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Road Shape Modelling from Digital Map Data

- and Implementation of a Map Supported Cruise Control

Master of Science Thesis

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Abstract

In recent years, the use of digital map data with road attributes has spread from in-vehicle navigation systems to more sophisticated driver assistance systems. The data can be used together with a GPS positioning system to provide information about the road network close to the vehicle. The information is sufficient for navigation purposes but for the advanced applications, a more accurate model of the road ahead is needed.

This thesis proposes a method for road modelling from commercially available map data using a spline interpolation algorithm. The algorithm has several features, such as a possibility to change the smoothness of the spline and to model intersections and right-hand traffic. The road models can be used in applications where a preview of the road shape is of interest. An example application is also developed; a map supported cruise control.

The map supported cruise control uses speed limits and road curvature calculated from the model to automatically adjust the target speed of the cruise control before sharp turns and changes in speed limits. A vehicle model is used to predict the deceleration, which in turn is used to decide when to lower the target speed.

The road models are verified against collected GPS-data and it is shown that the models provide better fit to road shape and curvature, compared with the source map data. The improvement is most obvious in sharp curves and intersections. The models were also implemented in a test truck. On-road tests enabled comparison of the driver’s speed with the recommended maximum speed calculated from the road models. The tests showed that the developed models are accurate enough to be used for automatic speed adaption.

The on-road tests also showed that the map database environment used has to be improved. For example, speed limits are often missing in the map data and errors were found in the position mapping. The map supported cruise control worked well in the few test drives conducted. To improve and expand its use the brakes of the truck must be utilised. Unfortunately, this was not achieved in this study. The final conclusion is that the concept, or a simplified version of it, is promising and might be considered as a feature in future trucks.

Key words: Digital map data, ADAS, electronic horizon, road shape modelling, cruise control.

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Simon Andersson & Johannes Aronsson

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Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
ADASRP	ADAS Research Platform
B-Spline	Basis Spline
CAN	Controller Area Network
EH	Electronic Horizon
EMS	Engine Management System
GPS	Global Positioning System
GUI	Graphical User Interface
HMI	Human Machine Interface
MSCC	Map Supported Cruise Control
PIP	Packaged Industrial PC
UDP	User Datagram Protocol
VEB	Volvo Engine Brake
VECU	Vehicle Electronic Control Unit

1 Introduction

This first chapter will give an introduction and describe the motivation behind this thesis as well as present its purposes and objectives. Also presented here are the limitations of the thesis. Last in this chapter is a short outline of the rest of the report.

1.1 Thesis Motivation

Many vehicles of today are equipped with a navigation aid system built around digital map data and a Global Positioning System (GPS) receiver. The digital map data describes the road network in an area and the GPS-receiver provides a positioning of the vehicle in the road network. The information is used to describe the surroundings of the vehicle to the driver or to other vehicle systems. If a predefined route is known, the system can also provide preview information of the intended vehicle path.

A vehicle system that could benefit from preview information about the road network is the driver cruise control. The cruise control aims at keeping the vehicle at a target speed set by the driver. However, the speed of the vehicle needs to be decreased in sharp curves and changed as the speed limit of the road changes. If the preview information could be used to automatically decrease the target speed of the vehicle at the appropriate time, there would be a potential benefit in driving comfort, safety, and fuel economy.

Recently tests have been performed at Volvo Technology AB to see if it is possible to provide a recommended speed for a heavy-duty truck based on preview information of the vehicle path. A conclusion from the tests was that the value of the road curvature given in the digital map data could not be used for speed recommendation. The tests also found weaknesses in how sharp curves and intersections where represented in the digital map data. These shortcomings need to be addressed if the digital map data is to be used for automatic speed adaptation.

Presented in this thesis is a road shape modelling method that uses the geometrical shape of the road, represented by coordinates in the digital map data, to calculate the curvature of the road. The challenge lies in providing a robust road shape modelling method to describe a realistic vehicle path by suppressing the weaknesses in the digital map data. The curvature value from the road shape model is used together with speed limit information to implement a cruise control function that adapts the vehicle speed.

1.2 Purposes and Objectives

The purposes and objectives of this master’s thesis are listed below.

Purposes:
- Find methods to address weaknesses in the available digital map data.
- Investigate if digital map data can be used for automatic speed adaptation.

Objectives:

- Develop algorithms to model road shape from digital map data.
- Use the curvature and speed limits of a road to enhance the function of an existing cruise control function with automatic speed adaptation.
- Implement and test the developed functions in a test truck.

1.3 Limitations

The following limitations are made in this report:

- Road slope or banking will not be considered.

  The digital map data has data tables for road slope and banking. However, the data exists only for very few roads and collection of new data is outside the scope of this report. Therefore road slope and banking will be disregarded in both the road shape modelling and the deceleration model for the truck.

- Known vehicle parameters are assumed.

  Vehicle parameters such as wheel radius, gear shift maps, and vehicle weight are known. These have been acquired from data sheets or by measurements.

- An existing cruise control function will be used for the speed adaptation function.

  The test truck used in this work is equipped with a cruise control from the factory. To simplify the task of engine control the speed adaptation will be done by controlling the set speed of the existing cruise control.

1.4 Outline

The thesis is structured as follows: In chapter two a short background to the thesis will be given. It includes an introduction to advanced driver assistance systems as well as the software and the digital map data used in this report. Chapter three will summarize the theory of the splines and the spline interpolation that are used in the road shape modelling. The road shape modelling itself is presented in chapter four. The chapter explains how the splines are used together with three developed algorithms to accurately model the road. Chapter five presents the map supported cruise control. It includes a deceleration model of the test truck and also explains how the set speed of the cruise control is calculated from the output of the road shape models. A brief description of the implementation in the test truck is given in chapter six. Next, in chapter seven, the results from the test drive sessions are presented. Conclusions from the results are presented in chapter eight and recommendations for further work are given in chapter nine.

2 Background

This chapter starts by describing the idea behind an advanced driver assistance system. Also the digital map data and the software used, which are the base for this master thesis, will be described as well as some related concepts. Last in this chapter the shortcomings of the digital map data, which motivates the need for road shape modelling, is presented.

2.1 Advanced Driver Assistance Systems

An Advanced Driver Assistance System (ADAS) is used to assist the driver of a vehicle. The systems purposes vary but can be e.g. to improve safety, comfort, or fuel economy. Examples of ADAS that exists on the vehicle market today are the cruise control and the in-vehicle navigation systems. Some of the systems are regarded as standard equipment, such as the anti-lock braking system and the electronic stability control system.

A basic ADAS is built around a processing unit with input and output interfaces. The input to the system is sensor signals and possibly user parameters. The output is user feedback and vehicle control, see Figure 2.1.

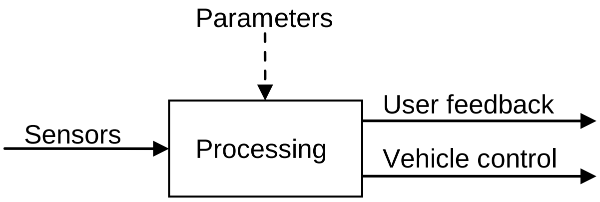

Figure 2.1 Functional layout of a basic ADAS.

The user feedback is used to warn or inform the driver of the current situation or vehicle status. Feedback is achieved using a Human Machine Interface (HMI), such as a display (visual feedback), audio device (acoustic feedback), or through an actuator, e.g. by applying a counter-force in the accelerator (haptic feedback).

The vehicle control changes the behaviour of the car. Examples of vehicle control actions are application of brake pressure in the case of an electronic stability control, or change of throttle angle in the case of a cruise control.

2.2 Digital Map Data

One popular group of ADAS are the in-vehicle navigation systems. These systems use digital map data together with a positioning system to assist in vehicle navigation. As the in-vehicle navigation systems have become more readily available in vehicles, the developers of other ADAS have begun to see the potential benefit of using the information provided by digital maps (Li et al, 2007).

The digital map data used in this thesis is provided by the company NAVTEQ. The data not only covers road geometry but also a wide set of attributes such as road classifications, traffic signs, and the radius of the road. The road geometry is represented by links, shape points, and shape lines. A link is a piece of road that connects two intersections. A link has two or more shape points that define its shape, and any two shape points are connected with a shape line (See Figure 2.2).

By definition from NAVTEQ the shape points are chosen from the points in their collected GPS data trace of the road network. The shape points are chosen so that the shape lines connecting them do not deviate from the GPS trace with more than one meter.

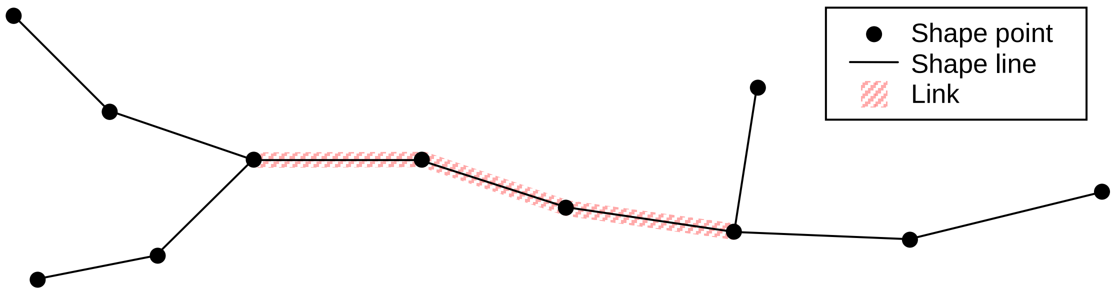

Figure 2.2 Illustration of the road network representation in the digital map data.

An attribute is defined as a start position on a link, a distance of validity, and type of attribute. The different types of attributes can be any of a set of pre- or user defined types. Examples of attributes are speed limits, number of lanes, and compulsory stops.

Another available attribute is the road radius. This is stored in each shape point and represents the radius of a circle that coincides with the road close to that point (See Figure 2.3).

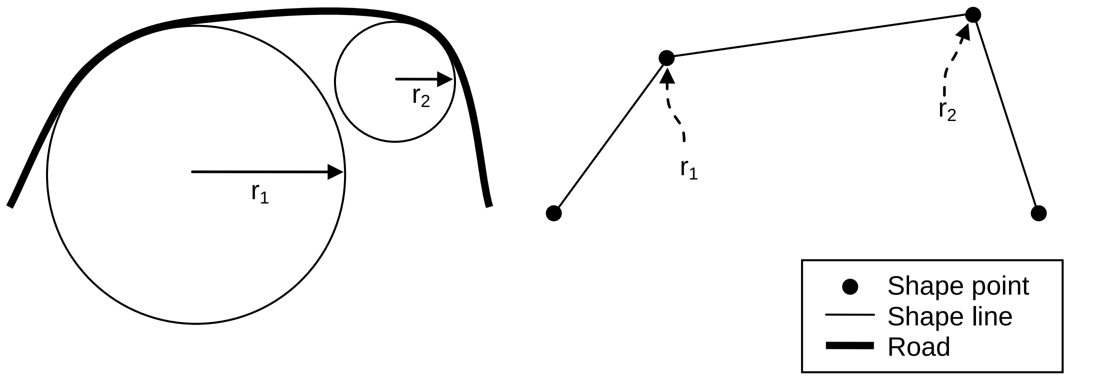

Figure 2.3 Illustration of the road radius attribute and how it is stored in the digital map data.

2.3 Electronic Horizon and Most Probable Path

An often used concept when dealing with digital map data is the Electronic Horizon (EH). This is a subset of the data that only contains information about the road network close to the vehicle. It can be defined as e.g. the data of all the roads within a given distance from the vehicle position. The advantage of using this concept is to limit the amount of data needed to be processed by an application that uses the digital map data.

The Most Probable Path (MPP) is a further limitation of the data consisting of one single path in the EH considered as the most likely one to be chosen by the driver. It is calculated by a probability model where the probability of making a turn in the next intersection is defined using a set of predefined criteria. One such criterion can be the assumption that a driver tends to favour larger roads with higher speed limits over smaller streets. Only the links with the highest probabilities gets included in the MPP. The calculation of the MPP will also consider any predefined routes entered by the driver. The links of such routes will automatically be chosen as the MPP since they form the intended vehicle path.

