Aquaplaning – Development of a Risk Pond Model from Road Surface Measurements

Examensarbete utfört i Reglerteknik
vid Linköpings tekniska högskola
av

Sara Nygårdhs

LiTH-ISY-EX-3409-2003
Linköping 2003

Aquaplaning – Development of a Risk Pond Model from Road Surface Measurements

Examensarbete utfört i Reglerteknik
vid Linköpings tekniska högskola
av

Sara Nygårdhs

LiTH-ISY-EX-3409-2003
Linköping 2003

Handledare:	**Leif Sjögren** Statens väg- och transportforskningsinstitut **Gustaf Hendeby** ISY, Linköpings universitet
Examinator:	**Inger Klein** ISY, Linköpings universitet

Linköping, 22nd September 2003

LINKÖPINGS UNIVERSITET	**Avdelning, Institution** Division, Department Institutionen för Systemteknik 581 83 LINKÖPING	**Datum** Date 2003-09-22

Språk Language Svenska/Swedish X Engelska/English	**Rapporttyp** Report category Licentiatavhandling X Examensarbete C-uppsats D-uppsats Övrig rapport ——	**ISBN** **ISRN** LITH-ISY-EX-3409-2003 **Serietitel och serienummer** **ISSN** Title of series, numbering

URL för elektronisk version
http://www.ep.liu.se/exjobb/isy/2003/3409/

Titel / Title
Vattenplaning - Utveckling av en riskpölmodell utgående från vägytemätningar

Aquaplaning - Development of a Risk Pond Model from Road Surface Measurements

Författare / Author
Sara Nygårdhs

Sammanfattning
Abstract
Aquaplaning accidents are relatively rare, but could have fatal effects. The task of this master's thesis is to use data from the Laser Road Surface Tester to detect road sections with risk of aquaplaning.

A three-dimensional model based on data from road surface measurements is created using MATLAB (version 6.1). From this general geometrical model of the road, a pond model is produced from which the theoretical risk ponds are detected. A risk pond indication table is further created.

The pond model seems to work well assuming that the data from the road model is correct. Determining limits for depth and length of risk ponds can be made directly by the user. MATLAB code is reasonably easy to understand and this leaves great opportunities for changing different parameters in a simple way.

Supplementary research is needed to further improve the risk pond detection model. Collecting data at smaller intervals and with more measurement points would be desirable for achieving better correlation with reality. In a future perspective, it would be wise to port the code to another programming language and this could make the computations faster.

Nyckelord
Keywords
Aquaplaning, Hydroplaning, Risk Pond, Road Surface Measurements, Road Surface Monitoring, Laser RST, Traffic Safety

Abstract

Aquaplaning accidents are relatively rare, but could have fatal effects. The task of this master's thesis is to use data from the Laser Road Surface Tester to detect road sections with risk of aquaplaning.

A three-dimensional model based on data from road surface measurements is created using MATLAB (version 6.1). From this general geometrical model of the road, a pond model is produced from which the theoretical risk ponds are detected. A risk pond indication table is further created.

The pond model seems to work well assuming that the data from the road model is correct. Determining limits for depth and length of risk ponds can be made directly by the user. MATLAB code is reasonably easy to understand and this leaves great opportunities for changing different parameters in a simple way.

Supplementary research is needed to further improve the risk pond detection model. Collecting data at smaller intervals and with more measurement points would be desirable for achieving better correlation with reality. In a future perspective, it would be wise to port the code to another programming language and this could make the computations faster.

Acknowledgements

I would like to thank the following people, who helped me to accomplish this work: Leif Sjögren, my supervisor at VTI for coming up with the idea for this master's thesis, his never-ending enthusiasm and for always having time to discuss the work. Thomas Lundberg, for helping me with the logic in the algorithms, his patience when answering every question I have had and for letting me ride the Laser RST. Peter Andrén, for happily helping me solve any MATLAB problem I have had. Olle Nordström, for discussing experimental setups. Gustaf Hendeby, my supervisor at LiU, for taking active interest in how the work is progressing and giving me pieces of advice on everything concerning both MATLAB and the report. Inger Klein, my examiner at LiU, for approving on the master's thesis and helping me to limit the work. My mother, for helping me with difficulties in the English language. My boyfriend Rolf, for supporting me in every way. Finally I would like to express my appreciation for all the nice people at VTI, and my friends and family for their support, which has made the process so much easier and more fun.

Table of Contents

1 Introduction

There are 138 000 km of public roads in Sweden. In the year of 2001 an amount of 6.4 milliards Swedish crowns were invested in the roads run by the State (which sum up to about 98 000 km) and 7.3 milliards SEK were used for management and maintenance [9].

Aquaplaning accidents are not very common. For instance, in the years of 1992-1998 less than one percent of the total amount of traffic accidents was classified by the police as related to aquaplaning [22]. Considering the low rate of accidents that can be said to be associated with the phenomenon, aquaplaning seems to be a small problem. Although small, it is a problem that could theoretically be eliminated if it was possible to predict the risks. The main issue of this master's thesis is to investigate this possibility, using parameters that are already being collected, but used for other purposes.

1.1 Structure of the Report

In **Chapter 1 - Introduction**, the background to the problem that should be solved is presented together with limitations made, some possible applications and the method used for fulfilling the purpose of the work. In **Chapter 2 - Background** some basic concepts are defined, and the chapter also covers facts about road surface measurements and some previous studies on aquaplaning. **Chapter 3 - Model Development** includes a definition of risk ponds and a description of how the road and pond model are constructed. A validation of the pond model on synthetic road profiles and a visual validation of the models on a real road are presented in **Chapter 4 - Validation**. In addition, the chapter examines the consistency of the models. **Chapter 5 - Discussion and Conclusions** contains the advantages and disadvantages of the models, conclusions that could be drawn and suggestions for future research and improvement of the model. In **Appendix A – Programme Examples** specifications for the ponding programme are given together with some examples on how to use the programme. Abbreviations and explanatory text are finally found in **Appendix B – Glossary**.

