission levels are applicable under different conditions. Possibly, a maximum power output is desired in hilly terrain, while a fuel efficient drive with a limited power output is desired on a level road and a low-emissions drive is desired in an urban area. Another driver or haulage contractor may have other goals, such as an optimally fuel efficient drive at all times. A positioning system could help with these settings.
Other beneficial areas within engine control are real-time scheduling and control of engine auxiliaries, vehicle accessories connected to the engine and On Board Diagnostics (OBD).

It seems clear that there are two main levels of detail on the desired information to send to the engine ECU. In a first embodiment the information comprises the above mentioned characteristics (geographical, topographical and jurisdictional). In a second embodiment the information comprises a complete topographical map. Which level of detail to choose depends on the assumed application and how much effort the assumed improvement is worth. Naturally, a combination of the two information detail levels could be possible. For example it would be valuable to know both the jurisdictional zone and topographical detail information. For a further discussion, see Section 3.4.

Figure 21 illustrates the most active assignees within this field of science. Remarkable is that one of Scania’s main competitors, Volvo Lastvagnar, is such a large player within this field. A more thorough investigation of the Volvo Lastvagnar patents and applications show that most of them are connected. The inventors are the same, the means for solving the problem is the same, only the solution is applied to different problems.

Figure 22 illustrates the trend of publication within this field of science. Clearly, most patents within this field are published after the year 2000. One reason for that could be the removal of the intentional degradation of the civil GPS signal on 2 May 2000. More information on this matter can be found in Section 2.3.2.

![Figure 21: Main actors within this field of science.](image-url)
Figure 22: Publication year within this field of science.
3.4 Conclusions of the Patent Mapping

In this part of the thesis an extensive mapping has been performed on how positioning systems can be used to support adaptive cruise control (ACC) systems, Section 3.1, gear changing systems, Section 3.2, and engine control systems, Section 3.3. Furthermore, a new method for exhaust aftertreatment control, and in particular selective catalytic reduction (SCR) has been introduced, Section 3.3.4.

It can be concluded that look-ahead control, where the vehicle position in relation to the upcoming road section is utilized, could give better fuel efficiency, lower emissions and less brake, transmission and engine wear.

The internal report [5] will serve as a work of reference for concerned departments at Scania within this field of technology and hopefully reveal new development possibilities. Surely there are also several other areas (cooling system, air suspension, driver training etc.) that have been excluded from this mapping where applications can be found and that may be subject to future patent research.

The applications within the investigated areas can be divided into five major classes, based on the information detail level, as illustrated in Figure 23. Each of these classes will be described below. It shall be mentioned that these applications are bound to the restrictions given in Section 1.2. There may be several other applications that use a positioning system in a vehicle, but these are not discussed here.

![Figure 23: Applications for GPS aid in a vehicle.](image)
Classical Applications
The classical applications of GPS aid in a vehicle are related to positioning as such. Typical examples are route guidance and fleet management systems, where a 2D digital roadmap is coupled to a GPS system and the position is snapped to the nearest road.

Applications given a Jurisdictional or Geographical Zone
The simplest extension to the classical applications is to provide information coupled to a specific region on a digital roadmap. Regions can be jurisdictional (related to accepted noise and/or emission levels in a city or a country) or geographical. One of the simplest applications is to store the speed limit for each road and use that as a desired speed for the current road (Intelligent Speed Adaptation). More complex applications can be engine or gearbox control based on regions. It should be mentioned, however, that the approach to use information on the current geographical region or type of road does not necessarily require a positioning system.

One example is the method described in the Volvo Technological Development Corporation patent [54]. In the patent it is claimed that several in-vehicle sensors (non-gps), can be used to classify the traffic environment. Specifically, four classes of driving environments; highway, main road, suburban traffic and city traffic are mentioned. The collected information can comprise acceleration pedal position, gear selection, turn indicator activity, vehicle speed, steering wheel angle, engine speed and brake activity. A neural network then calculates a probability of a certain driving environment class based on the collected information over a time window. The size of the time window is a trade-off between resistance to data variations (such as a short stop at an intersection on a main road) and the capability to quickly detect real changes in the driving environment.

Another example is the method described in a Scania CV patent application [55], where city traffic situations are identified, utilizing information like vehicle speed, but in particular by measuring a difference between a right wheel and a left wheel distance. If the distance exceeds a threshold value and the vehicle speed is below a threshold value, $v_{city}$, the vehicle has experienced a city traffic situation.

Positioning systems, such as GPS, offer several advantages compared to the above mentioned systems. Positioning systems are predictive and the mapping to a specific zone is relatively simpler and more accurate. It can also relatively easily be determined in which jurisdictional zone the vehicle travels.

Applications given the Road Geometry
The next class of applications comprise applications based on road geometry. Such information can either be provided directly from a map database (curvature, bank angle, ramp information etc.), or be extracted from node data in a detailed digital map. Typical applications are speed limiting devices for curves, rollover warning systems and Adaptive Cruise Control help systems (such as driving path recognition). Also, engine controllers and especially gear changing systems might benefit from knowing the curvature of the road ahead.

The most necessary information, when it comes to safety and/or driver comfort, is curve geometry and conditions. The simplest implementation is to somehow gain knowledge of the curve radius and calculate a recommended maximum speed, given an allowed maximum lateral acceleration. Other, more advanced implementations also gather information on the friction between road and tyre and the road bank angle. This requires curve radius, bank angle
and road surface information (asphalt, gravel…) from the navigation system. It could also be relevant to provide information from other in-vehicle sensors on road temperature and moisture or road friction estimated from braking wheels or from an ABS or a TCS system. In Appendix A it is shown how information on road bank angle affects a recommended curve speed and also how an error in curve radius affects the recommended curve speed.

So called rollover warning systems are well known, but generally they measure the current lateral acceleration, and the driver is warned if a threshold acceleration is exceeded. Thereafter speed could be reduced, either manually or automatically. In particular tank or bulk transports, more prone to roll over because of their floating load, could benefit from such systems. The benefits would be even larger if information was known ahead.

However, professional drivers are expected to know which speed they can keep in a curve, since that is part of their training. Hence it is uncertain if any haulage contractor would pay for such a product, even if the theoretical idea is good. This could possibly be subject for a future market research.

Applications given the Road Topography
The fourth class of applications comprise applications based on road topography. It is within this class that the most beneficial applications are found, and especially those related to optimization of fuel efficiency, performance and emission control. The applications generally relate to longitudinal speed control, where a chosen parameter is optimized (in general fuel efficiency). However, it might also be beneficial to utilize road inclination for engine control purposes, gearbox control purposes and/or exhaust aftertreatment purposes.

Most investigated patent documents, in this class, claim some sort of improved fuel efficiency. The main reason for this is probably that fuel consumption is one of the major contributors to the total economy of the vehicle. Hence customers are appealed by fuel efficient trucks. Even a small change (a few percent) in fuel consumption may make a vast difference for the owner of the vehicle. There are also environmental benefits bound to a better fuel efficiency. Naturally, the most important piece of information in this class is the road inclination.

Other Applications
Finally, the fifth class contains two simple, but useful applications related to a specific position. The first application is imitating systems, which controls a system in a vehicle at a specific position in exactly the same way as it was controlled the last time the vehicle was in, on that position. The second application is learning systems, which monitor an action at a specific position, analyze the action and then improve the taken action when the vehicle approaches the same position next time.
4 Real-time Implementation of a Predictive Speed Controller

The aim of the predictive speed control is to increase the vehicle speed where it is relatively cheaper and to decrease speed when a high vehicle speed is relatively more expensive. The purpose is to create a control performance such that less fuel is consumed, without reducing the average speed of the entire road section. This is made possible through knowledge of the relative position of the vehicle in relation to the terrain.

As concluded in the patent mapping and in particular Section 3.1.2, predictive speed control is a research intensive field and several simulations have been performed indicating a substantial reduction in fuel consumption when using predictive speed control. However, before this work no method existed for real-time tests in real trucks. It has therefore been the aim of this work to solve the twofold problem of developing a working test platform for real trucks and to apply a known control method.

In Section 4.1 the applied control method is described, Section 4.2 describes the developed test platform, Section 4.3 describes an initial comparative fuel test and Section 4.4 is a summary and conclusion of this real-time implementation.

4.1 The Applied Control Method

In this work a method for optimal control based on model predictive control (MPC) and dynamic programming (DP) has been used. This method has previously been described and also simulated with promising results in the Master’s thesis [60]. However, other control methods could also be chosen. The greater part of the platform is algorithm independent and it has been the aim of the work to create a platform where algorithms easily can be exchanged. An example of another algorithm is given in [43].