2.4 Advanced Driver Assistance System Research Platform

The Advanced Driver Assistance System Research Platform (ADASRP) is a software application provided by NAVTEQ. It uses their digital map data as a base for ADAS prototyping. ADASRP runs in a Microsoft Windows environment on a PC. It can process sensor inputs from a GPS receiver, a gyroscope, and an odometer to position a vehicle in the road network of the digital map data. NAVTEQ provides a “plug-in” solution containing these three sensors in a product called SensorBox.

The EH is the main entry point for most plug-in applications for ADASRP. ADASRP uses a probabilistic algorithm when construction the EH where each link, starting from the current link, has a probability of being included in a sub-tree of links that forms the EH. The algorithm is iterated until a criterion, often a maximum depth of the horizon in length or number of links, is met. The input from the SensorBox is used to position the vehicle in the map and get a starting link of the EH. The EH is then updated as the vehicle moves along its path. The MPP will also be recalculated if a deviation from the presumed path is detected.

A graphical representation of an EH tree and an MPP are presented in Figure 2.4 below. In our application the MPP is assumed to represent the path that the driver will drive and it is used as an input to the road shape modelling algorithms.

Figure 2.4 Graphical representation of the links included in the EH (left) and in the MPP (right). The truck position is marked with a dot. Pictures are from the ADASRP graphical interface.

2.5 Shortcomings of the Digital Map Data

After an initial analysis of the digital map data some shortcomings could be identified. These shortcomings were also a reason for Volvo to request better modelling of the roads from the digital map data. The shortcomings are:

- The shape points and shape lines describe the centre line of the roads, while a driver will drive on the right (or left) hand side of the road. This must be taken into consideration in the road shape modelling to accurately describe the vehicle path (see Figure 2.5 below).

- The curvature (the inverse of the road radius) in the map data is given in low resolution. It is also only present in the shape points and is thus not given very often.

- The curvature is sometimes incorrect. On small curvy roads and in intersections the curvature in the map data was found to deviate a lot from curvature calculated from measurement data.

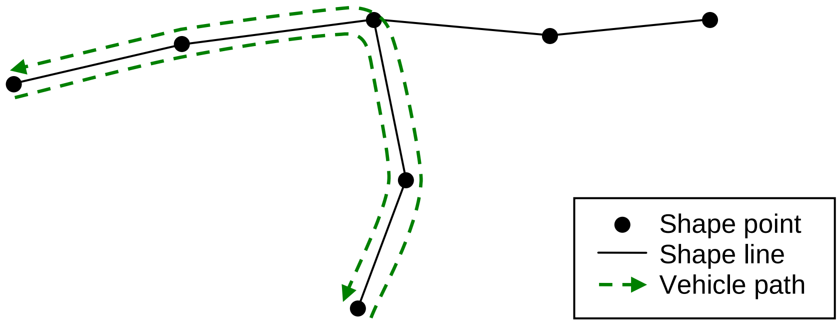

Figure 2.5 Illustration of the road shape stored in the digital map data and the actual vehicle path.

3 Spline Theory

In this chapter the theory of splines and spline interpolation/curve fitting is presented. The concept of smoothing splines to provide a soft curve fitting is also introduced. Spline interpolation with smoothing is the method used in this thesis to model the roads from the digital map data.

3.1 Definitions of Splines

A spline is a function that is defined piecewise by polynomials (The Mathworks, Inc., 2009). It is built up by a number of low degree polynomial functions where each one represents a certain part of the spline. This makes the spline easy to control locally. Two common ways of representing a spline are the Basis form (B-splines) and the piecewise polynomial form (The Mathworks, Inc., 2009).

A B-spline is completely defined by a set of control polygon vertices with corresponding basis functions. This is illustrated in Figure 3.1. The control polygon vertices are points which determine the geometrical appearance of the spline. The curve generally follows the shape of the control polygon. The basis functions are functions which determine the weighting of the vertices at a certain point on the spline.

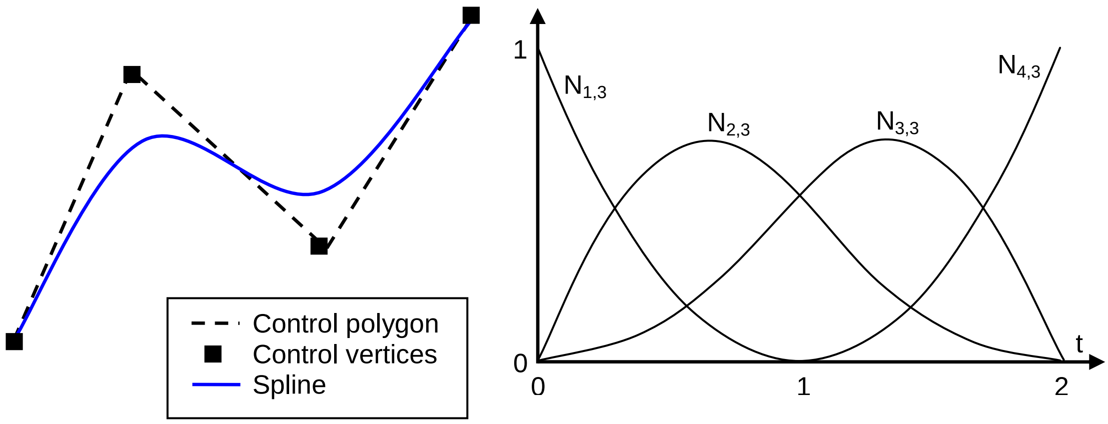

Figure 3.1 A control polygon with four vertices together with the corresponding basis functions, $N_{1,3} \dots N_{4,3}$*, completely describes a third order spline.*

The B-spline curve of order k as a function of the parameter t is given mathematically by Rogers (2001) as

$$P(t) = \sum_{i=1}^{n+1} B_i N_{i,k}(t) \quad t_{\min} \leq t < t_{\max}, \; 2 \leq k \leq n+1 \tag{3.1}$$

Here, B_i is the position vector of the i:th of the $n+1$ control polygon vertices. The $n+1$ basis functions $N_{i,k}$, is defined by the Cox-de Boor recursion formulas as

$$N_{i,1}(t) = \begin{cases} 1 & \text{if } x_i \leq t < x_{i+1} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{and } N_{i,k}(t) = \frac{(t - x_i) N_{i,k-1}(t)}{x_{i+k-1} - x_i} + \frac{(x_{i+k} - t) N_{i+1,k-1}(t)}{x_{i+k} - x_{i+1}} \tag{3.2}$$

In these formulas x_i denotes the i:th value in a so called knot vector. These knot values have a significant influence on the basis functions and different properties can be achieved depending on the choice of the knot vector. The only requirement when choosing the values is that they satisfy $x_i \leq x_{i+1}$. Depending on the knot vector a spline is classified as either a uniform or a non-uniform spline. A uniform spline has the values of the knot vector evenly spaced while a non-uniform spline can have unequally spaced and multiple internal knot values. The number of knot values in a knot vector is $n+k+1$.

A spline of order k is formed by polynomials of degree $k-1$, hence a 4^{th} order B-spline curve is a piecewise cubic curve and therefore often called a cubic spline. A spline of order k has the property that its derivatives of order $1,2,\ldots,k-2$ is continuous over the entire curve. This implies that a spline has continuous curvature if the order is 4 or higher.

Another previously mentioned property is the possibility to control the spline locally. Each point on the spline curve is determined by only the k closest control polygon vertices.

The other way of representing a spline, which is used frequently in MATLAB, is the piecewise polynomial form. The spline is described in terms of several connected polynomial functions represented by coefficients and of its so called breaks, ξ. The breaks corresponds to the values of the parameter t where the next polynomial function defines the spline, dividing the spline into l pieces. In the simplest case (the spline is not vector-valued) the j:th polynomial function is described by The Mathworks, Inc. (2009) as

$$p_j(x) = \sum_{i=1}^{k} (x - \xi_j)^{k-i} C_{ji}, \quad j = 1:l \tag{3.3}$$

Here the C matrix contains of coefficients and has the number of rows as the number of pieces and the number of columns as the order of the spline.

3.2 Spline Interpolation and Curve Fitting

In the previous section spline construction from a control polygon is described. If instead a spline is requested that follows a set of data points, the problem is to find the control polygon vertices that satisfies this request for a given knot sequence. This is referred to as spline interpolation when the data points coincide with the spline, or spline curve fitting where the spline is an approximation to the data points.

Rogers (2001) states that for the data points $D_1, D_2, \ldots, D_j$ to coincide with the spline curve using B-spline representation (3.4) must be satisfied.

$$\begin{aligned} D_1(t_1) &= N_{1,k}(t_1)B_1 + N_{2,k}(t_1)B_2 + \ldots + N_{n+1,k}(t_1)B_{n+1} \\ D_2(t_2) &= N_{1,k}(t_2)B_1 + N_{2,k}(t_2)B_2 + \ldots + N_{n+1,k}(t_2)B_{n+1} \\ &\vdots \\ D_j(t_j) &= N_{1,k}(t_j)B_1 + N_{2,k}(t_j)B_2 + \ldots + N_{n+1,k}(t_j)B_{n+1} \end{aligned} \tag{3.4}$$

Or more compactly written in matrix form:

$$D = N \cdot B \Rightarrow B = N^{-1} \cdot D$$

Solving the equation system would give the control polygon vertices $B_1, B_2, \ldots, B_{n+1}$ describing a spline which coincides with all of the data points. With a high number of data points the equation system will grow and become hard to solve. One solution to this problem is, as in e.g. MATLAB Spline Toolbox, to use sparse matrix algorithms (The Mathworks, Inc., 2009).

Sometimes the spline used for following a set of data points has two demands: it should interpolate the points but it should also have certain smoothness. These demands are contradictive, it might be hard to find a spline which passes exactly through each point but at the same time has a requested smoothness.

De Boor (1978) suggests a method which handles both these demands where the aim is to minimize the expression

$$p\sum_{k=1}^{j} w_k \left| D_k - P(t_k) \right|^2 + (1-p)\int_{t_1}^{t_j} (P''(t))^2 \, dt \tag{3.5}$$

This expression is valid only for cubic splines. P is the spline, D_k the data points and w_k weights that can be used to give different points different importance. The weight factor, p, can be given values between 0 and 1. It is used to balance the two demands, if a lower p is chosen the spline is smoother but it gets farther away from the data points. When $p = 0$ the resulting spline is the least square straight line approximation to the points and when $p = 1$ it becomes the so called variational, or natural cubic spline, which coincides with all of the data points.

When a vector valued spline is to be constructed, a problem is to choose $t_1, t_2, \ldots, t_j$, the parameter values which corresponds to the location of the data points. Rogers (2001) suggests a method where these parameter values are based on the chord lengths between the data points. For *j* values, the l:th value is calculated as

$$t_1 = 0$$
$$\frac{t_l}{t_{\max}} = \frac{\sum_{s=2}^{l} |D_s - D_{s-1}|}{\sum_{s=2}^{j} |D_s - D_{s-1}|} \qquad l \geq 2 \tag{3.6}$$

Where t_{max} can be chosen as the maximum value of the knot vector, or simpler, the total length of all the chords.

4 Road Shape Modelling

This chapter explains the road shape modelling and its output, the curvature of the road, used later in this work. It also explains the method used; how the splines are constructed from the shape points of the digital map data and the reason for using smoothing. Last in this chapter, three developed algorithms are presented which improves the performance of the modelling.

4.1 The Road Shape Modelling Concept

The purpose of the road shape modelling is to provide a mathematical model of how the truck will move in terms of its coordinates based on the digital map data. If this model is implemented using parametric curves the curvature can be calculated using (4.1). This curvature can, together with other attributes, serve as input to other applications, for example a map supported cruise control which is described in the next chapter. Hence, the performance of the applications using the calculated curvature strongly depends on the accuracy of the road shape modelling.