1.2 Goals in Transport Policy

As stated by the Swedish Parliament in 1998, the main issue of the transport policy is "to provide a socio-economically efficient transport system that is sustainable in the long term for individuals and the business community throughout the country" [9, p. 5]. This can be further divided into six minor goals:

- An accessible transport system
- A high level of transport quality
- A positive regional development, by levelling out differences in the potential for development within different parts of the country, and by counteracting the disadvantages of long transport distances
- Safe traffic approaching no dead or seriously injured persons due to traffic (the so called "zero-vision")
- A sound environment

- An equal opportunities road transport system supporting the needs of both men and women

1.3 Problem

Accidents due to unsatisfactory surface characteristics are mainly caused by loss of gripping power, such as aquaplaning. The Laser Road Surface Tester (RST) collects data about the road surface characteristics, but the data is not adapted directly for measuring the accident risk. The task of this master's thesis is to use data from the Laser RST to detect road sections with risk of aquaplaning.

1.4 Possible Applications

A new tyre of a car has a tread depth of 9 mm [31]. The Swedish law obliges private cars to have tyres with a minimum tread design depth of 1.6 mm in summer and during the winter the required profile depth is 3.0 mm in the main pattern [30], [45]. This means that today every citizen has a responsibility for his or her car to keep it in a good shape and prevent it from losing gripping power. It is interesting, though, that according to studies made about aquaplaning [31], the road surface is of much greater importance than the tyres used. As stated in [44], a road shall not be the cause of any unacceptable risk for accidents when used, and the road surface shall be such that permitted vehicles can traffic the road safely. Improving grip on wet roads is one of the most critical areas for both tyre and road development.

If it was possible to prevent aquaplaning by using the parameters deciding the characteristics of the surface of a road, it would be very wise to do so. Most studies so far performed on aquaplaning examine how to design a new road to minimize the risk of water ponding. To get one step further on the way to achieve the "zero vision" (i.e. no deceased road users) an appropriate geometric design of the roads, also after years of usage and wear, would be desirable.

1.5 Limitations

This study does not take all factors that could lead to aquaplaning into account. The models are for instance independent of the vehicle using the road. Weather conditions have also been ignored. A main prerequisite is that there is always enough water on the road to fill all cavities in it. Examples of neglected parameters that contribute to the risk of aquaplaning are [5], [13], [29]:

- Vehicle and Driver Characteristics
    - Pressure between Vehicle and Road
    - Type of Tyres
    - Speed
    - Braking
    - Acceleration
    - Recognition of Bad Weather and Road Conditions

- Weather Conditions
    - Rainfall Intensity
    - Rainfall Duration
    - Water Composition

- Road Geometry and Environment
    - Curvature
    - Junctions
    - Sight Distances

Further limitations are the selection of roads in the study. The data that is handled is taken from major roads with flexible pavement in the region Mälardalen in Sweden.

1.6 Purpose of the Work

The aim of this master's thesis is to discover aquaplaning risk ponds. The main purpose of the work has been to create a programme that can be used to detect dangerous road sections. Aquaplaning accidents could hereby be prevented from happening. This work is a first study with the intent of supporting further studies leading to possible inclusion of additional measures in the decision support systems used by the Swedish National Road Administration.

1.7 Method

Through literature studies the subject of aquaplaning was examined and an understanding of data available was accomplished. A three-dimensional model based upon data from road surface measurements, namely hilliness, mean transverse profiles and crossfall for a short road section was then created. Subsequently, a model based upon the longitudinal profiles instead of hilliness was completed. With this general geometrical model of the road, a search for theoretical water depths could be carried out. The theoretical risk ponds where aquaplaning could occur were detected and a risk pond indication table was further created.

In Figure 1.1 a diagram over the main steps in fulfilling the purpose of the work is shown.

1.8 Alternative Approaches on Aquaplaning

When examining the subject of aquaplaning, some different approaches are possible. One is to apply flow theory and calculate how the water will behave depending on rainfall intensity and geometry data. See for instance [25], where differential equations considering hydraulics show water motion in open channels. Likewise, in [17] water film thickness and aquaplaning speed on a section of main road are calculated dependent on slopes, angle of rainfall input, mean texture depth etc.

Another main area of significance is statistics. Examples of interesting data that could be investigated are weather conditions, number of accidents and road surface data. If there is a strong correlation between the number of aquaplaning accidents and certain road geometry parameters, then conclusions about hazardous areas could probably be drawn. Using statistics a pond index with respect to many parameters should be possible to create.

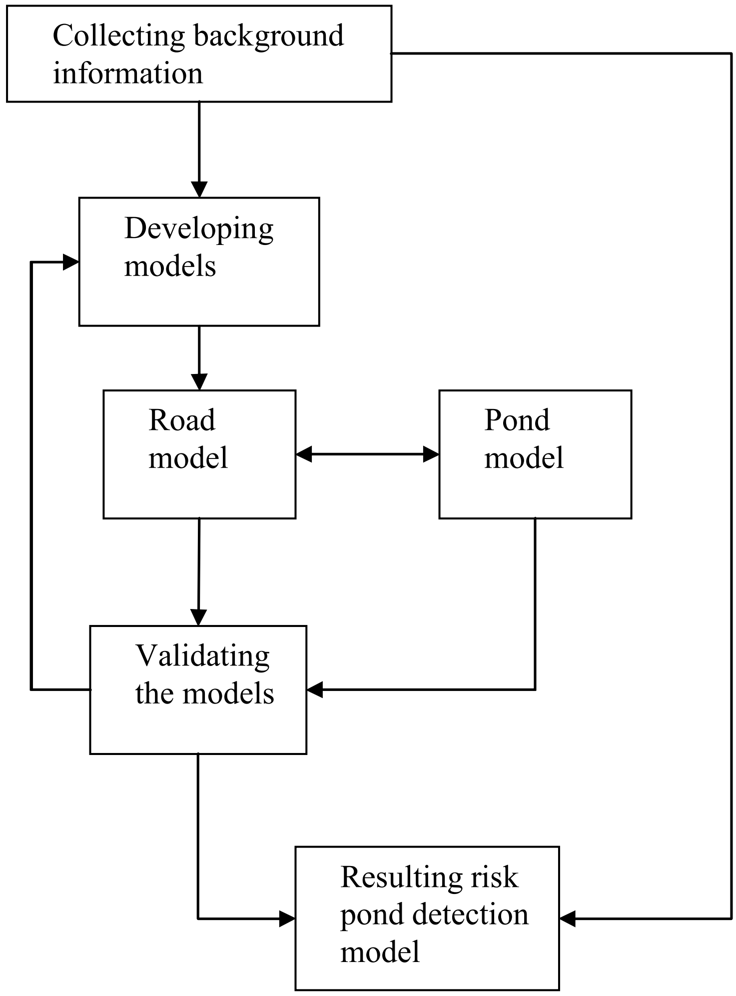


Figure 1.1. Flow chart showing the main steps in fulfilling the purpose of the work.