4.1.1 Model Predictive Control (MPC)

The idea of MPC is to use a model of the system one aspires to control in order to predict future values of output signals. If the future responses to different control signals are known, the control signals can be optimized with respect to any chosen parameter. MPC is well covered by Maciejowski in [56], Löfgren in [57] and in part by Glad and Ljung in [58]. The used vehicle model is described in detail in Section 4.1.2.

The MPC-control loop structure can be described as [58]:

<table>
<thead>
<tr>
<th>MPC algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. At the time ( t ), calculate or predict a number of future output signals ( \hat{y}(t+k</td>
</tr>
<tr>
<td>2. Set up a criterion based on these variables and optimize with respect to control signals ( u(t+j), j = 0,1,\ldots,N ).</td>
</tr>
<tr>
<td>3. Apply ( u(t) ).</td>
</tr>
<tr>
<td>4. Wait for the next time step ( t+1 ) and return to 1.</td>
</tr>
</tbody>
</table>
Central problems are the choice of output signal horizon $M$ and control signal horizon $N$. Typically, the output signal horizon is chosen such that the steady state response of the chosen control signals is included. That is, the system response beyond the transient response should be included. Normally, the control signal horizon is chosen shorter than the output signal horizon, since the former primarily decides the size of the optimization problem.

The development of MPC was driven by the process industry, where the powerful linear quadratic gaussian (LQG) theory never quite reached a massive breakthrough. The reason for this is primarily the difficulties handling control signal constraints in LQG controllers.

The optimal operating point of a typical process unit often lies at the intersection of control signal constraints, such that a controller must maintain the system as close as possible to these constraints without violating them. Therefore it is of particular interest to use a method that can easily handle constraints, such as MPC. Further, process units are typically complex, nonlinear, constrained multivariable systems whose dynamic behavior changes with time, due to changing operating conditions and catalyst aging. Therefore, it is desirable to solve a dynamic optimization problem online at each control execution, such that the future behavior over a time horizon over a time horizon ahead, known as the prediction horizon (output signal horizon) is optimized with respect to any chosen control parameters. By using only the first input of the optimal control sequence and then solve the problem again at the next time interval using updated process measurements, the system becomes more tolerant for modeling errors and disturbances.

The main difference between the conventional MPC approach and the method which has been implemented here is that this method calculates and actuates control signals at specific distance intervals instead of time intervals. However, this is further described in Section 4.1.3.

4.1.2 The Vehicle Model
The MPC vehicle model must be accurate enough to give good predictions, yet its complexity must be relatively low, in order to implement the controller in real time. Therefore the driveline is modeled physically with engine, clutch, transmission, propeller shaft, final drive, drive shaft and wheels as illustrated in Figure 24. This approach is well known and is covered in [59] and [60] and partly in [61]. The actuation delay in the cruise controller is not modeled; instead it is assumed that a desired speed is actuated immediately. This simplification is done to keep the complexity of the model down and could lead to modeling errors. However, it is assumed that these modeling errors are negligible.

![Figure 24: Vehicle model.](image-url)
Engine Model
The delivered engine torque is a function of engine speed and fueling. An engine map is created by performing steady state measurements for a set of different engine speeds and fuel rates. Such a map for the engine of one of the test trucks is illustrated in Figure 25. Since the map is created from steady state measurements, the internal friction from the engine is included in the map.

It is claimed in [60] that the engine map is fairly linear in engine speed, $N$, and fueling, $\delta$, and that therefore the following approximation can be used to get an analytical expression for the engine torque $\hat{T}_{map}$:

$$\hat{T}_{map} (N, \delta) = a_N N + b_\delta \delta + c_\epsilon$$  \hspace{1cm} (4.1)$$

if the accelerator opening degree is more than zero. This forms an engine map which is visualized in Figure 26.

However, it is not possible to inject an infinite amount of fuel at all engine speeds. Hence, the fueling, $\delta$, is a bounded function of the engine speed which varies between $0$ and $\delta_{max}$ with the control signal $P$.

$$\delta = P \cdot \delta_{max} (N)$$  \hspace{1cm} (4.2)$$

which results in the engine map which is illustrated in Figure 27.

The mass flow of fuel [g/s] is determined by the fueling [mg/stroke] and engine speed [rpm] as

$$\dot{m}_f (N, \delta) = c_f N \delta$$  \hspace{1cm} (4.4)$$

where $n_{cyl}$ is the number of cylinders and $n_r$ is the number of crankshaft revolutions per stroke.
Figure 25: True engine map.

Figure 26: Linearized engine map, no fueling boundary.
It is obvious that the bounded engine map, which is formed from an analytical expression, is significantly different from the true engine map. It is probable that an expression which better matches the true engine map would give a better control. One way to improve the model is to use a look-up table for the engine torque, where for a certain fueling and engine speed a torque is delivered. Another way is to find a better matching analytical expression. This could be subject of future work.

**Driveline Modeling**

For the rest of the driveline, simple physical modeling is used.

Through the combustion of fuel the engine delivers a torque, $T_e$, which also includes the internal friction of the engine. If the engine mass moment of inertia is $J_e$, and the external load, from the clutch, is subtracted, Newtons second law can be applied:

$$J_e \ddot{\varphi}_e = T_e - T_c$$  \hspace{1cm} (4.6)

The clutch connects the engine with the transmission and is assumed stiff, which preserves the load torque and angle.

$$T_c = T_i$$  \hspace{1cm} (4.7)

$$\dot{\varphi}_c = \dot{\varphi}_e$$  \hspace{1cm} (4.8)

The transmission is modeled with a conversion ratio, $i$, and an efficiency, $\eta$, mapped to each gear. The inertia of the transmission is not considered at all and gear shifts are assumed to be instant. That is a change of gears means an immediate change of conversion ratio and efficiencies.

$$T_i \dot{\varphi}_i = T_p$$

$$\dot{\varphi}_c = i \dot{\varphi}_i$$
The propeller shaft connects the transmission with the final drive and is also assumed stiff, which preserves the torque and angle.

\begin{align*}
T_p &= T_f \\
\dot{\vartheta}_p &= \vartheta_f
\end{align*}

(4.9) \hspace{1cm} (4.10)

The final drive is modeled like the transmission, neglecting inertia, but with a conversion ratio, \(i_f\), and an efficiency, \(\eta_f\).

\begin{align*}
T_f i_f \eta_f &= T_d \\
\dot{\vartheta}_f &= i_f \dot{\vartheta}_f
\end{align*}

(4.11) \hspace{1cm} (4.12)

The drive shafts connect the final drive with the wheels and are also assumed stiff, preserving torque and angle.

\begin{align*}
T_w &= T_d \\
\dot{\vartheta}_w &= \dot{\vartheta}_d
\end{align*}

(4.13) \hspace{1cm} (4.14)

Finally, the wheels are modeled neglecting wheel friction \(T_{fric,w}\), but with the wheel inertia \(J_w\), wheel radius \(r_w\) and the resulting friction force at the wheel, \(F_w\). The brake torque is modeled as a \(k_B B\), where \(B \in [0,1]\) is the brake control signal and \(k_B\) is a constant parameter.

\begin{align*}
J_w \ddot{r}_w &= T_w - k_B B - r_w F_w \\
\dot{\vartheta}_w &= \dot{\vartheta}_w
\end{align*}

(4.15)

**Longitudinal Forces**

The vehicle is affected by longitudinal and lateral forces. In this model the lateral forces are ignored. The longitudinal forces are aerodynamic drag, rolling resistance, gravitational force and the resulting friction force at the wheel. These forces are illustrated in Figure 28.

![Figure 28: Longitudinal forces acting on vehicle.](image)
The aerodynamic drag, \( F_a \), is estimated by

\[
F_a = \frac{1}{2} c_w A_a \rho_a u^2
\]  

(4.16)

where \( c_w \) is the air drag coefficient, \( A_a \) is the maximum cross section area of the vehicle and \( \rho_a \) is the air density. Finally, \( u \) is the velocity of the truck.

The rolling resistance, \( F_r \), is modeled proportional to the normal force of the vehicle on the tires, \( F_N \). The mass of the vehicle is \( m \) and the current road slope is \( \alpha \).

\[
F_r = c_r F_N \tag{4.17}
\]

\[
F_N = mg \cos \alpha \tag{4.18}
\]

The gravitational force, \( F_g \), is

\[
F_g = mg \sin \alpha \tag{4.19}
\]

Combining all longitudinal forces Newton’s second law yields

\[
m \ddot{u} = F_w - F_a - F_r - F_g
\]

(4.20)

where \( F_w \) is the resulting friction force at the wheel.