For a vector-valued function in the plane given parametrically, f(t) = [x(t) y(t)], the curvature is defined as (Weisstein):

$$\kappa(t) = \frac{\left| x'(t) y''(t) - y'(t) x''(t) \right|}{\left(x'(t)^2 + y'(t)^2 \right)^{3/2}} \qquad (4.1)$$

The curvature in a point on a curve can be interpreted as the inverse of the radius of a circle that approximates the curve close to that point. Large curvature values therefore correspond to a sharp curve. Sometimes the inverse of the curvature is used instead, referred to as the radius of curvature.

The chosen method of modelling the road shape is spline interpolation of the shape points contained in the MPP available from ADASRP. Other methods to represent the road shape could be considered, e.g. representing the road shape with circle arcs, straight lines and clothoids (see e.g. Jiménez et al, 2009). One reason for choosing spline interpolation is that it is relatively easy to implement using existing algorithms. A second reason is that the shape of the interpolated spline is easy to control by adding shape points or moving the existing ones, which is used in this work and described later in this chapter.

4.2 Construction and Smoothing of Splines

The shape points are interpolated with non-uniform cubic splines (order 4). In this way the spline has continuous second derivates which also implies continuous curvature. The curvature of the constructed spline is evaluated at a number of linearly spaced t-values. The number of t-values is proportional to the length of the MPP to get approximately the same distance between the evaluation points.

When interpolating the shape points there is a need to smoothen the spline using the criteria described in (3.5). Interpolation with a spline that coincides with all the shape points (natural cubic spline) results in too high and too many curvature peaks. If this curvature should be used for speed recommendation the recommended speed would be very low as it indicates several sharp curves. The phenomenon is described Figure 4.1. The smoothing can be seen as low pass filtering letting the important road shape through and suppressing the small curves that arise from e.g. inaccuracies or rounding errors. Another reason for smoothing the spline is to model that the driver sometimes doesn't follow the centre line exactly and tends to take short cuts.

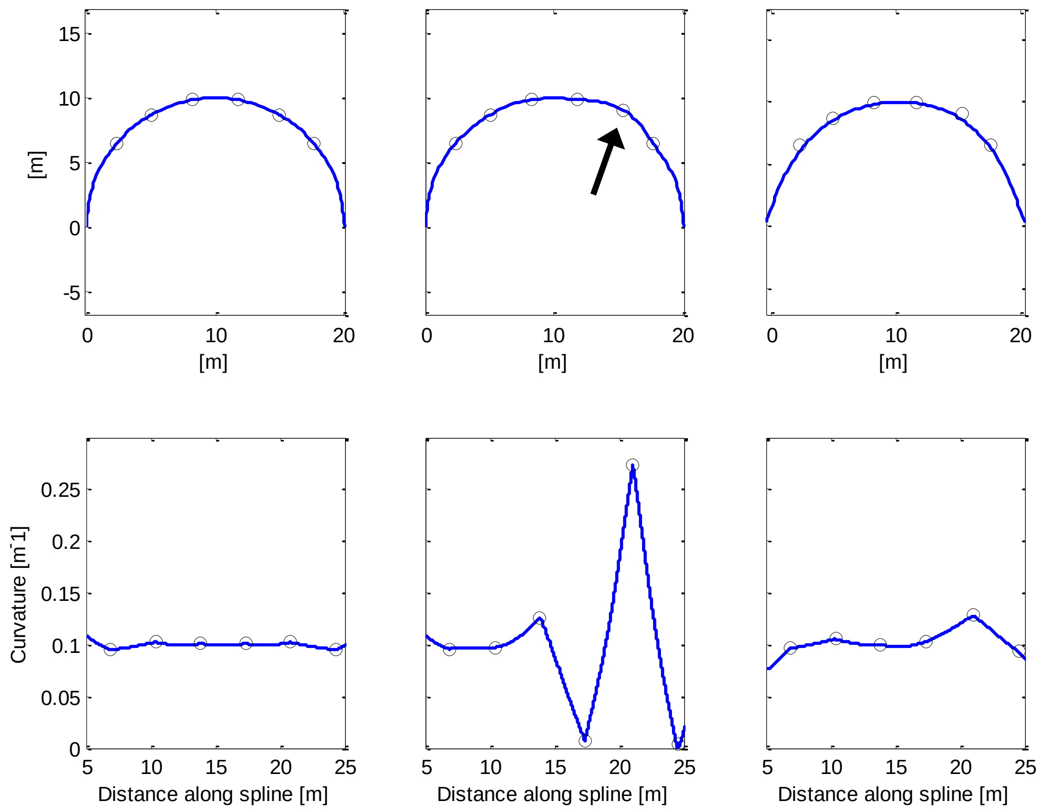

Figure 4.1 Spline interpolation of points lying on a circle with a radius of 10 m. The curvature values marked with circles in the lower picture corresponds the points interpolated marked in the upper picture. In the left column the points lies exactly on the circle and thus the curvature is stable around 0.1 m^{-1}. In the second column the point marked with an arrow is moved 0.5 m out from the circle centre representing an inaccuracy. This results in a peak in the curvature in this point. The solution is to smooth the spline showed in column three. The spline deviates a little from some points but the curvature clearly shows that this is a curve with a radius of approx. 10 m.

The smoothing could be controlled with the weight factor, p, as explained in section 3.2. However, using the same value of p for different sets of points could lead to different amount of smoothness since it depends on the lengths between the points. Therefore, as the Spline Toolbox User's Guide (The Mathworks, Inc., 2009) suggests, the average spacing of the points, h, is taken into account when p is calculated as

$$p = \frac{1}{1 + \frac{h^3}{s}} \tag{4.2}$$

Here, s (which is referred to as the smooth factor) is instead used to control the smoothing. According to the Spline Toolbox User's Guide (The Mathworks, Inc., 2009) the area of interest when choosing the smooth factor is often a value around six. A smaller factor gives a smoother spline and a larger one forces the spline closer to the points. The smooth factor has a large impact on the resulting curvature, as is seen in Figure 4.2.

In this thesis a smooth factor of 0.5 is used. This value results in a smooth curvature while the spline still lies close to the shape points. It was also verified later in this work when the chosen smooth factor value delivered realistic speed recommendations. The smooth factor can be tuned in the interface of the road shape modelling plug-in (see Appendix B).

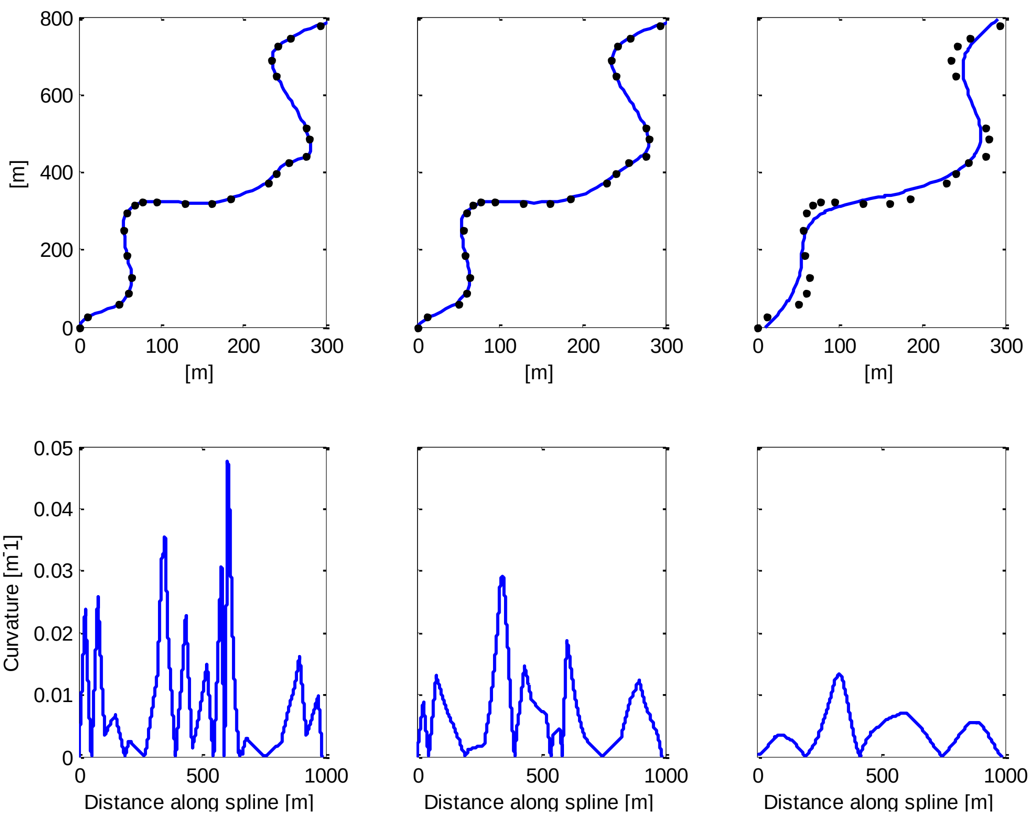

Figure 4.2 Illustration of how the smooth factor influences the spline interpolation (top row) and corresponding curvature (bottom row). The smooth factors used are, from left to right, 500, 5 and 0.05.

4.3 Algorithms for Improved Road Shape Modelling

When interpolating the shape points with splines the resulting curves follows the shape lines in most cases. But sometimes the curves deviate from the shape points and shape lines. Some cases are also identified where the curve does not represent a realistic vehicle path. Three algorithms which move the shape points or add extra points were therefore developed to address these situations.

4.3.1 Intersection Modelling

In each intersection there is a shape point representing the middle of the intersection. If this point is used for interpolation the spline will describe a very wide curve in the intersection and will deviate a lot from the shape lines. To address this, an algorithm was developed that inserts a circular arc of five extra shape points in intersections. The radius of the circular arc is set to a predefined value. A graphical illustration of this algorithm is presented in Figure 4.3.

To determine if a shape point is an intersection point the easiest approach is used, namely to check if the angle between the two shape lines connected to the shape point exceeds a predefined value.

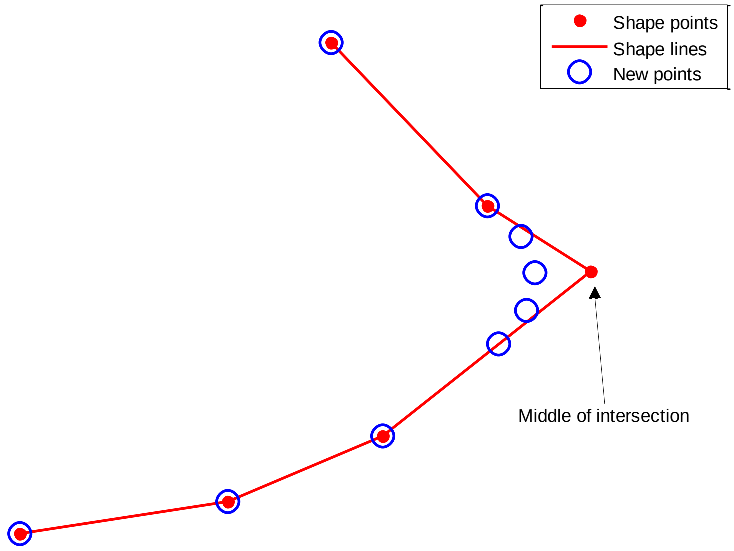

Figure 4.3 Illustration of the intersection modelling algorithm. The red dots are the original shape points from the digital map data and the blue circles represent the shape points at the output of the algorithm.

The intersection modelling algorithm has no or little effect when it is not combined with the shape point distribution algorithm (described in the next section). A comparison of a spline constructed with and without the intersection modelling algorithm is shown in Figure 4.4. The left picture, without the algorithm, shows the typical behaviour with a too large turn radius (approx. 40 m) and large deviations from the centre line. In the right picture a circular arc with a radius of 15 m is introduced and the resulting spline shows a more realistic behaviour.