2 Background

This chapter deals with essential background knowledge. A few notions are clarified, followed by basic facts about road surface monitoring and a description of the Laser RST and some of its parameters. Finally, Section 2.6 deals with literature from interesting organizations on the subject of aquaplaning.

2.1 Definitions and Explanations

In the report some vocabulary is used that needs further clarification. This is done in the following in an attempt to simplify for the reader. (See also Appendix B.) In Subsection 2.1.1 different types of aquaplaning are described and an explanation of the concept water build-up is given, whereas Subsection 2.1.2 deals with how a paved road is constructed.

2.1.1 Definition of Aquaplaning

Aquaplaning, in American literature referred to as hydroplaning, occurs when the tyre of a vehicle is totally separated from the pavement by a continuous layer of water (full dynamic aquaplaning). The friction is then almost zero and the driver will have severe difficulty steering the vehicle [27], [40]. The condition of small, but not zero, friction is called partial aquaplaning.

Water Build-up

When a vehicle travels along a wet road, the water may accumulate and form a wedge between the road surface and the tyre. This is called water build-up and is shown in Figure 2.1. Water build-up leads to aquaplaning since water is continuously under the wheel.

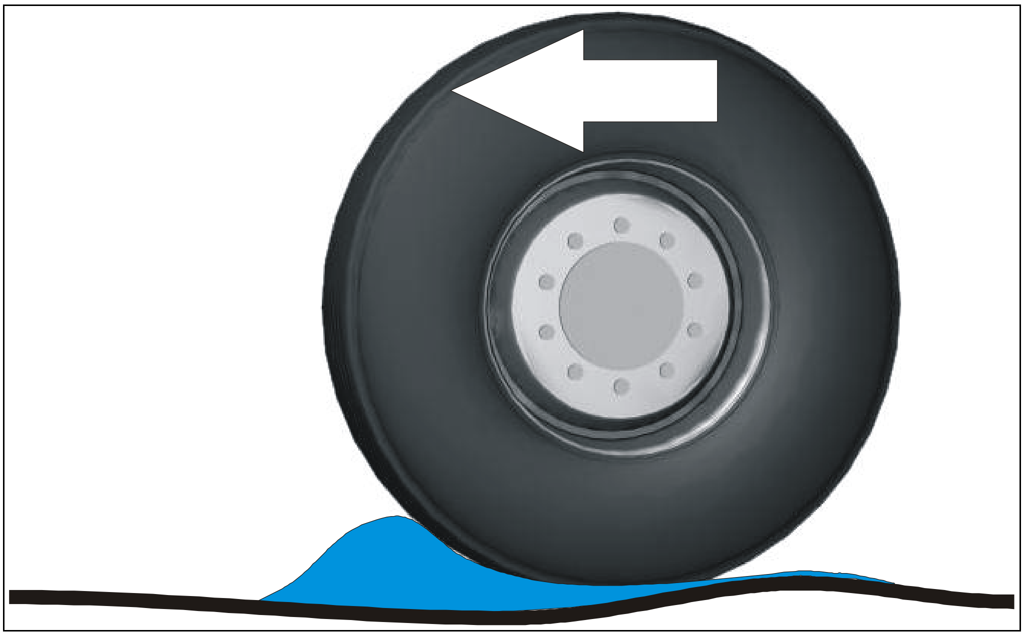


Figure 2.1. Sketch of water build-up when travelling on wet road.

One must however take into account that there are several types of the phenomenon. According to for example [5] (or [24], [36]) these can be divided into the viscous, the dynamic, and the tyre-tread-rubber reversion aquaplaning.

Viscous Aquaplaning
On a flat surface with low texture, viscous aquaplaning can occur. A continuous water film between the tyre and the road surface is then the result of too little microtexture [29]. (See Subsection 2.5.5.) Viscous aquaplaning happens mostly when speed is high but can occur at any speed at small water amounts.

Dynamic Aquaplaning
Even if the surface of the road is drained and texture is high, dynamic aquaplaning may occur, because the tyre is incapable of transporting water away from the road fast enough. The risk of dynamic aquaplaning increases with speed.

Tyre-tread-rubber Reversion Aquaplaning
A third type is the aquaplaning which occurs at high pressures between tyre and road surface when heavy vehicles such as lorries and aeroplanes lock their tyres at roads with good macrotexture but bad microtexture [23], [24]. When braking, the temperature between the tyre and the road increases. The result of the warmth is that the vehicle slides on a mixture of heated rubber from the tyre, water and fumes.

According to [5] amongst others ([6], [36] etc.), accidents due to full dynamic aquaplaning are comparatively rare. However, partial aquaplaning is a phenomenon experienced by many drivers and could have serious consequences [8].

Throughout this work, focus is set on the dynamic type of aquaplaning.

2.1.2 Pavement Construction

An asphalt road normally consists of three layers [49]. Directly above the original ground subbase is positioned. Above the subbase, a layer of unbound road base is placed. For roads with a high Annual Average Daily Traffic (AADT), a base course of up to 190 mm is further put upon it. Finally, a wearing course with a thickness of about 40 mm is positioned on top of the road. Altogether, the structure is between 125 and 1400 mm thick.

There are several different types of wearing courses that can be used, depending on what surface characteristics are critical for the particular road (see Figure 2.2). In an aquaplaning aspect, the surface water drainage ability is important. There are two major ways to avoid a continuous water film between the tyre and the surface [10], [48]. One of them is to make a surface treatment, which is a surfacing with chippings (a stone material) on a bituminous base course. Where this is made, surface texture is good and the water is lead under the peaks of the texture. Another, and very different way of handling the problem, is to use porous asphalt (ABD). This wearing course has a flat surface but contains many cavities, which make the water quickly drain down to the surface of the underlying layer. A term often used is open-graded surface. Although ABD has a very good drainage capability and also contributes to a lower noise-level, it is not a widely used wearing course in Sweden today [49]. The main reason for this is the relatively high cost associated with ABD. After some years of usage the cavities are obstructed, which makes the life of the road shorter.