**Complete Driveline Model**

Assuming gear is not in neutral, the vehicle velocity is given as

\[
\dot{u} = \frac{\dot{\varphi}_w r_w}{i_i i_f} \frac{\dot{\varphi}_e}{\sin \alpha}
\]

(4.21)

If the equations are combined they yield an expression for the complete driveline model:

\[
N = \frac{30}{\pi} \dot{\varphi}_e = \begin{cases} 
\frac{30 i_i i_f}{\pi} u, & G \neq 0 \\
N_{idle}, & G = 0
\end{cases}
\]

(4.22)

where \( T \) is the engine torque, \( v \) is the velocity, \( P \) is the pedal signal and \( G \) is the chosen gear.

\[
T(v, P, G) = T_e (N, P, G)
\]

(4.23)

where \( N \) is the engine speed. The connection between the engine speed and vehicle velocity is

\[
N = \frac{30}{\pi} \dot{\varphi}_e
\]

(4.24)
Fuel Consumption

From (4.22) we know the expression for the complete driveline model. To simplify the description we use the notation in below. The expression for the complete driveline model will be denoted $f_1$. To model fuel consumption we also need to set an expression, $f_2$, for the fuel mass flow as a function of the given parameters speed, $v$, slope, $\alpha$ and the other inputs, $P$ and $G$ denoted $u$:

$$\begin{align*}
\dot{v} &= f_1(v, u, \alpha) \\
y_1 &= v \\
y_2 &= f_2(v, u, \alpha) = \dot{m}_f
\end{align*}$$

(4.25)

However, the time dependent variable, $\dot{v}$, must be converted to a position dependent variable:

$$\frac{dv}{dt} = \frac{dv}{ds} = \frac{ds}{dt} \Rightarrow \frac{dv}{ds} = \frac{1}{v} \frac{dv}{dt}, v \neq 0$$

(4.26)

It is further assumed that the inputs and disturbance (slope) are constant for the duration of each stage grid:

$$u(s) \equiv u_k, \quad \forall s \in [kS, (k + M)S]$$

(4.27)

If we use Euler’s integration method, with the step length $h$, we get for the velocity:

$$v_{k+1} = v_k + \frac{h}{v_k} f_1(v_k, u_k, \alpha_k), \quad k = 0, 1, \ldots, M \quad v_k > 0 \quad \forall k$$

(4.28)

To determine the consumed fuel mass, the output signal, $y_2$ (fuel flow) is integrated using Euler’s method with the step length $h$. If we divide each stage grid in $M$ steps we get a step length $h = \frac{S}{M}$ and the fuel consumption is given as:

$$m_{f,k+1} = m_{f,k} + \frac{h}{v_k} f_2(v_k, u_k, \alpha_k), \quad k = 0, 1, \ldots, M \quad v_k > 0 \quad \forall k$$

(4.29)
Discrete System Description
If the expression for the fuel consumption is added, the complete discrete system description is

\[ v_{k+1} = v_k + \frac{h}{v_k} f_1(v_k, u_k, \alpha_k) \]

\[ g_{k+1} = g_k \]

\[ c_{M+1} = \begin{cases} 1 + c_0, & g_{M+1} = g_0 \\ 1, & g_{M+1} \neq g_0 \end{cases} \]

\[ m_{f,k+1} = m_{f,k} + \frac{h}{v_k} f_2(v_k, u_k, \alpha_k) \quad k = 0, 1, \ldots, M \quad v_k > 0 \quad \forall k \quad (4.30) \]

Cost Function
The cost function is set to:

\[
\mathcal{J}(v_k, v_{k+1}, u_k, u_{k+1}, \alpha_k) = \left[ \begin{array}{c}
Q_1 & Q_2 & Q_3 & Q_4 & Q_5 \\
\end{array} \right] \\
\begin{array}{c}
\frac{m_{f,k}}{\kappa(e_k)e_k^2} \\
\kappa|v_k - v_{k+1}| \\
\kappa|G_k - G_{k+1}| \\
B_k \\
\end{array}
\] \quad (4.32)

where \( \kappa \) is a step function

\[ \kappa(t) = \begin{cases} 
1, & t > 0 \\
0, & t < 0 \end{cases} \quad (4.33) \]

The penalization factors, \( Q_i \) through \( Q_5 \) are:

\( Q_1 \) \quad The required fuel mass
\( Q_2 \) \quad Velocities below reference
\( Q_3 \) \quad Velocity changes
\( Q_4 \) \quad Gear shifts
\( Q_5 \) \quad Brake use
4.1.3 Dynamic Programming (DP)

MPC generates a rather difficult optimization problem. Therefore a solution method called **dynamic programming** (DP) has been applied to the problem. The idea of dynamic programming is to split a large and complex optimization problem to a series of smaller problems which are easier to solve. The problem is simply divided into many steps which are solved sequentially. To each step belong a number of states, containing all information necessary to calculate the effects of a decision on future events. The approach is to in each stage choose the cheapest of a set of states in that particular step. The cost function for this particular problem is stated in (4.32) and results from the vehicle model. DP is well covered by Bertsekas in [62].

**DP Algorithm**

In this problem a velocity, \( v \), and a gear number, \( g \), forms a state \( i = \{v,g\} \). The set of possible states, \( S_k \), in each stage, \( k \), is therefore generated from the range of possible velocities, \( V_k \), and the range of possible gears, \( G_{v_k} \). Hence we get:

\[
S_k = \{ \{ v, g \} | v \in V_k, g \in G_{v_k} \}
\]  

(4.34)

The initial node is denoted \( s \) and the terminal node is denoted \( t \). The costs are denoted:

\[
a_{k}^{i,j} = \text{transition cost at step } k \text{ from state } i \in S_k \text{ to state } j \in S_{k+1}.
\]

\[
a_{N}^{i} = \text{terminal cost of state } i \in S_N.
\]

The search space is limited such that a gear shift can only be performed after at least \( k_{lim} \) steps. The gear number is denoted \( g \) and the number of steps since the last gear change is denoted \( c \).

The following dynamic programming algorithm is used [60]:

<table>
<thead>
<tr>
<th>DP Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Let ( J_N(i) = a_{N}^{i} = 0 ).</td>
</tr>
<tr>
<td>2. Let ( k = N-1 ).</td>
</tr>
<tr>
<td>3. Let ( J_k = \min_{j \in S_{k+1}} { a_{k}^{i,j} + J_{k+1}(j) }</td>
</tr>
<tr>
<td>4. Repeat step 3 for ( k = N-2, N-3, \ldots, 0 ).</td>
</tr>
</tbody>
</table>

The optimal cost is \( J_{0}(s) \) and the sought control is the optimal control set from \( s \).
State Augmentation and Size of the Problem

Since the states contain the velocity and the gear number it must also be chosen how much difference in velocity that should be necessary to characterize a new state. This difference is called velocity discretization, $\delta$, and is one of the most important algorithm parameters. Naturally, the smaller the velocity discretization, the more states there are to choose from in each step and the problem grows. Likewise the distance between stages affects the number of states and hence the size of the problem. This distance is called the stage grid, $S$.

At every step, $i$, the algorithm needs to process all combinations of states in stage $i$ and $i+1$. Hence the number of possible combinations is the product of the numbers of states in the two stages.

Therefore, at every step, the number of operations will be proportional to the square of the number of states, $n^2$. That is, the total number of operations for an optimization over a prediction horizon of $N$ steps is $Nn^2$.

For this reason it is important to limit the search space (velocities and gears) as much as possible. The upper and lower bounds of the velocity search space are obviously given as the reachable velocities when full and no throttle respectively are applied, given the same gear. The search space of reachable velocities is also limited by the upper and lower limits that are chosen before start, $v_{\text{max}}$ and $v_{\text{min}}$.

The velocity state space is illustrated in Figure 30. The lower bound in the last stage is increased to the reference velocity. This can further restrict the search area, when the dark area is removed.
The search space for gears can also be limited. With a given velocity, only a subset of the gears can be selected. The constraining factor is the engine speed. In other words

$$G_{v_k} = \{ G \mid N_{\text{min}} \leq N(v_k, G) \leq N_{\text{max}} \} \cup \{0\}$$

(4.35)

where $N(v_k, G)$ is the engine speed at velocity $v_k$ and gear number $G$ with parameters $\{i_i, n_i\}$ and hence:

$$N(v_k, G) = \frac{30 \cdot i_i \cdot i_f}{r_w} \cdot v_k, G \neq 0$$

(4.36)
4.1.4 Parameter Choices

Before the algorithm was tested on a real truck, a few simulations were made, using an SHTL-model instead of the real truck in order to investigate the real time running potential of the algorithm given different algorithm parameters. SHTL stands for Scania Heavy Truck Library and is an hierarchical model structure described in Modelica. More info on SHTL can be found in the Master’s Thesis [63]. It was assumed that a parameter set which simulates well within real-time with an SHTL model would work online in a real-time implementation in a real truck, since the real time communication between the vehicle’s CAN network and Simulink is much faster than the SHTL-model.