Figure 4.4 Two spline interpolations. The left picture without the intersection modelling algorithm and the right picture with the algorithm turned on.

4.3.2 Shape Point Distribution

A problem when interpolating the shape points is that they are not uniformly spaced. The lengths of the shape lines vary and this can have a negative effect on the resulting spline. The shape point distribution algorithm adds extra points to ensure that neither of any two connected shape lines is longer than a factor times the other. The result is that the spline is forced closer to the shape lines in-between the original shape points.

An example of the result of the shape point distribution algorithm is shown in Figure 4.5. In the left picture, without the algorithm, a typical scenario is shown where the shape points are tightly located just before a curve and the distance to the next shape point is relatively large. Here the spline deviates from the shape line with approximately 30 m. NAVTEQ:s way of road representation guarantees that the shape lines does not deviate from the originally collected GPS points with more than 1 m, so the behaviour in the left picture is not desirable. Also here the spline constructed without algorithms results in too large turn radius. When the algorithm is applied six new points are added, forcing the spline closer to the centreline.

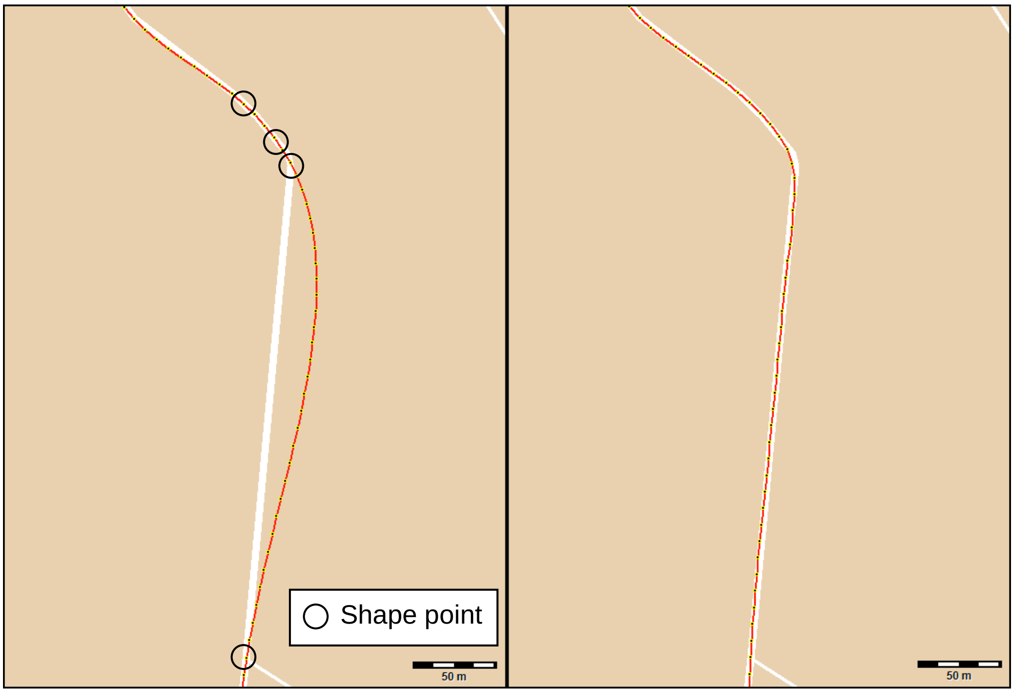

Figure 4.5 Two spline interpolations. The left picture without the shape point distribution algorithm and the right picture with the algorithm turned on. The original shape points are marked by circles in the left picture.

4.3.3 Right-hand Traffic Modelling

The shape points in ADASRP represent the centre line of the road. To get more realistic curvature values the shape points are moved to model right-hand traffic. This can be done by moving all points to the right in the driving direction. A vector which starts in the shape point is calculated as the vector that has the same angle to both of the connected shape lines (see Figure 4.6). Then the shape point is moved along the direction of this vector a certain distance. At the start and end of the MPP the shape points are moved along a vector which is perpendicular to the connected shape line.

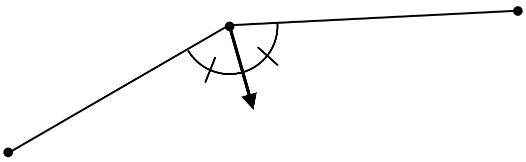

Figure 4.6 Three shape points connected with two shape lines. The arrow shows the direction that the right-hand traffic modelling algorithm moves the middle shape point.

The distance the point is moved is set to half the width of the lane, assuming the truck drives in the centre of the lane. The default lane width in the road-shape modelling is set to 3.5 m, resulting in each point moving 1.75 m to the right in the driving direction. This width is based on Vägverket (2004) which states that all newly built roads with a width of more than 6.5 m has lane widths between 3.25 and 3.75 m.

The result of the right-hand traffic modelling algorithm is shown in Figure 4.7. Here the lane width is set to 3.75 m and the truck is supposed to travel from the lower right corner to the upper left.

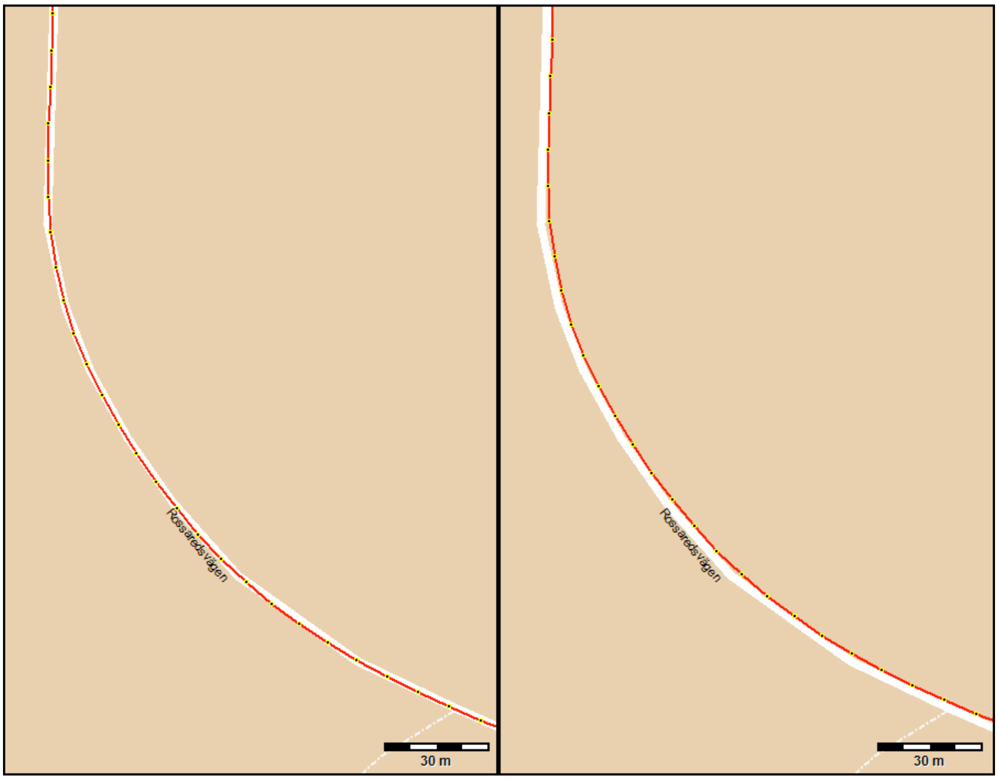

Figure 4.7 Two spline interpolations. The left picture without the right-hand traffic modelling algorithm and the right picture with the algorithm turned on.

5 Development of a Map Supported Cruise Control

This chapter presents how the road shape models are used for speed adaptation using the existing cruise control of the truck. This is referred to as a Map Supported Cruise Control (MSCC). First it is explained how a maximum recommended speed profile along the future path of the vehicle is calculated. A deceleration model is then described which is used to calculate a set speed for the existing cruise control function.

5.1 Calculation of Recommended Maximum Speed

The recommended maximum speed, as defined here, is the maximum speed the driver can maintain through a curve without feeling any discomfort. The discomfort occurs when a large centripetal force is exerted on the driver. A large centripetal force corresponds to a high lateral acceleration. Therefore the recommended maximum speed can be based on that the lateral acceleration should be kept under a certain threshold.

Previous tests on Volvo Technology suggest that for a good comfort level this threshold should be set between 1.5 and 2.5 m/s^2. Similar tests have also been conducted by Sahlholm et al (2007) suggesting a threshold of 1.5 to 2.0 m/s^2. Using the definition of lateral acceleration the recommended maximum speed can now be calculated as

$$a_{lat} = v^2 \kappa \Rightarrow v_{\max} = \sqrt{\frac{a_{lat,threshold}}{\kappa}} \qquad (5.1)$$

This equation assumes that there is no road cross fall. The curvature, κ, is the curvature derived from the spline described in the previous chapter.

One of the attributes available in ADASRP is the speed limit of the road. To be sure to fulfil the speed limits on the parts of the road where it is relatively straight the final recommended maximum speed is calculated as the minimum of the speed limit and the recommended maximum speed based on the curvature (See Figure 5.1).

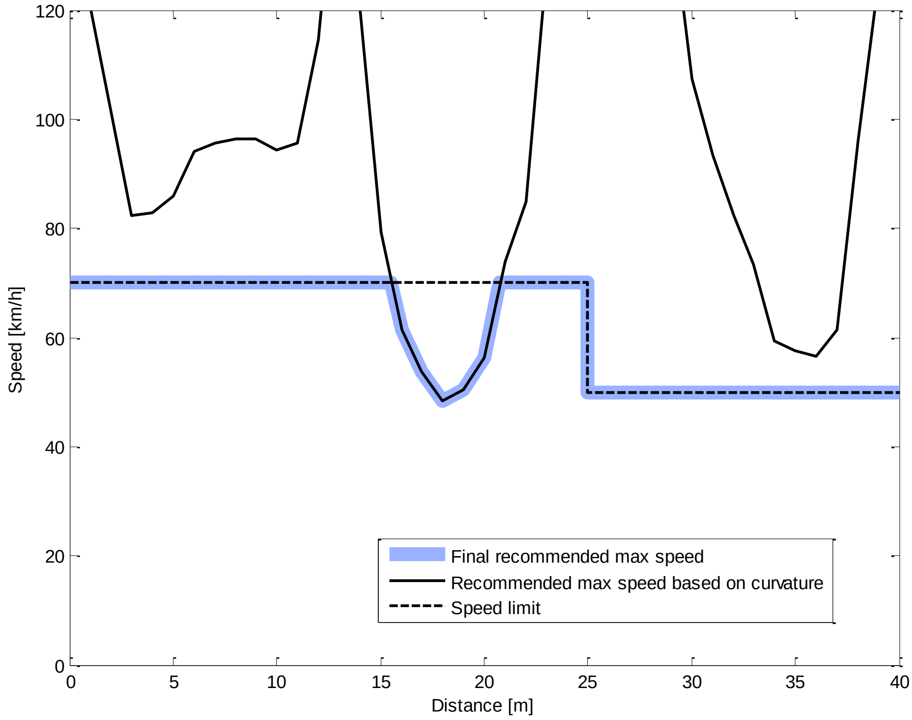

Figure 5.1 Illustration of how the recommended maximum speed is calculated as the minimum of the recommended max speed based on curvature and the speed limit.