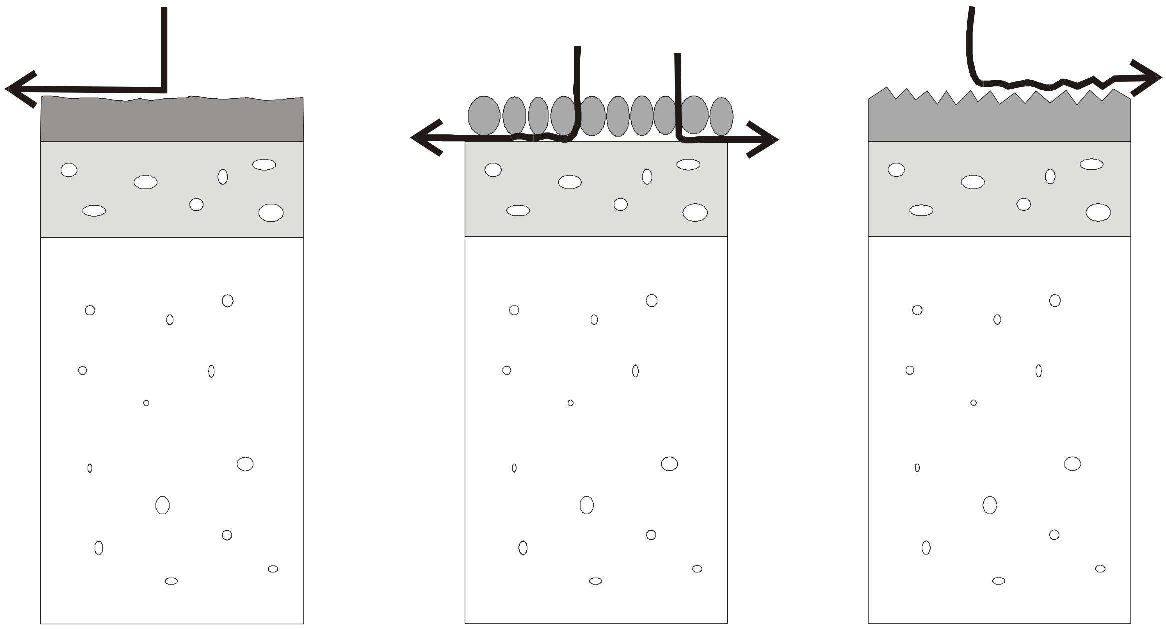


Figure 2.2. Outline diagram of pavements with different wearing courses. At the bottom there is subbase, followed by a section of unbound road base. On top the different wearing courses are shown. The sketch to the left shows an ordinary pavement, whereas the middle sketch illustrates porous asphalt, and the right picture demonstrates the effect of surface treatment.

Designated hard asphalt concrete drainage (HABD) was first used in Sweden in 1976 [2]. After a test period Swedish norms for HABD were set up in 1984. One interesting conclusion of tests made was that with an AADT below 30 000, the life of the HABD was as long as the more widely used dense-graded asphalt concrete. In comparison, the drained asphalt concrete can reduce traffic noise by 8 dB and engine noise by 2-3 dB. With a smaller particle size, more open-grading and a thicker pavement, traffic noise is reduced. Since the HABD also contributes to better wet friction and less splash and spray, it was considered beneficial for the road users.

2.2 Road Surface Monitoring

Road network surveys are conducted due to several reasons. In short, they shall provide basic input for [38]:

- Presenting the condition of the road and the need to take action
- Presenting the results that are achieved
- Allocating funds
- Verifying earlier assumptions of deterioration
- Determining initial values for deterioration models
- Deciding when to maintain and with which maintenance measure
- Indicating where action should be taken
- Research and development

When surveying a road one specific lane in a specific direction is measured. For the years of 2001-2004 the following programme has been established for measuring the Swedish roads [38]:

I. Annually surveyed roads are European highways, national highways and roads with an AADT>4000. Included are also roads exposed to heavy traffic. The coverage is about 18 000 km.
II. Roads surveyed every other year are primary county roads (road numbers less than 500) and major roads less exposed to heavy traffic. The coverage is about 11 000 km.
III. Roads surveyed every third year are the remaining paved roads except for roads unsuitable for the measurement vehicles to travel. The coverage is about 50 000 km.
IV. Roads where major repair work has been completed. Within a year after a road has gained a new wearing course, it should be surveyed.
V. Apart from the other categories, there are some complementary surveys based on regional needs beyond the national programme. For instance, there could be a need to measure a certain road more often or to survey all lanes of a highly trafficked motorway.

When summing up the annual amount of surveyed roads from categories I-III, the concluded mean value is about 40 000 km. In addition there are of course the remaining categories IV and V.

2.3 Measuring Methods

In the early days of road surface monitoring, the inspection of the characteristics of a road was conducted manually [3], [39]. An example of an early used method was measuring by putting a ruler along the ground to estimate the deviation of the road surface and a straight line. A further developed measuring device is the straightedge, which is sometimes used even today for estimating unevenness [39]. Libella and Scanlaser are examples of towed recording devices ("rolling straightedge") that have been used. See Figure 2.3. It is a fact, that man is not very well adapted for performing objective and repeatable measurements [3]. New devices have continuously been invented in order to simplify for the inspectors and to try to standardize measurements. With time, the measuring has been refined to more sophisticated measuring techniques. During the years of 1975-79 data was collected by a SAAB RST (Road Surface Tester) which had 25 mechanical gauges and a gyro [39]. In the 1980's, the gauges were replaced by contactless measuring techniques, such as laser.

2.4 Survey Vehicles

Annually the roads in Sweden are measured with special survey vehicles. During the period of 2000-2004 this is done by a device called the Laser Road Surface Tester, or, in short, the Laser RST (see Figure 2.4). The surveys have been accomplished by the Swedish National Road Administration (SNRA) since the year of 1987 [26], [37]. Measures are being more and more sophisticated and new measures are gradually being developed. Until now, survey data has been used mainly in order to maintain the roads. The Laser RST represents a typical survey vehicle. The first one was built in 1981 by the Swedish Road and Traffic Research Institute (VTI) [3], [4].

The Laser RST consists of hardware, software, the operator and data handling.

Figure 2.3. The Scanlaser with its measuring wheel [39].