The real time running potential is measured using the ratio between computational and simulated time. This ratio is called $q$ and is a mean value over the entire road profile and what it means is described in Table 1.

<table>
<thead>
<tr>
<th>$q$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 1$</td>
<td>The system can be simulated faster than real time</td>
</tr>
<tr>
<td>$= 1$</td>
<td>The system can be simulated precisely in real time</td>
</tr>
<tr>
<td>$&gt; 1$</td>
<td>The system can not be simulated faster than real time</td>
</tr>
</tbody>
</table>

Table 1: Real time running potential, $q$.

For the measurements the same parameters as in [60] have been used. The results are shown in Figure 31. A linear dependence of the prediction horizon can be assumed in all cases. This can be shown through the reasoning in Section 5.7 in [60]. Small differences from the linear dependence are probably dependent on other computer tasks rather than the prediction horizon. The measurements have been made on an Intel Pentium III running at 1.0 Ghz. The Matlab version used is 7.0.1 R14.

Several conclusions can be drawn from the results. The measurements differ significantly from the ones made in [60, Section 6.7]. The main reason for this is the time it takes to run the SHTL truck model. A few measurements show that the time necessary from SHTL model input to output is the major part of the necessary computer time (almost one second per iteration). The time the controller needs to process and actuate the reference speed is significantly smaller.

If the parameters stage grid = 50 m and $\delta = 0.2$ km/h are used (where $\delta$ denotes the velocity discretization), the lowest $q$ ratios result for each prediction horizon above 500 m. This was expected, since these are the least precise parameter choices. When the system is simulated with respect to fuel efficiency the best results are also received with these parameters. The very best result was given at a prediction horizon of 1500 m (Steps = 30) and therefore these parameters have been used in the fuel test (Section 4.3). In [60] the best results were given at a prediction horizon of 2000 m, but there a simpler model has been used.

Even if the SHTL-model is not used in the real-time implementation, it can still be assumed to give responses reasonably close to those of the real truck and that the parameters shall be chosen such that they provide the best results with the SHTL-model.
Velocity discretization = 0.2 km/h, Stage grid = 25 m

Velocity discretization = 0.2 km/h, Stage grid = 50 m
Figure 31: The ratio $q$, which is the required computer time in seconds to simulate the system one second for different algorithm parameters (velocity discretization and stage grid).
4.2 Test Platform

To enable tests in a real truck a test platform has been developed. The test platform consists of a user interface, an underlying control structure with an implemented control algorithm for model predictive speed control (Section 4.1), CAN software drivers and a hardware interface. The platform structure is illustrated in Figure 32.

![Figure 32: Test platform.](image)

The approach is to deliver a reference speed to the ordinary cruise controller in the vehicle. There are two main advantages with this approach compared to controlling the engine directly:

- The safety aspect: The ordinary cruise controller can easily be disengaged by depressing the brake or clutch pedal(s).
- The complexity aspect: Considering the way an engine is constructed, the sending of a reference speed is the easiest way to keep the complexity of the implementation down. Individual engine components are then controlled internally in the engine without risk of damage to any engine parts.

4.2.1 Controller Area Network (CAN) connection

The controller area network – CAN, developed by Bosch, is the most widely spread in-vehicle network and has been incorporated in ISO 11898. CAN is a distributed network, built up of interconnected nodes, or ECUs, where each node may start their transmission when the bus is idle. The conventional CAN is an implementation of the priority triggered *carrier sense multiple access/collision resolution* (CSMA/CR) protocol [64].

The test platform is software-based and installed in a laptop which is connected to the CAN in the truck. Once the controller is activated, a reference speed is delivered to the cruise controller in the test vehicle. The test truck then feedbacks the signals distance, speed, ambient pressure and temperature, upon which the controller responds by changing the control signals based on the vehicle speed, reference speed, road profile ahead and vehicle mass. The general information flow is illustrated in Figure 33. The exact exchange of CAN-messages and the hardware interface is described in the internal report [65].
However, the approach also has a downside. By converting control signals such as throttle and fueling to a reference speed numerical or modeling errors may arise and simulation results may differ from actual results.

A CAN message, or frame contains a start of frame (SOF) bit, a header field, a data field, a cyclic redundancy check (CRC) field, an acknowledgement field and an end of frame (EOF) field. If two nodes try to transmit a frame at the same time, the frame with the highest priority, determined from a simple arbitration process, will be sent.

The physical layer of CAN realizes the logical AND-operator. That means that if at least one of the nodes is transmitting a “0”, then the bus will be in that state. Therefore a node transmitting a “1” will observe a “0” on the bus and stop its transmission immediately. This will be illustrated with a simple example, where three nodes intend to transmit a frame at the same time:

<table>
<thead>
<tr>
<th>Node</th>
<th>First bits of identifier</th>
<th>Bit 0</th>
<th>Bit 1</th>
<th>Bus value:</th>
<th>Bit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>010…</td>
<td>0</td>
<td>1</td>
<td>0 1 0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>100…</td>
<td>1</td>
<td></td>
<td>Stop transmission!</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>011…</td>
<td>0</td>
<td>1</td>
<td>0 1 1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: CAN arbitration example.

The CAN physical layer is typically a twisted pair cable, with transfer speeds of up to 1Mbps. The standard is considered very reliable. Therefore it is primarily used to communicate data between the engine, brake and transmission controllers, such that required real-time responses are maintained.

The CAN standard defines the physical layer and data link layer. To standardize message contents and improve interoperability between ECUs a higher level protocol, J1939, is used to connect all ECUs on three different buses interconnected by a gateway.

In this work an existing hardware interface between a USB-port on the laptop computer and the vehicle’s CAN has been used. CAN drivers are publically available from the Kvaser [66] homepage.
4.2.2 The Control Loop
The control loop is implemented as a model structure in Simulink and is illustrated in Figure 34. The structure contains the following blocks:

**The Controller Block**
The controller block contains the MPC algorithm as described in Section 4.1. This block puts out new optimal control signals when the vehicle has traveled a distance corresponding to the stage grid (which is the distance between two steps in the DP-algorithm).

**The Ref_truck Block**
The ref_truck block converts the control signals from the controller block to a reference speed by (4.28) in Section 4.1.2. The purpose of this is explained in Section 4.2.

**The Truck Block**
The truck block handles all communication with the real truck over CAN. The function is called when a reference speed is delivered from the ref_truck block.

Upon a function call, the truck function immediately actuates the real vehicle’s reference speed by delivering a CAN message to the conventional cruise controller. Next, it reads out the traveled distance, vehicle speed and a set of diagnostic messages from the truck’s CAN. If the vehicle speed differs from zero the chosen offset and/or velocity drift is gathered from the graphical user interface (GUI) (see Section 4.2.3), the GUI is updated with the new parameters and the traveled distance and vehicle speed is put out. If the vehicle speed equals zero the control loop is disabled until the vehicle starts moving. The behavior of the truck function is described through a flow chart in Figure 35.

**The Unit Delay Block**
This block delays the input signal one sample period.

**The Add Block**
In this block an offset is added to the distance measurement from the real vehicle. The sum of the distance measurement and the offset is delivered as the distance to the controller together with the vehicle speed from the truck block. The need for this offset is explained in Section 4.2.4.

Finally the controller calculates new optimal control signals based on the chosen prediction horizon (a vector containing the slope angles ahead based on the reported distance from the add block), current vehicle speed (from the truck), reference speed (from the GUI) and vehicle mass (from the GUI).

**The RTBlock block**
This block contains a MATLAB s-function which allows a Simulink model structure to run at the same time as the real time processes. RTBlock has been developed by Leonardo Daga and is available at his homepage [67]. The benefits of using this block is that the reported running time is the actual time and not simulated time.
Figure 34: The Simulink control loop.
Figure 35: Truck function flowchart.
4.2.3 The Graphical User Interface – RT Interface.

In the development of the test platform a graphical user interface (GUI), called RT Interface, has been created in Matlab. The GUI is closely coupled to the control loop in Simulink which has been described in Section 4.2.2. The interface enables the user to perform the following tasks:

- Load a road profile
- Change algorithm, algorithm parameters and penalization factors
- Change test vehicle, vehicle parameters and vehicle model parameters
- View current speed, position, torque, fuel rate and altitude
- Offset the current position
- Start and stop the controller
- Manually initialize and shutdown the CAN connection if desired
- Manually read CAN data if desired

A snapshot of the program is given in Figure 36.