5.2 Deceleration Model

To predict how the truck decelerates a simplified model of the truck is used. The slope information of the road is not taken into account in this work, and therefore it is assumed that there are no slopes on the road. It is also assumed that neither the foundation brakes nor the throttle are used during the deceleration phase. A modern truck is also equipped with several auxiliary brakes. The intention was to utilise the Volvo Engine Brake (VEB) in order to acquire extra braking force when needed, but this was not achieved in this work. Hence, the auxiliary brakes are not included in the model described below. The assumptions results in a total braking force described by Carlsson & Glad (2005) as

$$F_{braking} = F_{air\_resistance} + F_{rolling\_resistance} + F_{engine\_friction} \qquad (5.2)$$

The braking force consists of three parts: The air resistance, the rolling resistance and the engine friction:

$$F_{air\_resistance} = \frac{C_d A \rho}{2} v^2$$

$$F_{rolling\_resistance} = C_r mg$$

$$F_{engine\_friction} = T_{eng} \frac{N_g N_f}{R}$$

C_d = Numerical drag coefficient
A = Front area of truck
ρ = Air density
v = Speed of truck
C_r = Rolling resistance coefficient
m = Mass of truck
g = Gravitational acceleration
T_{eng} = Braking torque due to engine friction
N_g = Gear ratio of current gear
N_f = Gear ratio of rear axle
R = Wheel radius

The braking torque T_{eng} is a function which depends on the engine speed, ω_{eng}. It originates from a data table in a model for a similar engine. The acceleration can now be calculated as:

$$a = \frac{-F_{braking}}{m} \tag{5.3}$$

where m is the mass of the truck, 14 tons in this work. When all the truck specific and physical parameters described above are known this acceleration depends only on the engine speed and the current gear. As the test truck was equipped with an automatic gear box further simplifications of the deceleration of the truck can be made. With the use of a specific down shift strategy of the gear box each of the twelve gears are associated with a vehicle speed interval. Each gear is then connected to an approximate acceleration by calculating a mean of the acceleration over the engine speed interval where the gear is supposed to be active. The result of these simplifications is a table where an approximate deceleration is obtained given the current speed of the truck, see Table 5.1.

Table 5.1 Approximation of the deceleration of the truck for different speed intervals.

Speed [km/h]	Acceleration [m/s^2]
12 - 17	-0,36
17 - 23	-0,30
23 - 32	-0,27
32 - 42	-0,24
42 - 57	-0,22
57 - 72	-0,23
72 -	-0,25

5.3 Calculation of Set Speed Signal

Given a recommended maximum speed profile ahead of the truck the challenge is to calculate the set speed signal. It has to be set to ensure that the truck reaches the recommended maximum speed of a curve in time. Furthermore, the truck has to decrease the speed ensuring that the speed limit is reached when passing a speed limit sign. Therefore another speed profile is calculated which is used for the set speed signal calculation referred to as the reference speed. This speed can be described as the maximum speed allowed to be sure to reach all the recommended maximum speeds in time based on the deceleration model. It is depicted in Figure 5.2 as a green line.

From the recommended maximum speed and the reference speed described above a cruise control set speed signal can be calculated to send to the Engine Management System (EMS). The set speed signal is depicted as a dashed red line in Figure 5.2. When the reference speed goes below the recommended maximum speed it is time to lower the set speed to the next dip in the recommended maximum speed ahead. The reason for lowering this signal in large steps is to avoid oscillations in speed which might occur due to the dynamics of the cruise control. In the acceleration phase the set speed is equal to the recommended maximum speed.

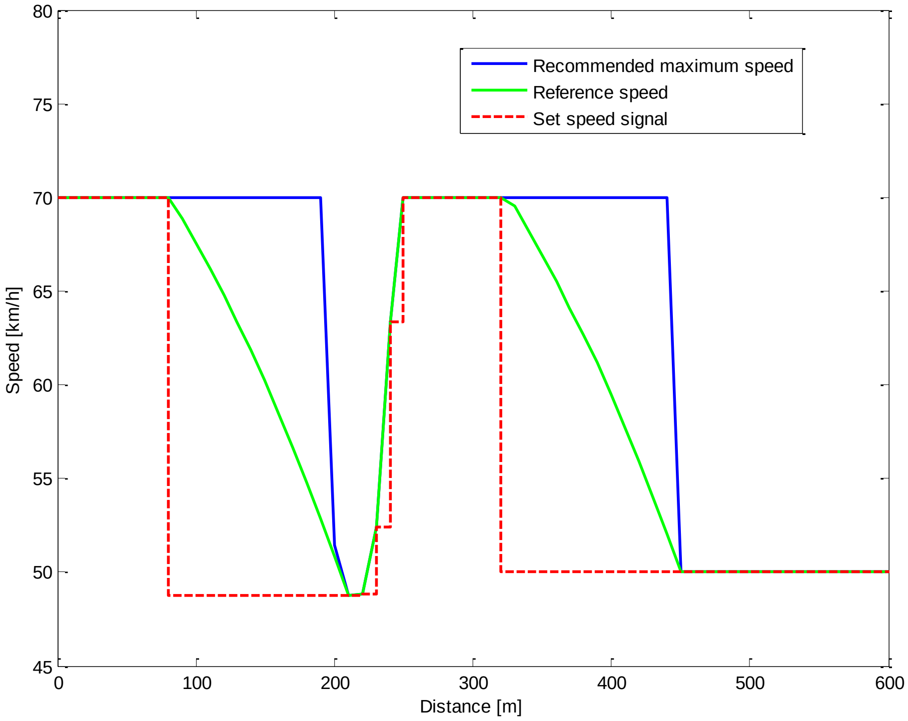

Figure 5.2 Graph of how the three described speed profiles relates to each other. This example corresponds to a road with an initial speed limit of 70 km/h, then a sharp curve and finally a decrease in speed limit to 50 km/h.

6 System Implementation in a Test Truck

This chapter explains the implementation of the system in a test truck. A brief overview of the hardware components of the system and their relations is given. The functionality of the code developed for the components is then described.

6.1 System overview

The complete system, the road shape modelling combined with the map supported cruise control, were implemented in a test truck. The hardware layout is shown in Figure 6.1. A more detailed explanation of the programs in the laptop, the Packaged Industrial PC (PIP) unit, and the gateway are given in the next section.

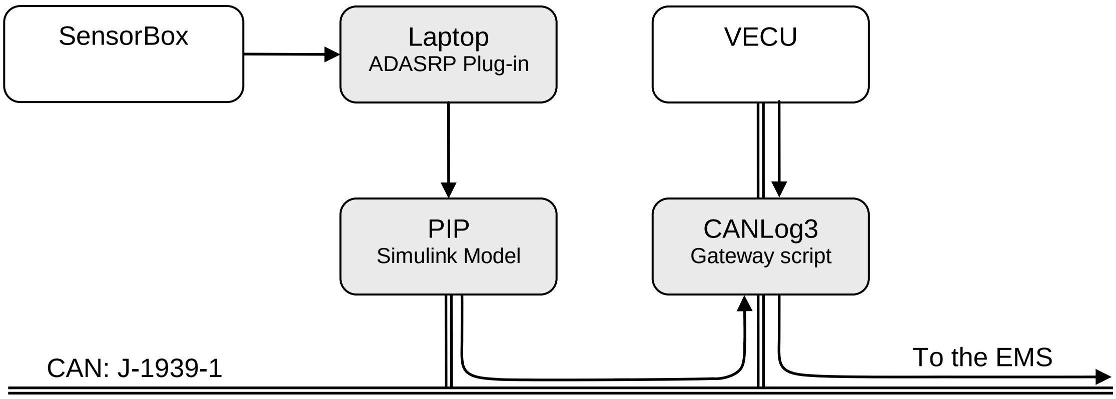

Figure 6.1 The sensor values from the SensorBox are sent to a laptop running the road shape modelling application as a plug-in to the ADASRP software. Here the position on the digital map is determined and a road shape model created which represents the road ahead of the vehicle. This model is sent from the laptop using a UDP protocol to a PIP unit running a Simulink model. Based on the road shape model the PIP calculates a set speed signal. This is sent through the vehicle's CAN network to a CANLog3 device with a gateway script. The gateway replaces the set speed signal from the Vehicle Electronic Control System (VECU) with the calculated set speed signal and sends it to the Engine Management System (EMS) for execution.

6.2 ADASRP Plug-In

The road shape modelling is implemented in C++ as a plug-in to ADASRP. The spline construction is implemented separate in MATLAB code which is called by the plug-in. The ADASRP software is run on a laptop in the test truck. An explanation of the graphical user interface of the software is available in Appendix B.

The execution order of the plug-in is shown in Figure 6.2. After the sensor values from the SensorBox have been read and the vehicle position has been determined the MPP is updated. A test is run to check if the MPP is changed. If this is the case the data in the MPP is extracted and used for further processing.

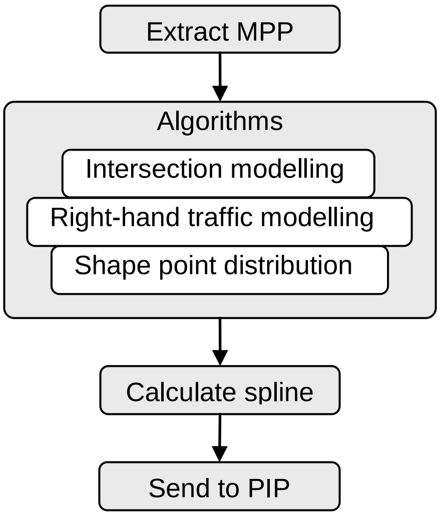

Figure 6.2 Diagram of the order of execution of the road shape modelling plug-in.

The MPP contains shape points in terms of geographic coordinates and the speed limits of the road in front of the vehicle. The coordinates are converted to Cartesian coordinates before they are subjected to the algorithms. Any of the three described algorithms are then applied to the shape points; intersection modelling, right-hand traffic modelling, and shape point distribution.

From the modified shape points a spline is calculated. The curvature is then evaluated in a number of points on the spline, called evaluation points.

Each time a new spline is calculated the information about the spline is sent to the PIP divided in packages. Each package carries information about one evaluation point on the spline in terms of curvature, distance to previous evaluation point and speed limit. To avoid data losses the number of packages sent is limited to 100 for each spline calculation. This means the spline ahead of the truck has a length of 1000 m if the resolution of the evaluation points is set to 10 m. Each time the vehicle position is updated the closest evaluation point is determined and the index of this is sent to the PIP.

6.3 Simulink Model

The map supported cruise control described in the previous chapter is implemented as a simulink model run on the PIP. When a new spline is received the model collects all the evaluation point packages before it overwrites the old spline that is stored in the model. When the spline has been overwritten the model calculates the recommended maximum speed along the spline. From this and the deceleration model the set speed signal is calculated.

To determine where on the spline the truck is located the evaluation point index sent from the road shape modelling plug-in is used. The calculated set speed corresponding to that evaluation point is then sent through the CAN network to the gateway.

6.4 CAN Gateway

The gateway acts as a filter between the VECU and the vehicle CAN network. It has been implemented in a CANLog-3 device from the company Vector. The device have been set up to pass all CAN messages but with an option to change the vehicle set speed message if a set speed message is received from the PIP unit. The message that is overwritten is sent to the EMS and the vehicle will then make an effort to reach the new set speed.

7 Results

This chapter presents the results of the tests performed on the road shape models and the complete map supported cruise control system. The first test presented is the comparison of the output of the road shape models with GPS-traces of the actual roads. Then the validation of the recommended maximum speed calculation by logging the driver's speed is presented. The last section describes the test drives where the complete map supported cruise control system is implemented.

7.1 Road Shape Modelling Results

The first of two GPS collections was carried out with the objective to find out if it is possible to relate the radius of the circle segment used in the intersection modelling algorithm to e.g. which road classes that intersects, intersection angle or other available attributes in the database. GPS information from nine intersections of different character were collected and analysed.

Although a tendency that intersections with larger roads have a slightly larger turn radius it is hard to see other relations. The turn radius varies a lot from case to case depending on for example terrain, traffic islands or departure lanes. One conclusion is however that the radius of curvature connected with the intersection shape point in the database is of no use as it differs a lot from the radius of curvature derived from the GPS data. An example of this can be seen in Figure 7.1.