Figure 2.4. The Laser Road Surface Tester [39].

2.4.1 Hardware

The transverse profile of the road is measured with 17 lasers strategically placed at a support beam at the front of the test vehicle (see Figure 2.5). Each of these transmits a ray of light at 32 kHz that appears as a spot on the surface of the road. The spot is detected by a light-sensitive displacement sensor in the support beam. After detection, a conversion into electrical signals representing the distance to the surface takes place [3], [4].

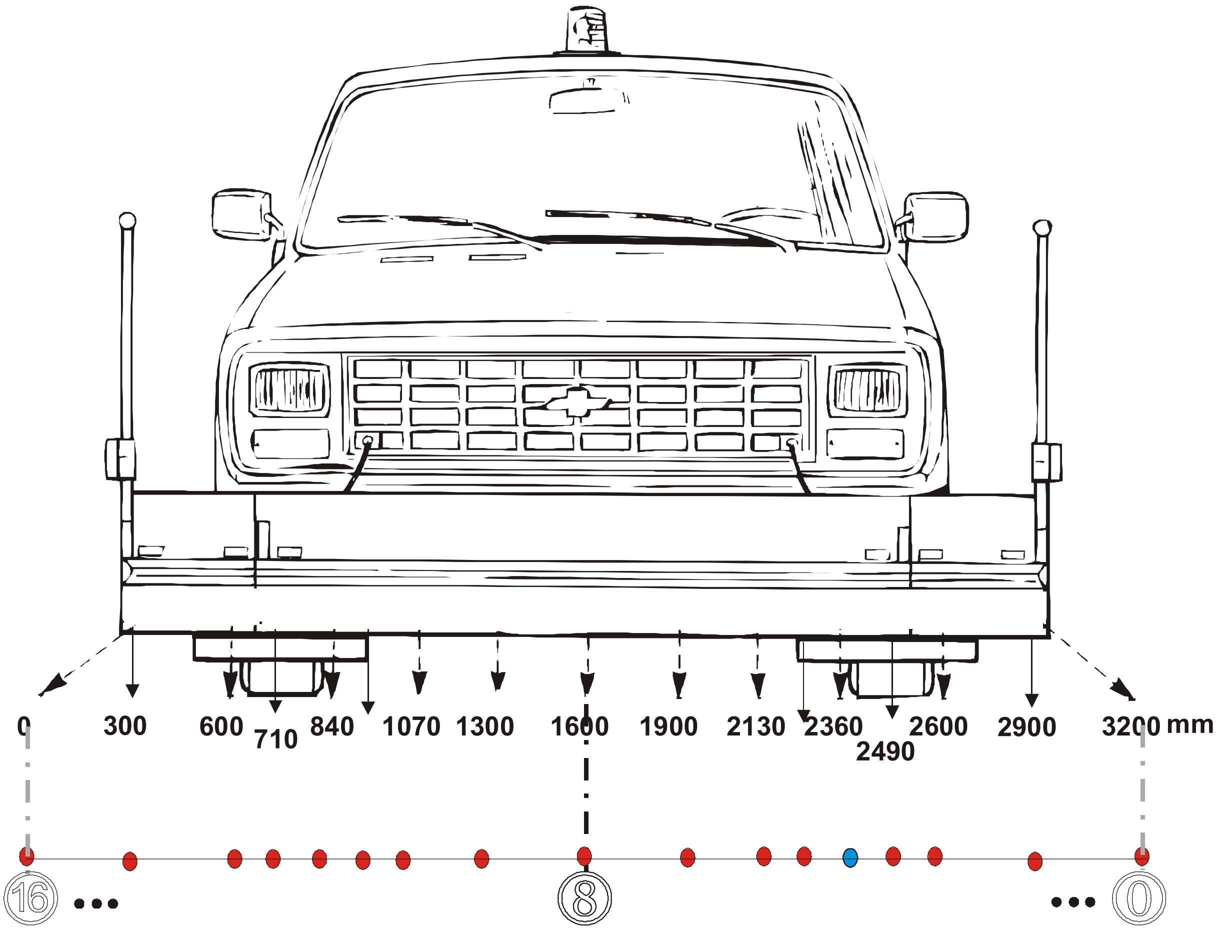


Figure 2.5. Sketch of the Laser RST with its 17 laser measurement points [39]. The numbers 0 to 16 at the bottom indicate the notation used for numbering the lasers.

The Laser RST is optimized to measure at varying speeds up to 90 km/h [4]. Compensation for acceleration and deceleration during the journey is also taken care of.

To determine the transverse slope (crossfall) of the road, an inclinometer and a rate gyro is used together with the laser information [4]. Another inclinometer is part of measuring what is referred to as hilliness.

2.4.2 Software

The electrical signals achieved from the displacement sensors are computer-processed in real-time. Instantly analyzing the data minimizes the risk of wrongly handled data by the operator and the cost of, for instance, redoing measurements at a later point of time.

2.4.3 Operator and Data Handling

The operator is a very important part of all automatic measuring systems. The driver must learn how to handle the test vehicle in order to achieve an optimal inspection of the road. Other key issues are that he or she needs to be able to calibrate and maintain the instruments and also to determine when a piece of equipment is out of order [4].

All processed data is stored on floppy disks. After data has been collected a verification process is being executed. With the aid of charts showing variations of data over time, and added correlation checks, the data can be considered well-substantiated.

2.5 Available Parameters

With the Laser RST the following parameters can be measured and calculated and are used today [38]: International Rougness Index (IRI), mean transverse profile, maximum rut depth, crossfall, texture, longitudinal profiles and hilliness.

2.5.1 International Roughness Index, IRI

IRI is an abbreviation of International Roughness Index and is meant to be the longitudinal unevenness of the road as the driver experiences it while driving a standardized car at the speed of 80 km/h. A low value indicates a comfortable road whereas a high IRI value indicates that something ought to be done in order to improve the ride quality. IRI is measured (as a standard) in the right wheel track [38]. An outline diagram of the IRI model is shown in Figure 2.6.