Figure 36: Snapshot of the RT Interface – MPC speed controller.
Road Profiles
A road profile is a set of two vectors of equal length: position and altitude, where position contains the positions of the altitude measurements in meters and the altitude vector contains the altitude measurements corresponding to the position of the same index. The positions where the altitude is measured must be equidistant. This is illustrated in Table 3.

<table>
<thead>
<tr>
<th>Road profile</th>
<th>altitude</th>
<th>position</th>
</tr>
</thead>
<tbody>
<tr>
<td>altitude</td>
<td>256</td>
<td>265</td>
</tr>
<tr>
<td>position</td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3: Altitude and position vectors.

The vectors altitude and position are stored in a Matlab matrix file (*.mat), and are loaded by a double left click on the corresponding matrix file in the file listbox.

The slope, $\alpha$, at each position is derived from a simple differentiation approximation:

$$\alpha = \frac{f(x + h) - f(x - h)}{2h}$$  \hspace{1cm} (4.37)

where $h$ is the distance between the measurements and $x$ is the current position. If a third vector, slope, should be included in the matrix file the values in slope are used at each position, and no differentiation approximation is done.

When a road profile is successfully loaded a message box is displayed with the message “Load successful”, while the corresponding road profile is shown in the graph window in the RT Interface.

When a profile is loaded the position slider is reset and the road profile graph is shown with a dashed blue line. This means that the current position is at the starting point of the road profile.

Changing the Algorithm Parameters
Before the controller is started, the algorithm parameters can be changed by moving the sliders in the lower left corner of the window. The parameters which can be changed are stage grid, number of steps, velocity discretization, minimum number of steps before a gearshift and the maximal allowed deviations from the reference velocity. Also, it can be chosen if neutral gear is to be allowed. In this version of the test platform the gear signal which is put out is not used in the real truck, but only in the truck model. In the real truck the automatic gear changing system OptiCruise performs the gear changes (see also Section 4.3.6).

The stage grid is the distance between each step in the DP-algorithm, the number of steps is how many steps ahead of the vehicle that is considered in the optimization. The prediction horizon, or distance ahead of the vehicle, which is considered, equals the stage grid multiplied by the number of steps. The velocity discretization is the difference in velocity necessary to characterize a new state in the dynamic programming algorithm. The concept of dynamic programming and the optimization algorithm is further described in Section 4.1.3. The max increase/decrease setting is the allowed deviation in vehicle velocity from the reference speed.
The default values for these parameters are given in Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>50 m</td>
</tr>
<tr>
<td>Number of steps</td>
<td>30 (corresponding to a prediction horizon of 1500 m)</td>
</tr>
<tr>
<td>Velocity discretization</td>
<td>0.2 km/h</td>
</tr>
<tr>
<td>Min. steps before shift</td>
<td>8 (400 m)</td>
</tr>
<tr>
<td>Max increase / decrease</td>
<td>5 km/h</td>
</tr>
<tr>
<td>Neutral gear not allowed</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Default algorithm parameters.

Once the start button is clicked the algorithm parameters cannot be changed. All controls are disabled and the text “Controller running” appears.

Changing the Vehicle Parameters

Before the controller is started, the vehicle parameters can be set by working the controls in the lower right corner of the window. Each test truck is connected to a model parameter file which contains most parameters for the corresponding vehicle. Figure 37 illustrates the created user interface for editing such files.

![Figure 37: Read or change vehicle model parameters.](image)

In addition the reference speed, mass and velocity drift (See Section 4.2.4) can be chosen with the corresponding sliders in the main GUI.
The default values for the vehicle parameters are given in Table 5.

<table>
<thead>
<tr>
<th>Test truck</th>
<th>Moster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference speed</td>
<td>82 km/h</td>
</tr>
<tr>
<td>Mass</td>
<td>40 ton</td>
</tr>
<tr>
<td>Velocity drift</td>
<td>2.00 %</td>
</tr>
</tbody>
</table>

Table 5: Default vehicle parameters.

Once the start button is clicked the vehicle parameters cannot be changed. All controls are disabled and the text “Controller running” appears.

**Changing the Penalization Factors**

Before the controller is started, the penalization factors used in the MPC optimization problem can be set by changing the corresponding controls. In the used model, there are five penalization factors: $Q_1$ through $Q_5$. These are further described in Section 4.1.2.

The default values for the penalization factors are given in Table 6.

<table>
<thead>
<tr>
<th>$Q_1$ (The use of fuel)</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_2$ (Speed below reference)</td>
<td>7</td>
</tr>
<tr>
<td>$Q_3$ (Velocity changes)</td>
<td>15</td>
</tr>
<tr>
<td>$Q_4$ (Gear shifts)</td>
<td>15</td>
</tr>
<tr>
<td>$Q_5$ (Brake use)</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 6: Penalization factors.

Once the start button is clicked the penalization factors cannot be changed. All controls are disabled and the text ‘Controller running’ appears.

**Running the Controller**

When the controller is started it is assumed that the vehicle is at the starting point of the loaded road profile. As the vehicle proceeds all parameters read from the vehicle’s CAN-network are displayed in the GUI, and a position graph is continuously updated. The purpose of the graph is to visualize the vehicle position in relation to the upcoming terrain. The vehicle is always at the utmost left part of the graph and the upcoming road profile is plotted with a red line.

The graph window is scaled such that the horizontal axis always covers three times the prediction horizon forward from the current position and the vertical axis always covers the altitudes between the highest and lowest altitudes of the loaded road profile.

A drift correction algorithm (Section 4.2.4) has been developed to correct for drift in the velocity and distance reporting, relative to the vehicle which measured the road profile. When the operator pushes the ‘Autosync’ button, the system tries to automatically correct for velocity drift relative to the road profile. If successful, the drift slider and indicator field are updated and the drift is added to the reported distance. If the synchronization fails a message ‘Sync failed’ appears and nothing else happens. The drift can also be set manually by moving the drift slider or by choosing a test vehicle.
If the indicated position still does not seem to correspond to the real position, the position can be manually offset by an arbitrary distance to better match the real position. The offset is changed by clicking the Inc./Dec. offset buttons. For each click the position is offset by the distance corresponding to the offset slider position. This ability has been added to correct the controller for road profile measurement errors, vehicle sensor errors or other errors resulting in the position not matching the road profile.

**Stopping the Controller**
The controller is stopped by clicking the ‘Stop’ button. The resulting action is a proper ending of the running Simulink simulation, the sending of an inactivation signal to the cruise controller and a proper CAN communication shutdown. After clicking the ‘Stop’ button a warning message is displayed, explaining the current action. The shutdown procedure may take up to 10-15 seconds in extreme cases. Under no circumstances must the RT Interface be exited before the shutdown procedure is completed and the ‘Controller running’ text has disappeared.

4.2.4 Drift Correction Algorithm
During test runs on true road profiles it could clearly be noticed that the predicted and actual road profiles tended to drift apart. This was expected due to the difference in reported distance between the test vehicle and the vehicle which measured the road profile and therefore a manual offset had been added to the program to correct for this drift.

However, it would be desirable to automatically correct this drift by comparing the measured road profile with the predicted road profile, and therefore a drift correction algorithm has been developed.

**Predicted Road Profile**
The predicted road profile is stored in a file as described in Section 4.2.3, and is a set of altitudes, each coupled to a position along the traveled road, relative to a starting position. Since these road profiles are measured with relative positioning the performance would most likely not improve if this speed controller worked with GPS. There would still be a drift. Only if the altitude measurements would be coupled to absolute positions it would be reasonable to integrate the GPS with this predictive speed controller. It should also be considered that equipment which enables reading of global position to CAN from the navigation system is relatively expensive at the time of writing. However, for future development full GPS integration could probably eliminate the drift problem entirely.

**Measured Road Profile**
The road profile can be measured in a number of ways while driving: For example barometrical measurements, GPS altitude or by the use of different in vehicle sensors. Exactly how that measurement is done is of less importance, but the result of the measurement must in any case be an altitude profile, where each position along the road is coupled to an altitude. In this chapter a few different methods will be described.

In the test platform a method which utilizes barometrical altitude measurements has been implemented and tested.
The ambient conditions atmospheric pressure and temperature are available on the CAN-bus. The synchronization algorithm uses the barometrical formulae for height estimation, $z$, relative to a reference elevation:

$$ p = p_0 e^{-\frac{Mgz}{RT}} $$

(4.38)

where $R$ is the general gas constant, $T$ is the ambient temperature, $M$ is the average molecular mass of the atmosphere, $g$ is the gravity constant, $p_0$ is the pressure at the reference level and $p$ is the pressure at the altitude $z$.

This approximation is a somewhat modified version of the one presented in [68]. The temperature is assumed to be the same at the reference level as on the altitude of interest, compared to [68], where $T$ is the temperature at the reference level.