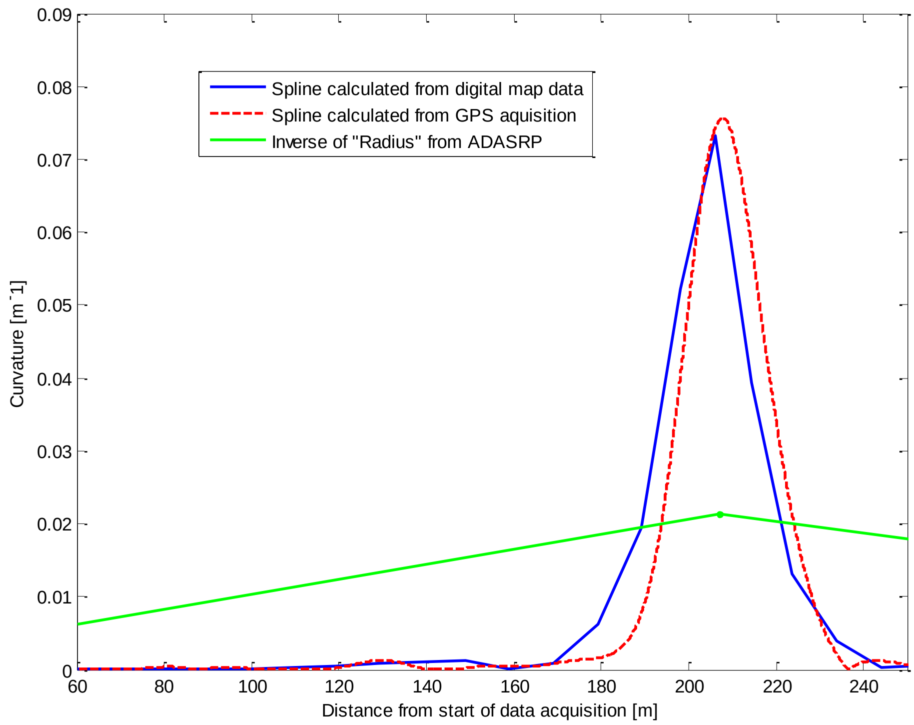

Figure 7.1 The picture compares the three values of road curvature in an intersection: The curvature of the spline calculated from the digital map data, the curvature of the spline calculated from the GPS-acquisition, and the inverse of the road radius attribute from ADASRP. As can be seen the radius attribute states that the radius of this intersection curve is around 50 m while in reality it is around 13 m.

Based on the GPS collection result the radius of the circular arc is set to 15 m in every intersection. This is not the optimal choice but it is better than using the radius of curvature given from the database or not modelling the intersection at all.

A second GPS measurement collection was carried out to verify the calculated splines against real data. Position data from 15 road stretches were collected, including some special cases as motorway junctions, roundabouts and city driving situations. When the collected position data were compared with the calculated splines the result was that they followed each other very well. This was expected as the spline is calculated from digital map data which in turn originates from GPS data. However, some differences could be seen at some locations, for example at speed reduction obstacles.

To visualize the road shape modelling one of the collected road stretches is used as an example. The data represents a relatively small and curvy road. A part of this road was selected, and a comparison between the collected GPS positions and the calculated spline can be seen in Figure 7.2. As can be seen the curves are very similar in this scale.

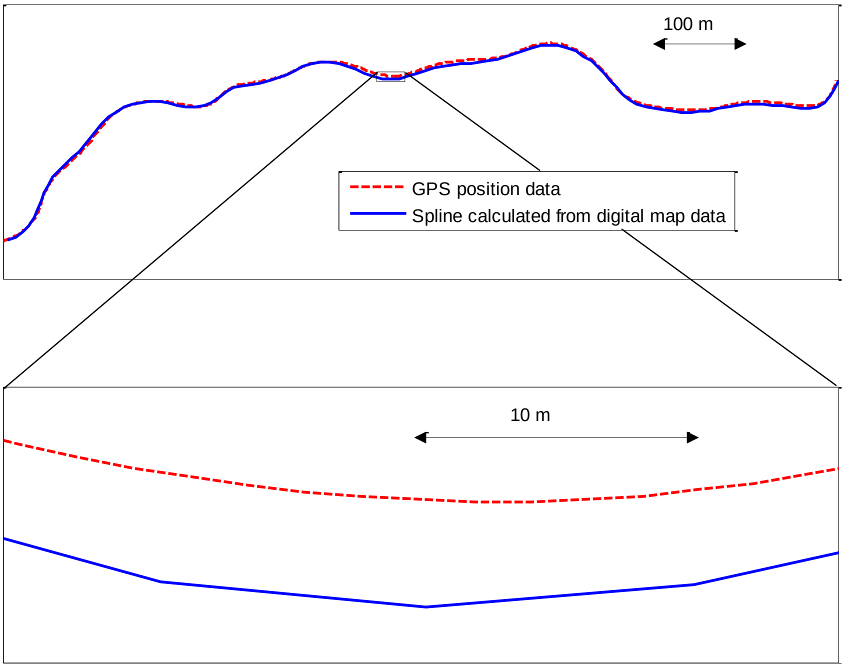

Figure 7.2 Comparison of a stretch of road as described by collected GPS position data (dashed line) and a spline interpolation of the shape points in the digital map data (solid line). The maximum deviation between the two is shown in close up in the bottom part of the figure.

The most interesting parameter when using the models for speed adaptation is not the exact position but the curvature. To obtain the curvature a spline was calculated from the GPS data. This spline was smoothed with a low smooth factor to suppress some of the noise but keep the "main" shape of the road. From this spline the curvature was calculated. A comparison between the curvature derived from the GPS data, the curvature calculated from digital map data and the curvature given in ADASRP is shown in Figure 7.3.

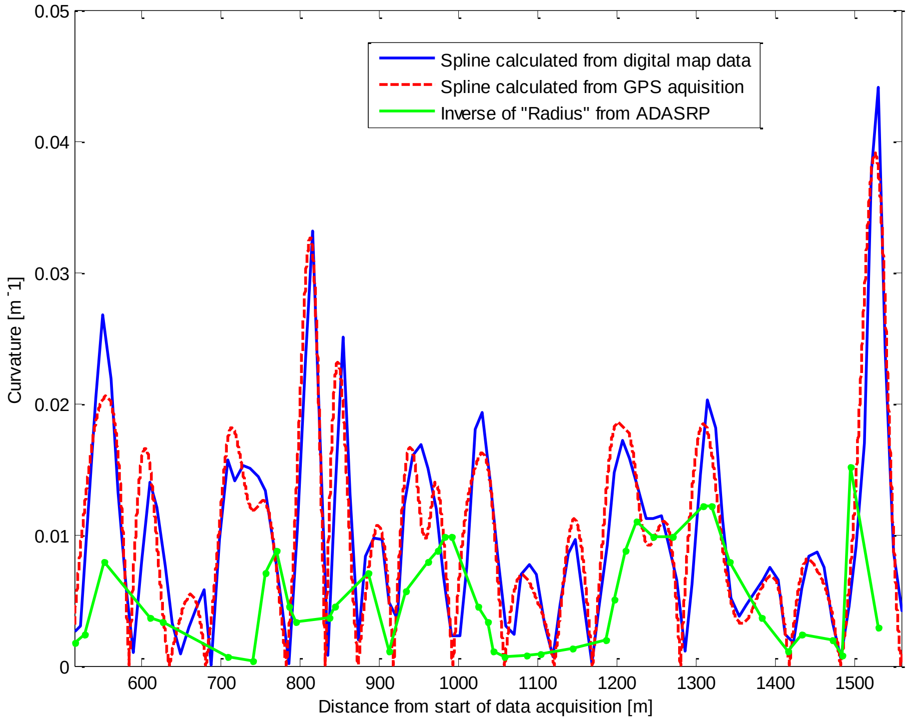

Figure 7.3 Comparison of curvatures. The spline calculated from the digital map data better captures the curvature profile from GPS acquisition than what an interpolation of the curvature given in ADSRP does.

7.2 Recommended Maximum Speed Validation

The recommended maximum speed was validated by logging it together with the vehicle speed when a test driver where driving the truck. The situations that were of interest where when only the road shape and the speed limits limited the driver's choice of speed, since our model does not handle other traffic hindrances such as stop signs or traffic congestion.

What is of interest in the logs is only the lowest dip of the recommended maximum speed in each curve as this value will be used as the set speed of the truck. The goal is to achieve a recommended maximum speed in the dips that is equal to, or slightly lower than the speed the driver chose. This will ensure that the recommended maximum speed is not too high in the curves when using it for speed adaptation.

The results showed that the dips in vehicle speed corresponded well with the dips in the recommended maximum speed. The result shown in Figure 7.4 below is a good representation of the test drive. The result is from a test drive through two consecutive interchanges where the speed limit is 70 km/h. The driver reaches within 5 km/h of the calculated recommended maximum speed in each of the three large curves. Three more results of the recommended maximum speed validation are presented in Appendix A.

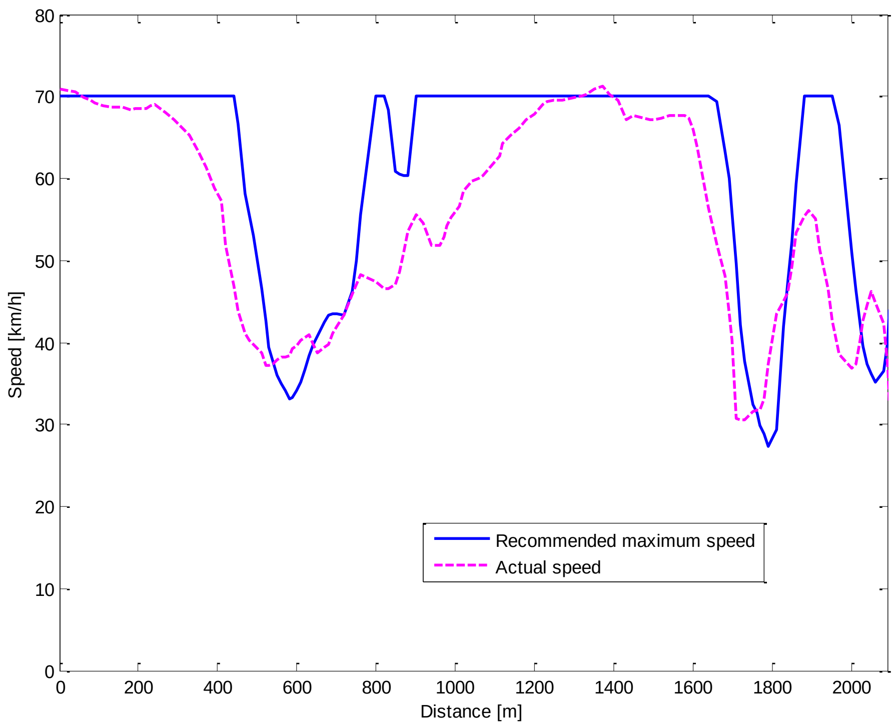

Figure 7.4 Result from test drive comparing the driver's speed with the recommended maximum speed calculated from the road models.

7.3 Map Supported Cruise Control Results

To verify the map supported cruise control tests were made where the speed of the test truck were set by the implemented system. The test driver engaged the cruise control and logging of the different variables were done. Two of the test logs are presented in this chapter.

7.3.1 MSCC Result 1: Agnesbergsmotet

The first test was made in Agnesbergsmotet. It is a junction that connects road 45 with Angeredsleden (See Figure 7.5). Both are large roads with speed limits of 80 km/h for trucks. The test route (marked with a dashed line) consists of two curves. The speed limit is lowered to 70 km/h approximately 600 meters before the start of the first curve and is set back to 80 km/h just before the second curve. The result of the test is shown in Figure 7.6.