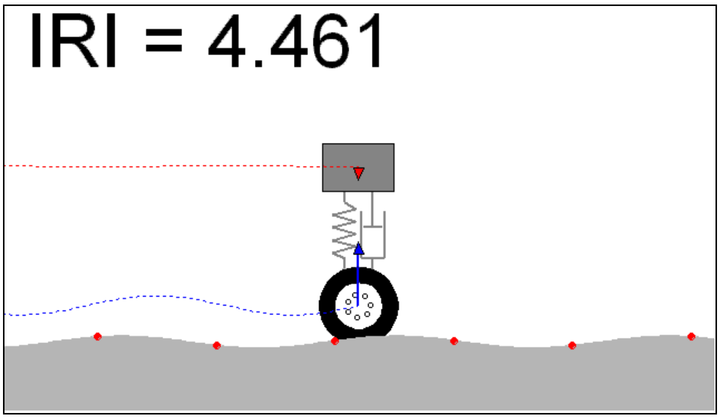


Figure 2.6. Outline diagram of the IRI model. Figure taken from [38, p. 8].

2.5.2 Mean Transverse Profile

The mean transverse profile is determined with the help of 17 lasers where the two outer measurement points are set to zero. The perpendicular distance from an imagined wire spanned between them to the intermediate points is then calculated. Every 10 cm the mean transverse profile is determined and after a distance of 20 m an average value is calculated and stored by the Laser RST. An example of a mean transverse profile is shown in Figure 2.7.

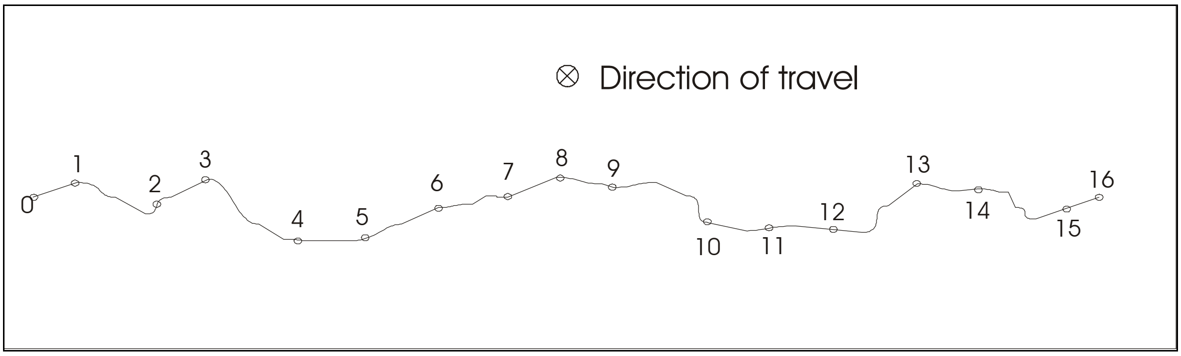


Figure 2.7. A sketch of a mean transverse profile with 17 measurement points, as numbered in the Laser RST.

2.5.3 Maximum Rut Depth

Maximum rut depth is a measure of transversal unevenness. It is measured by applying the wire surface principle, see Figure 2.8. The principle means stretching an imagined wire along the transverse profile and taking the largest value of the distance from the wire perpendicular to the measurement points. The Laser RST measures maximum rut depth once every decimetre but gives the result as a mean value over a length of 20 m, i.e. 200 values.

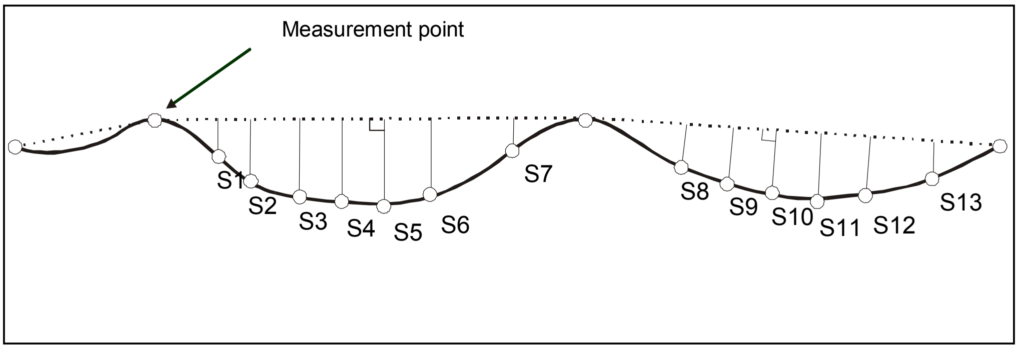


Figure 2.8. Rut depth calculated using the wire surface principle. In this example S5 is the maximum rut depth. Figure taken from [38, p. 11].

2.5.4 Crossfall

Crossfall is a measure of the transverse slope of the road. This is not taken into account by the mean transverse profile. The Swedish National Road Administration (Vägverket) accepts two ways of measuring crossfall; these are the surface line method and the regression line method. Both methods are used by the Laser RST. The latter means using the least squares regression method to adjust a line based on the 17 values collected from the lasers in the mean transverse profile. The slope of this line is then defined as the crossfall. See Figure 2.9 and Figure 2.10. According to the surface line method, the crossfall is the slope of the line defined by the two outer measurement points in the mean transverse profile.

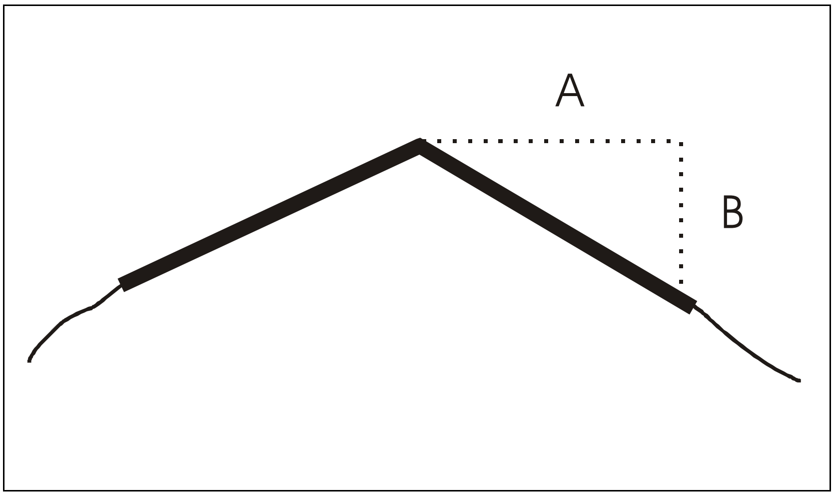


Figure 2.9. Definition of crossfall: The vertical distance (B), relative to the horizontal (A) when moving from the centre of the road perpendicular to the length of the road [46].