The barometrical formula follows from the hydrostatic equation:

$$ -\frac{1}{\rho} \frac{dp}{dz} = g $$

(4.39)

If the general gas law for dry air is applied, we get:

$$ \frac{dp}{dz} = -\frac{Mgp}{RT} $$

(4.40)

$$ \int_{p_0}^{p} \frac{dp}{p} = -\frac{g}{R_0} \int_{z_p}^{z} \frac{dz}{T} $$

(4.41)

For smaller altitude differences, the temperature can be assumed to be constant, $T$ and we get:

$$ \ln \frac{p}{p_0} = -\frac{gz}{RT} $$

(4.42)

or [69]

$$ p = p_0 e^{-\frac{Mgz}{RT}} $$

(4.43)

The ambient pressure signal has a resolution of 0.05 kPa, which corresponds to approximately 4 meters of elevation resolution, which also has been verified through a practical test. This resolution could definitely be enough to synchronize the profiles. The pressure signal is unfortunately somewhat “noisy”, which could lead to a few incorrect measurements. It is concluded that the signal needs to be filtered before use. Another problem is that the pressure at the reference level might change.

For further development it would be possible to transmit the pressure at a reference altitude over a wireless network to improve the tolerance for changing weather. It would also be reasonable to try other methods for altitude estimation. One such method is described in [70].
Synchronization
The synchronization is an iteration process through different offsets, where for each offset the sum of least square errors over a previous road section is calculated.

The sum of least squares provides a simple, but good measure of the correlation between a predicted and measured value. The larger the sum is, the larger the error.

\[ \text{error} = \sum_{i} (x_i - y_i)^2 \]

where \( x_i \) is the predicted altitude at position \( i \), and \( y_i \) is the measured altitude at position \( i \). Consequently \(|x_i - y_i|\) is the residual, the difference between actual and predicted altitude.

The calculation time for each synchronization cycle depends on the search area for offset steps. Measurements with an offset search area of 20 steps (~500 m) show a synchronization time of between 0.01 and 0.05 s on an Intel Pentium III, 1.0 GHz. Hence, it would be possible to run the algorithm every time new measurements are done. This process is a straightforward and effective way to find the offset drift which works perfectly well in the theory, but the synchronization has proven to be more difficult in a real vehicle due to inaccurate or imprecise altitude measurements.

Figure 38 shows the iteration process between the predicted and measured road profiles. The iteration variable \( i \) loops from \(-\text{stepsback} \) to \( \text{stepsback} \), where \( \text{stepsback} \) is the maximum offset in any direction for which a search is desired.

The synchronization follows these steps:

**Synchronization algorithm**

1. Get the last vector with measured altitudes
2. Iterate through different offsets for the vector of predicted altitudes, within desired boundaries
3. For each offset, find the sum of least square errors
4. Iterate until the sum of least square errors reaches within the desired tolerance and find the smallest value
5. The offset for which the smallest least square error is reached is the correct offset drift

![Figure 38: Predicted and measured altitude.](image)
A drift relative to the previous distance reporting is calculated as:

\[
drift\ _\ percent = \left(\frac{offset\ _\ drift}{reported\ _\ position}\right) \cdot 100
\]  
(4.44)

When a drift correction has been made, an additional \( drift\_percent \) is added to the reported distance. At the next drift correction the last drift is added to this drift and the distance is automatically actuated by changing the offset drift accordingly. This is illustrated by a simple example in Figure 39 with drift corrections at 10000, 20000 and 30000 m.

Immediately after each drift correction, the reported position and position on the profile are the same, and since the actual drift is considered to be close to constant the drift corrections are supposed to be smaller and smaller and eventually the drift will reach a steady state value which corresponds to the true drift in reported distance between the test vehicle and the vehicle which measured the road profile.

In the current version of RT Interface, a drift correction is performed every time the operator pushes the ‘Autosync’ button, but if the altitude measurements were better it would be reasonable to perform a drift correction at every iteration of the truck function.

Clearly the performance of the drift correction algorithm is affected by the poor altitude measurements. Further development with other sensors or a combination of other sensors, such as in [70] is necessary.
4.3 Fuel Test

The purpose of this work has not been to perform a series of fuel tests, but to create the prerequisites for such tests through the development of a test platform. However, to ensure the function of the test platform it has been found necessary to perform an initial comparative fuel test, where the predictive speed controller is compared with conventional CC.

4.3.1 Method

The purpose of the test has been to eliminate all other differences but the way the speed is controlled. This means similar test trucks, similar conditions and similar test distances such that measurement errors due to different weather and/or traffic conditions, inaccurate fuel sensors or other individual differences could be eliminated.

The fuel test was performed with two vehicles of the same configuration (as described in Section 4.3.2) traveling the same distance at the same time of day. The test was initiated with a reference drive, where both vehicles traveled the test distance using the ordinary cruise controller. After the reference drive, the difference in fuel consumption was noted and used to correct the consumption in the test drive.

In the test drive the test truck was equipped with the RT MPC speed controller, while the reference truck still was controlled with the ordinary cruise controller. After the test drive the fuel consumption was corrected for the difference in fuel consumption in the reference drive and the time difference between the vehicles.

The correction for the time difference was done by performing simulations with Scania’s fuel consumption simulation software STARS over the same profiles and find how much fuel was saved when the reference speed for the ordinary cruise controller was reduced such that the total travel time corresponded to the time of the RT MPC test drive.

In both trips the reference speed was set to 82 km/h for the ordinary cruise controller and 82 km/h ± 5 km/h for the MPC speed controller and the retarder was set to brake the vehicle at 91 km/h. Gear changes were performed automatically with OptiCruise and there was no manual pedal interaction during any of the trips.

The onboard computer was used to provide a measurement of the amount of consumed fuel and a clock was used for time measurements. At specific positions along the route, given by road signs, the parameters Consumed fuel [l] and Time [min] was noted on a report sheet.

Before each trip the vehicles performed a short drive in order to warm up the engines and start their test drive with the reference speed, such that the initial conditions were identical for both vehicles.

4.3.2 Test Trucks

The two test trucks have been labeled Truck 1 and Truck 2 respectively and are as similar as they could be in all aspects. The objective of the search for test trucks has been primarily to find test vehicles that only differ in the way the speed is controlled. However, even with the same front area, wheels, gearbox, engine and final drive individual differences could lead to different fuel consumption between the two vehicles. Therefore it was found necessary to
perform an initial reference drive where both vehicles use the ordinary cruise controller (CC) in order to find that difference.

The trailers used were Trailer 1 for Truck 1 and Trailer 2 for Truck 2. The trailers used are both three axled semitrailers, but they have slightly different front areas and Trailer 1 is covered almost all the way down.

The test trucks have the same tire dimensions and configuration, same engine, same gearbox and same final drive conversion ratio. Both test vehicles have also approximately the same age and traveled distance. The primary differences are the cab and trailer front areas. Naturally, this is not ideal, but when searching Scania’s vehicles this was the best test combination available.

Both vehicle combinations were weighed fully fueled. The results are presented in Table 7.

<table>
<thead>
<tr>
<th>Vehicle combination</th>
<th>Truck 1 + Trailer 1</th>
<th>Truck 2 + Trailer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>39.16 ton</td>
<td>38.21 ton</td>
</tr>
</tbody>
</table>

Table 7: Vehicle combinations.

4.3.3 Test Distance

The test distance is a return trip on Södertälje – Norrköping – Södertälje on the highway E4. This has been chosen because of the many hills and relatively large altitude differences on that road. It is the hypothesis that the larger the altitude differences and the larger the payload, the larger is the improvement in fuel efficiency when using the MPC speed controller. It is also beneficial to perform the test on a highway while the curve radii on such roads are so large that the lateral forces practically can be ignored. The road profiles for the two segments of the test distance, which have been evaluated, are shown in Figure 40 and Figure 41.

Figure 40: Test distance part 1, Järna – Getå/Kolmården.
Figure 41: Test distance part 2, Stavsjö-Järna.
4.3.4 Simulations

In order to evaluate the performance of the RT MPC controller, the system has been simulated on the two parts of the test distance. In Figure 42 and Figure 43 the simulation results in both directions are illustrated in two graphs where the cruise controller and MPC algorithm are compared. The graphs show the altitude, slope, velocity and pedal level plotted for positions along the entire test distance. In the velocity plot the reference speed, which is set in the GUI is marked with the notation $v_{\text{ref}}$, in this case 82 km/h. However, it is central to realize that $v_{\text{ref}}$ is not the reference speed which is sent to the CC in the truck, but the speed around which the vehicle speed is allowed to deviate, in this case by 5 km/h. The result is a vehicle speed between 77 km/h and 87 km/h. The simulations have been made using the simple vehicle model which was described in Section 4.1.2, with the exception of the engine model, which was more precise in this case (torque values from a look-up table).