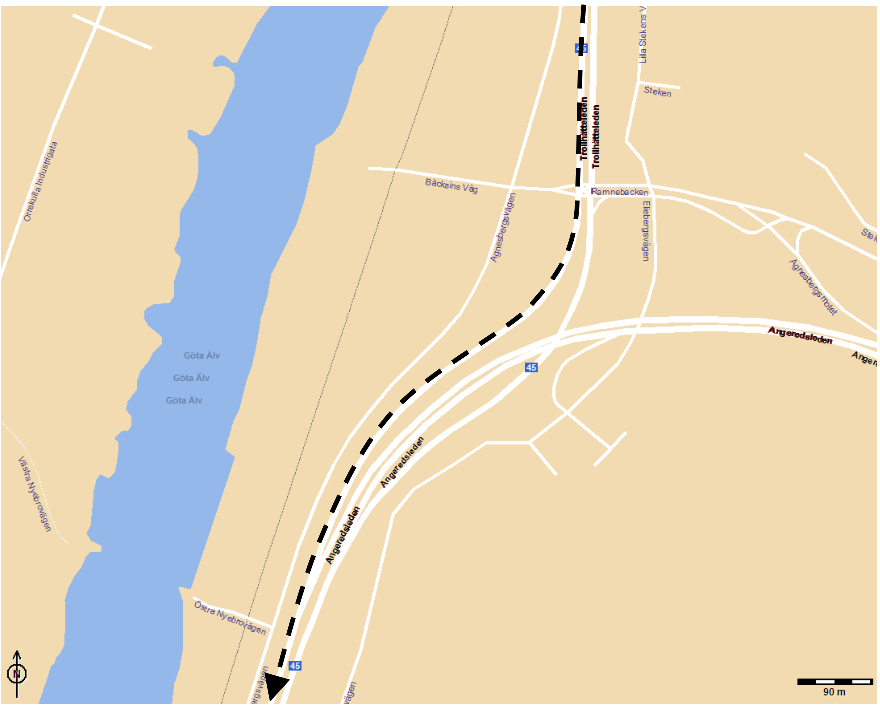

Figure 7.5 Map showing part of the road stretch used for testing in Agnesbergsmotet. The arrow indicates driving direction.

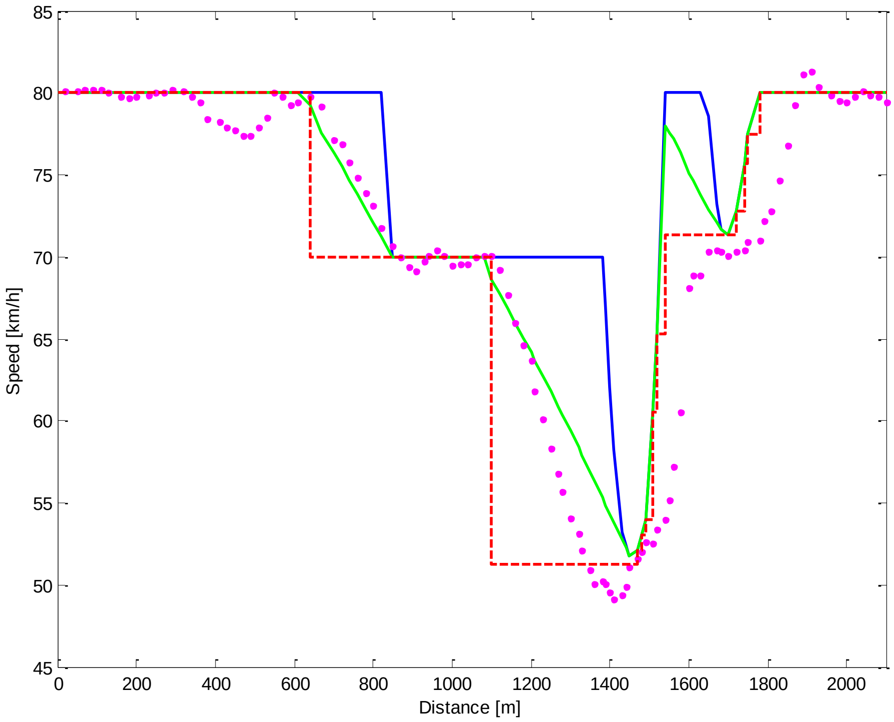

Figure 7.6 Result from test drive in Agnesbergsmotet. The solid blue line in the graph is the recommended maximum speed. From left to right it first shows the decrease in speed limit from 80 to 70 km/h, then a dip due to the first curve, then the speed limit is set back to 80 km/h, and finally another dip due to the second curve of the junction. The solid green line is the reference speed which is based on the deceleration model. The dashed red line is the calculated set speed that is sent to the truck. The purple dots are the measured vehicle speed.

As shown in the Figure 7.6 the truck reaches the dips of the recommended maximum speed in time. During the test drive both we and the driver felt that the system set the speed in time and that the speed held was comfortable.

7.3.2 MSCC Result 2: Klarebergsmotet

The second test was made in Klarebergsmotet. This junction connects the E6 with Norrleden (See Figure 7.7). In the test the truck exits the motorway E6 through a sharp off ramp. The speed limit of the motorway is 80 km/h for trucks and at the beginning of the off ramp the speed is lowered to 70 km/h. The result of this test is shown in Figure 7.8.

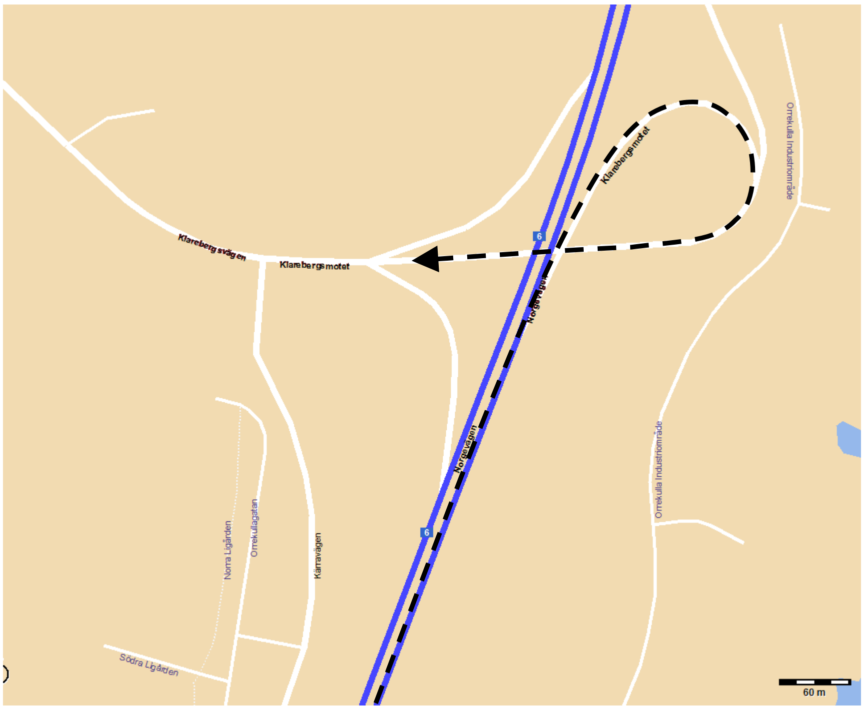

Figure 7.7 Map showing the road stretch used for testing in Klarebergsmotet. The arrow indicates driving direction.

In this test two defects are visible. The first one is due to the spline being updated too late and results in the set speed being lowered to late. It is visible in the figure as the offset between the actual speed and the reference speed. The vehicle speed will thus not reach the speed that is recommended in the curve ahead.

The second defect is a jump in the set speed (at approx. 670 m from the start of the log). This is due to a bug in ADASRP where the software maps the position of the vehicle back to the motorway resulting in a set speed of 80 km/h. Seconds later the software corrects the mistake and the set speed is set back to 33 km/h. The two defects leads to a too high entry speed in the curve forcing the driver to brake (indicated with arrow in Figure 7.8).

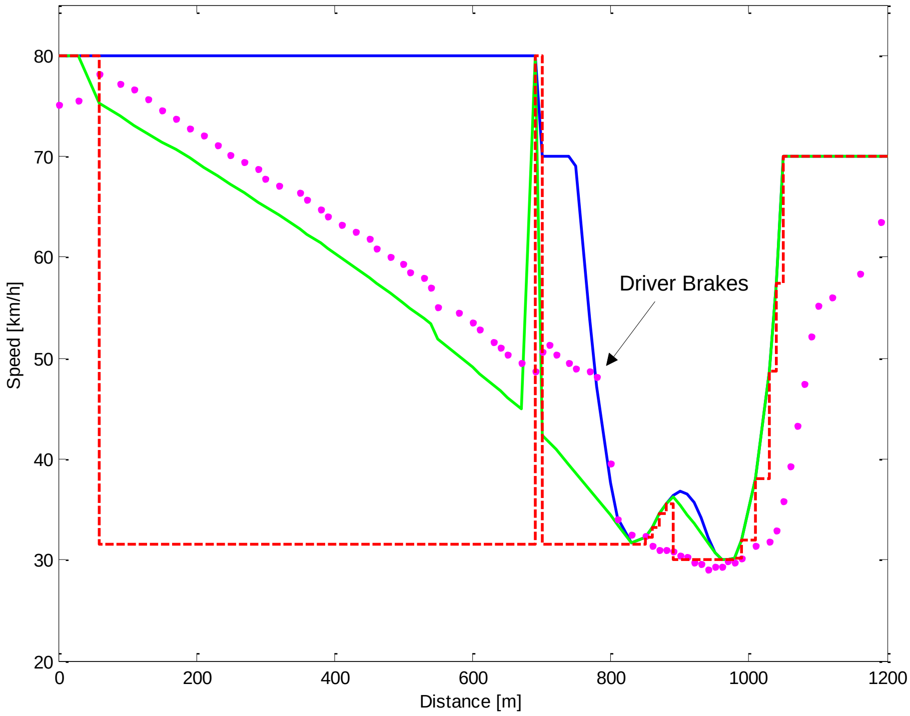

Figure 7.8 Result from test drive in Agnesbergsmotet. The figure shows the same set of speeds as the previous figure.

Some positive results are also visible in the figure. First, though the vehicle speed has an offset to the reference speed, it still has the same predicted deceleration. This shows that the deceleration model predicted the correct deceleration during the test. Secondly, after the driver brakes and disengages the system, he keeps the speed of the vehicle in the curve at approximately the same speed as indicated by the recommended maximum speed (solid blue line in the figure). This verifies that also the recommended maximum speed is in the correct speed range.

8 Conclusions

The shape of the constructed spline is describing the road better geometrically than the existing representation with points and lines. The curvature calculated from the spline approximates the curvature calculated from GPS acquisition. In some cases, especially intersections and curved roads, the curvature calculated in this work is more accurate than the curvature available from ADASRP. These results motivate the use of the road shape modelling rather than using the existing curvature information.

There are few roads where the curvature limits the recommended maximum speed, in most cases it is set to the actual speed limit. The larger roads (with speed limits 70-110 km/h) are often built relatively straight. When there are curvy parts on these roads the speed limit is often lowered accordingly and this speed limit is then lower than the recommended maximum speed calculated from the curvature. The exceptions, where a large curvature affects the recommended maximum speed, are primarily intersections, motorway junctions, and older roads with a speed limit of 70 km/h.

The map supported cruise control worked well in the few test drives conducted. The road models developed are considered accurate enough to serve as input to this application based on the recommended maximum speed validation. The predicted deceleration was accurate enough in most cases. The occasions were the actual deceleration differed from the predicted were probably caused by slopes in the road.

The distance demanded to decrease the speed before a curve can become very large if no brakes are to be used. In such cases longer splines in front of the truck are needed to discover sharp curves in time. However, there are some cases where brakes must be used if the map supported cruise control should work correctly. One obvious case is steep slopes where the vehicle will not decelerate at all.

An error of the map supported cruise control was caused by inaccurate position mapping in ADASRP. This has to be improved to avoid unwanted set speed signal peaks such as the one described in Figure 7.8. A problem discovered with the digital map data was the lack of speed limit information on many of the roads. Speed limits have to be available on more roads to have a functional map supported cruise control.

The final conclusion is that the concept of a map supported cruise control, or a simplified version of it, is promising and might be considered as a feature in future trucks.

9 Further Work

An issue that should be addressed in further work is the shortcomings of the position mapping service in ADASRP. The service has been found to have many flaws and a replacement service with better functionality might be needed.