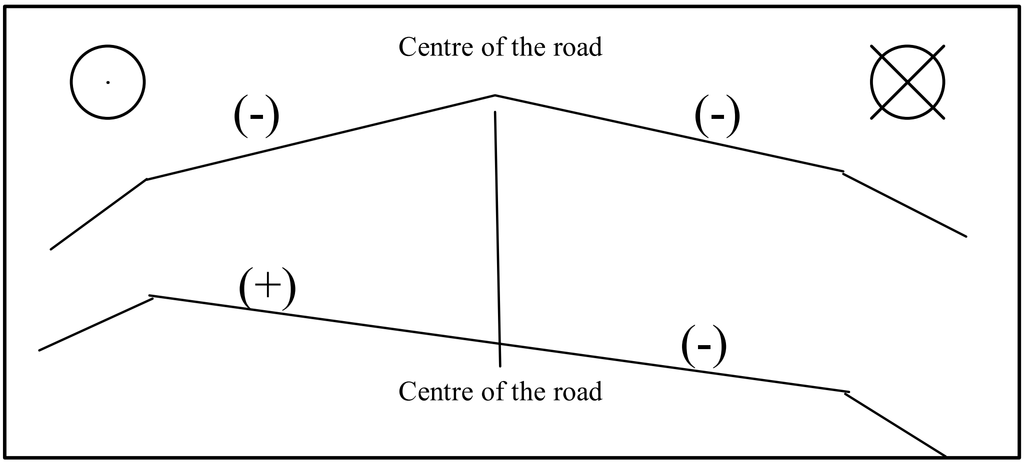
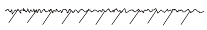


Figure 2.10. Sign determination of crossfall. Figure taken from [38, p. 11].

2.5.5 Texture

The asperity of a road surface is of importance when describing the characteristics of a road. The term used for this is texture. In itself, it can be divided into different parts [38]. The microtexture can be defined for wavelengths less than 0.5 mm (for instance the surface structure of a stone), the macrotexture for wavelengths between 1 and 100 mm (i.e. stones), whereas megatexture describes unevenness for wavelengths between 50 and 500 mm (potholes, edges etc.). It can be said that microtexture is of great importance for wet friction at low vehicle speeds while macrotexture on the other hand is vital at high speeds [15], [29]. Moreover, the mean profile depth (MPD) is measured over 50 mm long road profiles. Ruling texture measures are the Rough Root Mean Square (RRMS) and the Fine Root Mean Square (FRMS). In the future, however, there will probably be a change-over to the MPD measure [39]. In Table 2.1 different texture profiles together with their corresponding notation is shown.

Table 2.1. Schematic grading of the texture of the road surface. Table taken from [34, p. 14].

Surface	Texture profile	Microtexture	Macrotexture
1		Fine	Smooth
2		Coarse	Smooth
3		Fine	Rough
4		Coarse	Rough

2.5.6 Longitudinal Profile

The longitudinal profile is a measure of the unevenness along the road. It is in Sweden defined as the height variation over a length of 1 dm in the direction of travelling. The profile is the basis for the IRI and RMS-values described above and it is measured at a wavelength interval from 0.5 to 100 m [38].

2.5.7 Hilliness

Hilliness is the slope of the road in percent over a successive length of 20 m. It can be said to be a less accurate measure of the longitudinal road profile, because it is determined by inclinometers only [39].

2.6 Pavement Management Systems

The Swedish National Road Administration (SNRA) is aided by decision support systems called Pavement Management Systems (PMS). Generally PMS is not unambiguously defined, but can be thought about as an organized way of exploiting data for information and/or decisions about planning and optimizing road maintenance on a socio-economic basis [26], [39]. The Swedish PMS is made to support decisions concerning when, where and what measures should be taken on paved roads, planning budgets etc. It must however be emphasized that the purpose of the system is to support, not to decide. In reality, aspects like equality, trade and industry play important parts in the final decision.

Currently, the data from the Laser RST used in PMS is IRI, maximum rut depth, crossfall, transverse profile and (since 2001) the longitudinal profiles in both wheel tracks [38]. Other data is nonetheless collected and if it is of relevance for traffic safety, more data should, consequently, be included in the PMS.

When using PMS, interesting data is first collected and stored in databases. From the databases, analysis models are created. Once the important parameters are included in the system, the users can handle data and make their decisions on how to act. In the end, the collected data can be of a more “visible” benefit. The three main systems used by the SNRA today are called PMS Plan (Planning), PMS Vägnät (Road network) and PMS Objekt (Object) [47].

Traditionally PMS is used for management of road surfacing, i.e. pavement. The concept is however growing and considering the fact that it could be used on a more wide-ranged area of the road it may in the future be renamed to Road Management Systems [39].

2.7 Previous Studies

Topics related to aquaplaning have been treated in many studies before. Some of the reports published by interesting organizations were chosen for a more detailed review and summaries of these will follow in this section.

The organizations treated are the Swedish National Road Administration (SNRA), the Federal Highway Administration (FHWA), the Swedish Road and Transport Research Institute (VTI), the Transportation Research Board (TRB) and the American Society for Testing and Materials (ASTM). Conclusions of the reports are included in Subsection 3.1.2, which deals with the subject of defining a risk pond.

In the unpublished report [1], ordered by the SNRA, a literature study and logical reasoning leads to conclusions about the definition of a risk pond. Reference [11] is an American report where the Federal Highway Administration made a literature review, questionnaires and computer simulations together with field testing to obtain knowledge about how to minimize aquaplaning in view of pavement and geometric design criteria. A report frequently used as a reference, especially for Swedish measurements, is [31]. This is an experimental study conducted by the VTI, which analyses the influence of tyres, water depth, road surface and speed. The report [22], on the contrary, is based upon statistics about accidents and road surface conditions. Three reports by TRB, [18], [24] and [42], are, in order, concerned with a programme predicting the water film thickness, traffic safety on wet roads and parameters affecting the longest drainage path length for water on the road. The last organization that is given special attention is the American Society for Testing and Materials. Two articles, [5] and [16], resulting from a symposium about frictional interaction of tyre and pavement are the subject of the last subsection.