![Graphs showing simulation results](image)

Figure 42: Comparative simulation of the road between Södertälje and Norrköping.
Figure 43: Comparative simulation of the road between Norrköping and Södertälje.

It turns out that the simulations predict an average fuel save, when using the MPC controller, of 2.31% on the road from Södertälje to Norrköping and 2.75% on the road from Norrköping to Södertälje. The time difference is practically negligible in both cases (0.16% and 0.19% respectively).
4.3.5 Results

Reference drive

Part 1 Järna-Getå/Kolmården 96.5 km

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Truck 1 (CC)</th>
<th>Truck 2 (CC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported fuel consumption</td>
<td>27.0 litres</td>
<td>29.7 litres</td>
</tr>
<tr>
<td>Consumption l/100 km</td>
<td>28.0 litres</td>
<td>30.8 litres</td>
</tr>
<tr>
<td>Time</td>
<td>72 min</td>
<td>72 min</td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta fuel))</td>
<td>10.0 %</td>
<td></td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta time))</td>
<td>0.0 %</td>
<td></td>
</tr>
</tbody>
</table>

Part 2 Stavsjö-Järna 90.0 km

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Truck 1 (CC)</th>
<th>Truck 2 (CC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported fuel consumption</td>
<td>23.0 litres</td>
<td>25.0 litres</td>
</tr>
<tr>
<td>Consumption l/100 km</td>
<td>25.6 litres</td>
<td>27.8 litres</td>
</tr>
<tr>
<td>Time</td>
<td>67 min</td>
<td>67 min</td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta fuel))</td>
<td>8.7 %</td>
<td></td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta time))</td>
<td>0.0 %</td>
<td></td>
</tr>
</tbody>
</table>

Test drive

Part 1 Järna-Getå/Kolmården 96.5 km

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Truck 1 (CC)</th>
<th>Truck 2 (MPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported fuel consumption</td>
<td>26.9 liter</td>
<td>28.7 liter</td>
</tr>
<tr>
<td>Consumption l/100 km</td>
<td>27.9 liter</td>
<td>29.7 liter</td>
</tr>
<tr>
<td>Time</td>
<td>71 min</td>
<td>73 min</td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta fuel))</td>
<td>6.7 %</td>
<td></td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta time))</td>
<td>2.8 %</td>
<td></td>
</tr>
<tr>
<td>(\Delta fuel) corrected for reference drive</td>
<td>-3.3 %</td>
<td></td>
</tr>
<tr>
<td>(\Delta fuel) corrected for extra time</td>
<td>-1.4 %</td>
<td></td>
</tr>
</tbody>
</table>

Part 2 Stavsjö-Järna 90.0 km

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Truck 1 (CC)</th>
<th>Truck 2 (MPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported fuel consumption</td>
<td>23.6 litres</td>
<td>24.8 litres</td>
</tr>
<tr>
<td>Consumption l/100 km</td>
<td>26.2 litres</td>
<td>27.6 litres</td>
</tr>
<tr>
<td>Time</td>
<td>67 min</td>
<td>68 min</td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta fuel))</td>
<td>5.1 %</td>
<td></td>
</tr>
<tr>
<td>Difference relative to Truck 1 ((\Delta time))</td>
<td>1.5 %</td>
<td></td>
</tr>
<tr>
<td>(\Delta fuel) corrected for reference drive</td>
<td>-3.6 %</td>
<td></td>
</tr>
<tr>
<td>(\Delta fuel) corrected for extra time</td>
<td>-2.4 %</td>
<td></td>
</tr>
</tbody>
</table>

After correction from the reference drive the MPC controller saves 3.3 % fuel on a segment of the road towards Norrköping and 3.6 % on the road towards Södertälje, which is fairly better than in the simulations. However, the test drive also requires more time. After correcting also for the extra time, the fuel saved is 1.4 % and 2.4 % respectively. The procedure for that correction is described in Section 4.3.6. It is obvious that more tests are necessary to verify those results, since the fuel saved is basically within the margin of correction.
4.3.6 Comments and Problems

In the results, we have used the indicated fuel consumptions from the vehicle computer. It would have been reasonable to verify that measurement by refilling the tank to exactly the same level after the test drive. This was also the intention, but since only one of the vehicles (Truck 1) was equipped with a tank suitable for such measurements those measurements were omitted. It can be concluded that a test truck must be equipped with a smaller tank especially designed for that purpose for such measurements to be trustworthy. It is however assumed that the indicated fuel consumption does not change stochastically, but is induced with a constant relative error, such that the relative changes in fuel consumptions are correct.

It was also the intention to perform the measurement all the way to Norrköping and back to Södertälje. However, a few values had to be rejected due to missing time or fuel measurements, traffic disturbances or other factors. Hence, only trustworthy and reasonable values where the system could control the vehicle according to the MPC speed control algorithm have been accepted. For future tests it could be reasonable to have an automatic log of consumed fuel and time at specific global positions to eliminate the human factor. It would also be better to have time measurements in seconds.

Finally, it became very obvious that the road profile drifts in relation to the terrain. In the test drive this drift was corrected for manually. However, if the system should be further developed, it would be reasonable to use the position from a global positioning system (such as GPS) instead of the dead reckoning method which was used here. Naturally, this also requires the road profiles to be measured with a global positioning instrument. This matter has been further described in Section 4.2.4

The result differs slightly from the simulations described in Section 4.3.4. The most obvious explanation is modeling errors, since the model does not fully represent the dynamics and behavior of the real vehicle.

Also, in the test vehicle, gear shifts are performed by the automatic gear changing system OptiCruise and the controller’s suggested gear shifts are simply ignored. Therefore, the gear shifts in the real test and in the simulations could differ.

The choice between gear shift recommendations from the MPC-controller and from OptiCruise is a trade-off between different benefits and problems. The MPC-controller has access to the upcoming terrain and should theoretically give a better recommendation. On the other hand, it probably contains larger modeling errors than OptiCruise and may therefore recommend erroneous gear shifts, which in the worst case could harm the engine or transmission parts.

The MPC-controller should be weighed against OptiCruise, which is closely connected with the engine and has access to a lot of extra sensor data based on the current vehicle status. However, it lacks information about the upcoming terrain. It is not trivial to see which controller that makes the best choices, but by using OptiCruise, it is certain that no harm is done to the engine. Furthermore, by using OptiCruise it is only necessary to transmit a reference speed to the test vehicle and therefore the same test platform could be used also for speed control algorithms that do not recommend gear shifts.
However, technically it would not be a problem to let the MPC-controller perform the gear shifts and it would most certainly be interesting to see if the end result would be better in that case. Such an implementation could be subject for future work.

Another explanation for the difference is the positioning of the vehicle relative to the road profile. If only this positioning is slightly offset relative to the true position the end result will be another (worse).

In Section 4.3.1 it is explained that the time correction is done by performing fuel consumption simulations with different velocities. In those simulations the vehicle was simulated with the ordinary cruise controller (CC). First, a simulation was done with a vehicle speed such that the travel time is equal to the travel time for Truck 1 (CC) in the test drive. Next, the reference speed was reduced such that the travel time was equal to the travel time of Truck 2 (MPC).

The result was a difference in fuel consumption, \( \Delta_{\text{fuel}} = -1.9 \% \) on part 1 of the test distance and \( \Delta_{\text{fuel}} = -1.2 \% \) on part 2 of the test distance. These differences were then subtracted from the fuel difference after correction for the reference drive.

The reason for the time difference is probably that velocities below reference are not penalized enough.

### 4.4 Conclusions for the Real-time Implementation

Predictive speed control offers the potential to save fuel without any mechanical changes.

In this part of the thesis a test platform suitable for comparative fuel tests of predictive speed control algorithms in real vehicles has been developed. One speed control algorithm based on model predictive control (MPC) has been implemented and tested, but the interface was created in a way such that it easily can be extended with other algorithms. The system is operable in a real time environment in a Scania truck. The system also cooperates well with AiCC.

The implemented control could give a substantial reduction in fuel consumption. An initial comparative fuel test on a return trip Södertälje - Norrköping (Section 4.3) has been performed and shows an average reduction of consumed fuel by approximately 1.4 % on the road towards Norrköping and 2.4 % on the road towards Södertälje. The reduction in fuel is dependent primarily on vehicle weight and road slope. More fuel is saved in a net descent than in a net ascent. The result is also affected by the compensations which has been made for vehicle differences and time differences and more tests should be performed to verify that fuel actually is saved.