The current deceleration model does not include road slope or banking. A value of the road slope is available in the map data used, but only for very few roads. However, high quality map data for heavy duty vehicles, including road slope and banking, will be available for European roads within a couple of years. Adding these variables to the model should provide better functionality.

Implementation of brake control in the speed adaptation would be a large improvement. The auxiliary brakes were planned to be used but due to implementation problems they were not utilised in the final system. If control of the brake system could be implemented the functionality of the system could be secured in more situations.

An interesting further development would be to combine the system with the Adaptive Cruise Control (ACC). The functionalities of the ACC could provide for a more continuous and safer use of the system as the ACC adapts to vehicles in front of the truck and has an emergency braking function.

More tests needs to be done in order to draw stronger conclusions on the performance of the system. Especially low-speed situations, such as intersections and roundabouts, would be interesting to test. Also tests on driver acceptance of the system should be conducted.

More tests are also needed to trim the systems parameters. The smooth factor of the splines and the lateral acceleration threshold are two parameters that could be subjects for further investigation. They both have an impact on the recommended maximum speed in curves.

Finally, better feedback to the driver is needed. In its current setup the system only displays the current set speed in the instrument cluster. Other indicators could be an on/off signal and information on what is currently limiting the speed of the truck (e.g. symbols for speed limit, curvature, or the car ahead).

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Appendix A – Additional Results from Recommended Maximum Speed Validation

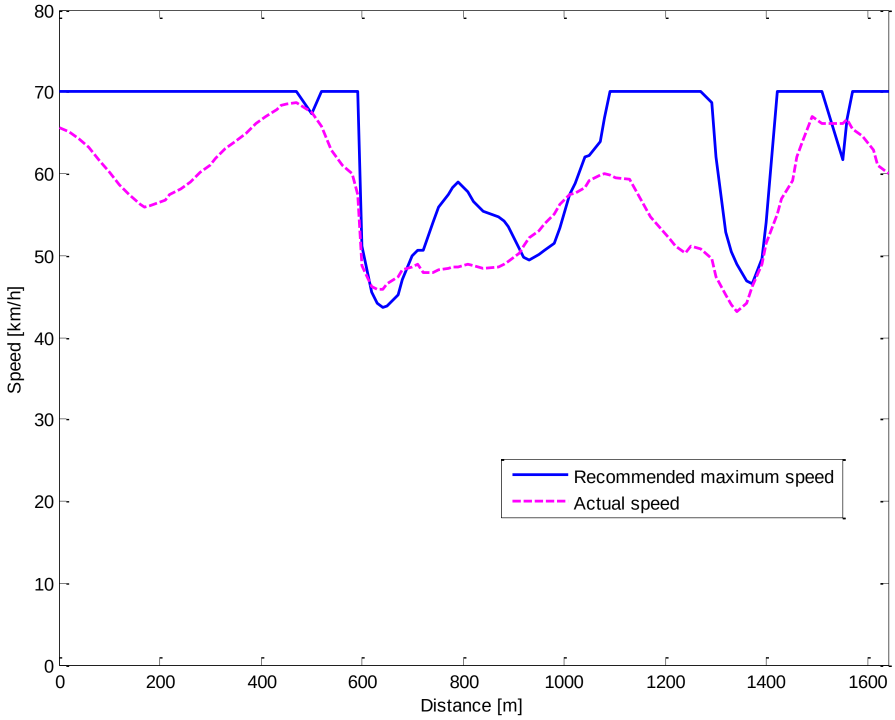

Figure A.1 Result from test drive comparing the driver's speed with the recommended maximum speed calculated from the road models.

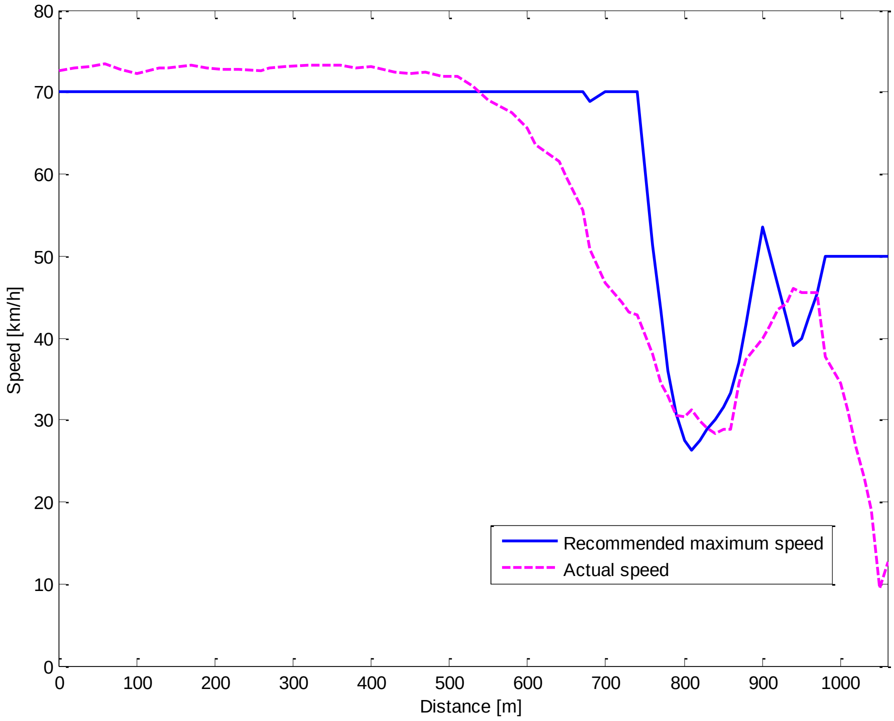

Figure A.2 Result from test drive comparing the driver's speed with the recommended maximum speed calculated from the road models.

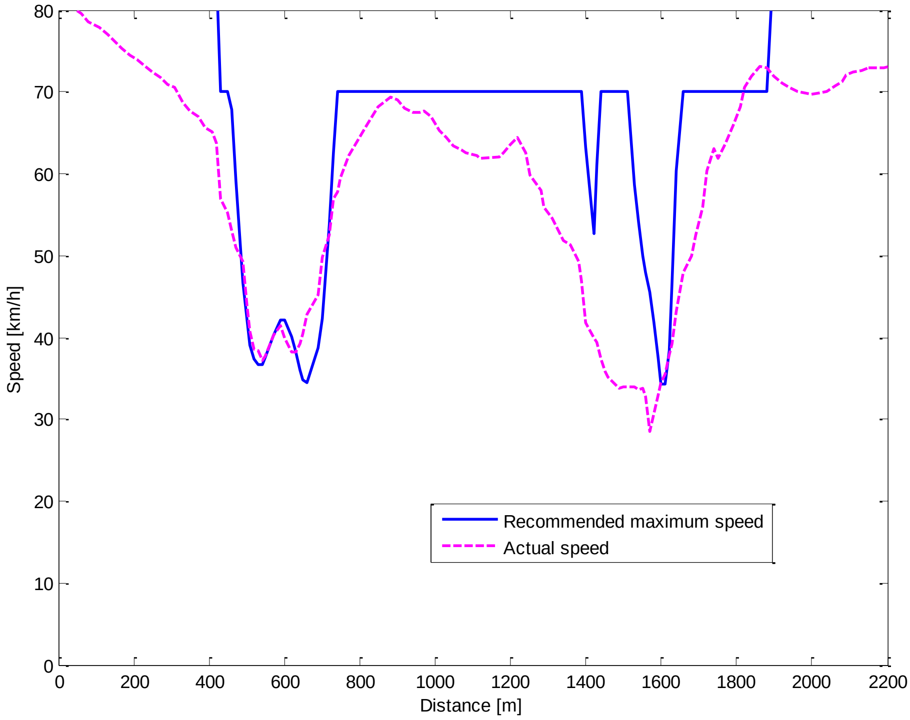

Figure A.3 Result from test drive comparing the driver's speed with the recommended maximum speed calculated from the road models.

Appendix B – GUI of Road Shape Modelling Plug-in

Figure B.1 shows the Graphical User Interface (GUI) of ADASRP. To the left is the map window where a graphical view of the roads is presented. The roads are represented with shape lines which are the connected white lines in the figure. The shape points are not visible. In the map window are also the constructed splines plotted when the plug-in is activated. The spline is the red curve and the yellow points with a black centre are the evaluation points.

To the right in Figure B.1 is the GUI for the road shape modelling plug-in. In the top of the GUI is a group box where it is possible to choose whether the spline should be plotted or not. Here is also where the smooth factor and the approximate resolution of the evaluation points can be set. The second group box is where the algorithms are applied. Different parameters can be set to trim the algorithms. Below this group box is a debug text window which prints information about the spline construction. Underneath this are buttons for plotting the curvature of the spline in a separate window, save the spline as a comma separated file, and clearing the debug text.

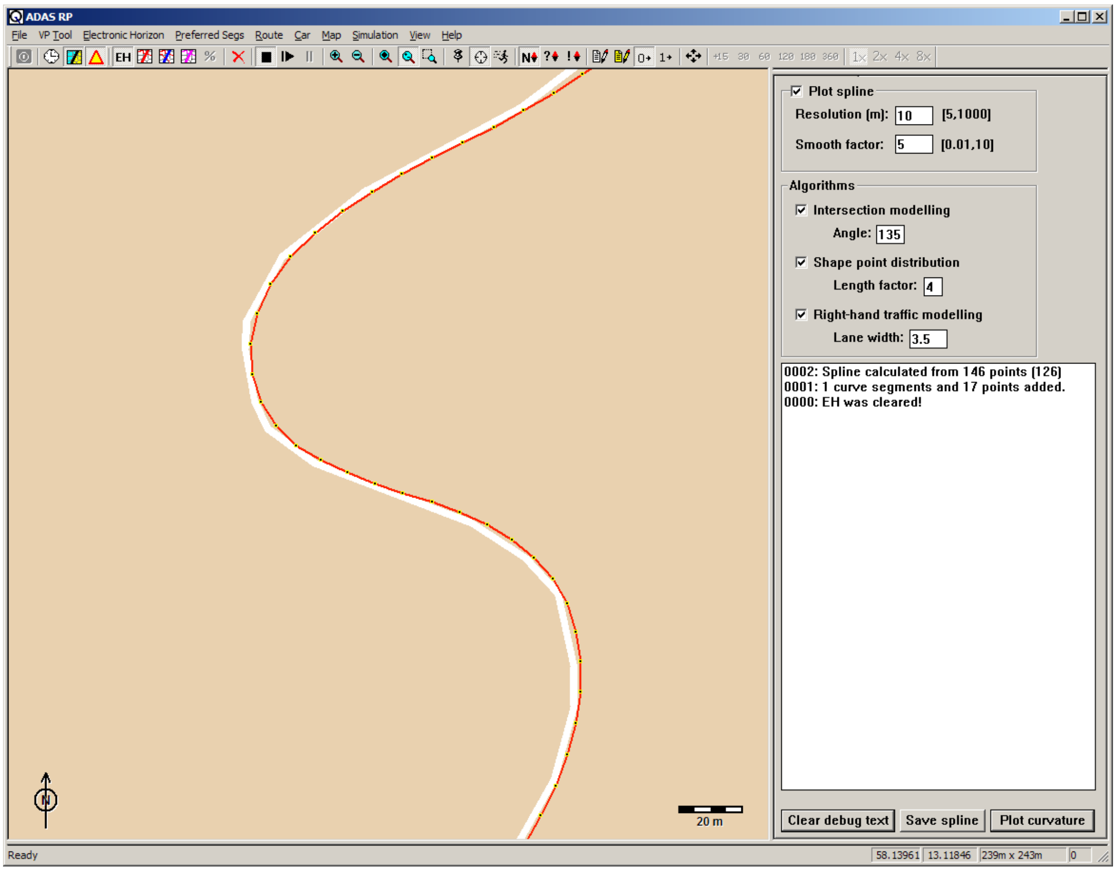

Figure B.1 The graphical user interface of the road shape modelling plug-in in ADASRP.