The main problem of model predictive speed control, which has become apparent through practical tests, is the positioning in the road profile. It is of greatest importance that the actual vehicle position is in good agreement with the position in the road profile. Since velocity drift is an issue whenever the actual global position is not used for neither profile measurements nor actual positioning of the test vehicle, a drift correction algorithm has been developed and implemented. However, in its present embodiment it has a rather poor performance. The limiting factor seems to be the real time slope estimation and altitude measurements.
In [70] a method for improved altitude estimations is described. This method shows a much better performance and it would be a natural step in the development of the RT interface to integrate that method with the drift correction algorithm described in Section 4.2.4.

It would also be interesting to implement an automatic road profile switch when the navigation system detects a change of roads.

For further comparative fuel tests it would be desirable to test the system using different velocity tolerances, but also to use different algorithm parameters and/or algorithms. The Master’s thesis [60] can give guidance to which parameter choices that should be tested. It would also be desirable to create a more detailed model for the engine torque for use in the controller.
5 Conclusions and Future Work

Patent mapping
The patent mapping shows that the use of positioning systems for control of vehicular systems is a very intensive field of research. Fields covered are aid to ACC, automatic gear changing systems and engine control. The purpose of the control aid is to save fuel, lower emissions and component wear sustaining a safe drive. It is obvious that a trade-off between the above control goals is necessary. Predictive speed control is one of the most straight-forward areas of use, where benefits such as less fuel consumption could be achieved. Therefore this has also been investigated further.

The choice of the covered fields was a request from the assignee, Scania, and the patent mapping will be used as a work of reference for concerned departments at Scania. Apart from the covering of the state of the art today, the ideas are valued and a few new solutions are suggested, most importantly aid from positioning systems for selective catalytic reduction, SCR.

Predictive Speed Control
Predictive speed control offers the potential to save fuel only by controlling the speed at the right moment. The idea is to utilize the own vehicle weight and gravity. It is cheaper to increase speed in a downhill slope than uphill. Furthermore, before an uphill slope it could be beneficial to increase speed. The aim of the control is to reduce fuel consumption, yet keeping the same average speed as conventional cruise control (CC).

The optimality of this is investigated through a relatively simple vehicle model. Given the road topography, a road profile, for a particular distance ahead of the vehicle’s current position an optimal problem can be solved, and a desired vehicle speed can be calculated online at each position. The method is called model predictive control (MPC) and the resulting problem is solved through dynamic programming (DP).

In this work the method has been applied to a real truck, through the development of a test platform on a laptop computer. Previously this and other methods could only be simulated. The result is a solution where a test engineer simply can bring a laptop computer with the test platform installed to a Scania truck, plugin a hardware interface and start driving.

The method has been thoroughly described, tested and evaluated and an initial comparative fuel test has been performed, where MPC is compared to conventional CC. The result is a reduction in fuel consumption of 1.4 % to 2.4 % when the MPC algorithm is used. However, it should be subject to future work to perform more comparative fuel tests to truly verify that fuel actually is saved. Factors that may affect the result are vehicle weight, road slope, model parameters, algorithm parameters, positioning errors and the corrections that has been made for individual differences. It should be mentioned that the aim of this work was to develop a test platform that enables tests with different parameters, not to perform a series of tests.

There is clearly a difference between performing simulations under ideal conditions, when a known model is used as the real truck and performing experiments in a real truck. Some of the main problems, which are discussed are modeling errors and positioning errors. Furthermore, the test method is described and discussed.
Appendix A – Effects of Different Information Levels

Lateral forces Free Body Diagram (FBD)
In order to determine a safe passing speed in a curve, several different methods have been presented in this thesis. To theoretically determine the speed when a vehicle starts to slide, a Free Body Diagram (FBD) for the vehicle must be drawn (Figure 44).

Forces at a threshold speed (maximum), just before the vehicle starts to slide:

\[ F_x : \frac{mv^2}{r} = N \sin \theta + \mu_s N \cos \theta \]
\[ F_y : 0 = N \cos \theta - \mu_s N \sin \theta - mg \]

This results in the following expression for the maximum speed:

\[ v_{\text{max}} = \sqrt{\frac{rg(\sin \theta + \mu_s \cos \theta)}{\cos \theta - \mu_s \sin \theta}} \]

where

- \( r \) is the curve radius,
- \( g \) is the acceleration due to gravity,
- \( \mu_s \) is the coefficient of friction, and
- \( N \) is the normal force from the road acting on the vehicle.

The main reason for the unwillingness to use this may be that it could be complicated to determine the coefficient of friction and road bank angle. Instead most patents use the estimation that a vehicle that travels a curve with the radius \( r \) at speed \( v \) is subject to a lateral acceleration of \( v^2/r \). Then a preset, accepted lateral acceleration is used to determine a velocity that will cause that acceleration in a known curve. For simplicity this will be used in the following calculations.
However, it is important to realize that it is not certain that the vehicle will not slide even if the accepted lateral acceleration is not exceeded. Likewise it is possible for the accepted lateral acceleration to be exceeded even though the vehicle does not slide. Hence, the ideal expression for the maximum velocity in a curve should be:

\[
V_{\text{recommended}} = \min(v_{\text{max}} \cdot \sqrt{a_{\text{lateral accepted}} \cdot r})
\]

This expression is, however, not used in any of the described patents.

**Lateral acceleration with or without road bank angle information**

A simplified expression for the lateral acceleration of a vehicle in a curve can be calculated as:

\[
a_{\text{l}} = \frac{v^2}{r} - g \cdot \sin(\theta)
\]

where \( \theta \) is the transverse slope (bank angle).

Most of the investigated patents exclude information on road bank. This calculus is performed to see how big the difference actually is when the second term in the expression above is included compared to when it is not.

The idea of building roads with a transverse slope is to use gravity to balance the lateral acceleration caused by driving in a curve with a certain velocity. The reduction in lateral acceleration is illustrated in Figure 45.

![Figure 45: Road bank illustration.](image)

Consider the graph in Figure 46. According to a publication from the Swedish road administration, Vägverket [71], the road bank lies between 2.5 and 5.5 percent on Swedish roads. In a curve with a 3% road bank, which is far from unusual, the lateral acceleration is reduced by 0.2 m/s\(^2\), indifferent of the curve radius.
That may not seem to be much, but compared to a road with no bank angle the velocity is allowed to increase with $3.6 \cdot \sqrt{0.2 \cdot R}$ km/h.
Figure 47: Allowed extra velocity if the road bank is 3%.

Considering that the minimum radius of a Swedish curve on a rural road with a 90 km/h speed limit is between 400 and 600 metres (according to [71]), the estimated safe velocity if the bank angle is not considered, can be as much as 30 or 40 km/h too low.

Hence, methods that do not consider the bank of a road for speed control in a curve may be very much too conservative when choosing their safe curve passing speed. If any kind of curve controller is to be developed based on data from a positioning system, information on road bank should be included in order not to annoy the driver, nor to lose time. However, one should realize that the estimated safe velocity on a typical 90 km/h rural road often is considerably higher than 90 km/h.

Another idea would be to detect a corner, and then utilize the type of road the vehicle travels, to add a constant term representing the allowed extra velocity due to the bank angle on that type of road.
Recommended velocity with or without exact curvature
To illustrate the problem Figure 48 can be used. The vehicle on the left side of the road travels through a curve with the radius $r_1$, which is a much gentler curve than the vehicle on the right side. Hence, from the same accepted lateral acceleration, different recommended velocities are assigned to the two vehicles, even though they travel through the same curve.

![Figure 48: Same curve, different curvature](image)

The following example is based on a rural road with one lane in each direction and aims to illustrate the problem. The total width of the road is 10 metres. From that, it can be assumed that the distance from centre of the road and centre of the driving path (centre of lane) is 2.5 metres. The difference in recommended speed in a corner is (not considering the bank angle of the road):

$$\Delta v_n = \sqrt{2.5 \cdot a_L}$$

This velocity difference above is plotted in the diagram in Figure 49.

![Figure 49: Deviation in recommended velocities, if centre of road was used.](image)

The ISO-standard 2631-1 has determined values for accelerations that can be considered comfortable for adults. According to that investigation, acceleration above $0.315 \text{ m/s}^2$ is no
longer considered comfortable. Accelerations above 2 m/s\(^2\) are considered really uncomfortable. This provides us with an appropriate scale to investigate the deviation from recommended velocities, if the centre of road was used instead of the actual driving path. This is illustrated in Figure 49.

This leads to the conclusion that the deviation is not extremely big, but one cannot disregard from the fact that different lanes give different curvatures and hence, different recommended velocities. However, it is not certain if it is better to keep a set of nodes for each lane, or if it is better to know the number of lanes and the total road width.

Even if positioning means in some cases are not accurate enough to determine which lane the vehicle travels, it can still make a vast difference if it is known which direction the vehicle is turning.
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