2.7.1 The Swedish National Road Administration

Lars-Olof Alm, former senior university lecturer at the Royal Institute of Technology (KTH), performed a literature study in 1995 on behalf of the SNRA in order to investigate the risk of dynamic aquaplaning [1]. Vehicle speed, depth and extension of the pond were factors that he analysed.

Because no overall standardization of measuring friction has been prevalent, a difficult task was to relate the values that have been gained by different kinds of measuring techniques. In Alm’s study, the used water depth is defined as the distance between the surface of the water film and the upper parts of the texture of the road. Under normal conditions the critical aquaplaning depth was about 4 or 5 mm. As he points out, it varies because of ambiguous methods of determining the critical friction coefficient.

Alm also reasons about the placement and size of ponds in terms of aquaplaning risk. (See Figure 2.11.) A pond situated in the middle of the road is considered to be “potentially harmless”, whereas two symmetrical and relatively small ponds in the wheel tracks are regarded as being of minor risk. On the other hand, asymmetrical ponds across the road and large ponds at one side of the lane are considered to constitute a risk. Further, Alm discusses the properties between the depth and length of an assembly of water. Arguing that the risk of aquaplaning should be determined by how long time is spent driving through the pond, a measure could be constructed by combining depth and length of the water accumulation.

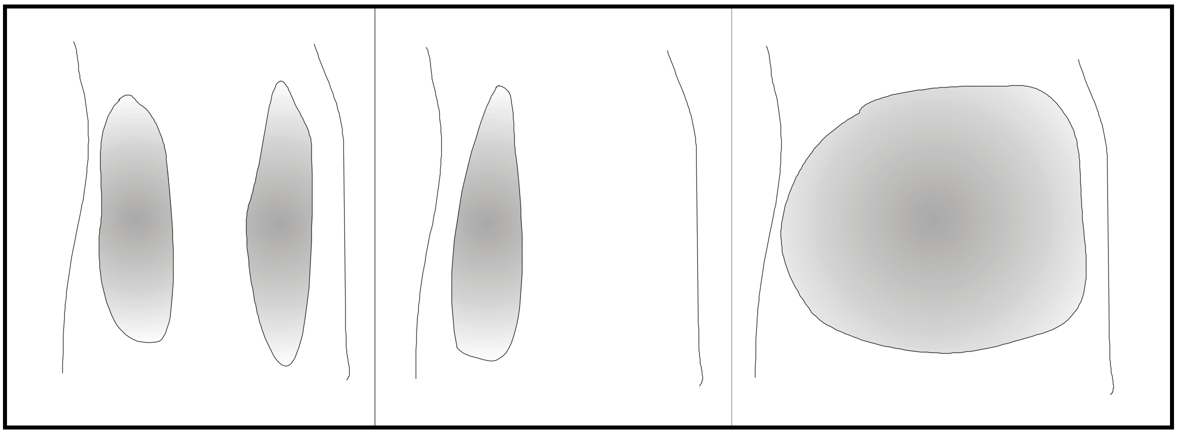


Figure 2.11. Different pond types. Left figure: Two ponds in the ruts. Middle figure: A single pond in the left rut creating asymmetrical friction. Right figure: A large pond across the whole road.

The main result of the study is that a risk of dynamic aquaplaning should be regarded to occur when an accumulation of water at the road surface has a maximum depth of at least 4 mm and the product of the length and the depth simultaneously is larger than 80 m·mm. These figures are based on a critical speed of between 60 and 80 km/h and a critical time spent in the accumulation of water of one second. In the analysis the width and coordinates of the water pond were not attended to, neither was the texture of the road.

2.7.2 The Federal Highway Administration

A report called *Pavement and Geometric Design Criteria for Minimizing Hydroplaning* was prepared for the Federal Highway Administration in Washington D.C. in December 1979 [11]. According to [11] variables that influence aquaplaning are surface texture, crossfall, drainage path length, rainfall, tread design depth, tyre pressure and vehicle speed. The first three factors are within the engineer’s control, whereas the last ones are outside of it. In the report it is stated that: “Loss of contact can occur between 40 and 45 mph (64 and 72 km/h) in ‘puddles’ of about 1 inch (25 mm) maximum depth and about 30 feet (9 m) in length.” (where “puddles” is the same as “ponds”) [11, p. 254].

2.7.3 The Swedish Road and Transport Research Institute

A Swedish report often referred to is [31], where theoretical results are tested in practice by the VTI. Although the study was conducted as early as in the years of 1967 to 1969, the results are still considered to be appropriate. The variable test parameters were type of tyre, tread design depth, water depth above the peaks of the texture, type of texture and speed.

The main results are as follows: At a given speed, the braking force between the road surface and the tyre depends on road characteristics, tyre characteristics and the amount of water. VTI made tests of surfaces that were dry, pure wet (no water layer above the peaks of the texture) and surfaces that had a layer of water above the peaks of the texture. At dry and pure wet surfaces the braking force was acceptable, independently of the type of tyre used, if texture was rough enough. Even on smooth surfaces with good microtexture the braking force was reasonable if the tyre was drained and had an appropriate tread design depth. A major fact was that at dry or pure wet surfaces applying low speeds is significantly more important than the tread design depth, unless the surface is extremely plane. When tests were performed on water depths above the peaks of the texture, asperity and tread design had more influence on the braking force. The critical speed of partial aquaplaning was regarded as relatively independent of the water depth at depths of 0.5-8 mm. The asperity of the road surface affected the braking force at a considerably higher level than the design of the tyre tread did, at increasing speeds and water depths. For water depths of 8 mm the critical speed for different types of tyres was determined to 85-105 km/h for rough road surfaces and to 65-80 km/h on smooth road surfaces. At 4 mm water depth the corresponding figures were 105-130 km/h and 65-90 km/h, respectively. Considering that most Swedish roads have a good texture and that the speed limit often is below 90 km/h, the normal aquaplaning water depth would be about 8 mm.

Another report by the VTI studied the influence of road surface condition on traffic safety [22]. With the help of regression analyses on data from 1992 to 1998, it was found that rut depth influences the rate of aquaplaning accidents more than crossfall does. See Figure 2.12 and Figure 2.13. However, this study looked upon the variables rut depth and crossfall unrelated to other road surface characteristics, but with the amount of precipitation per day as an additional influencing factor.

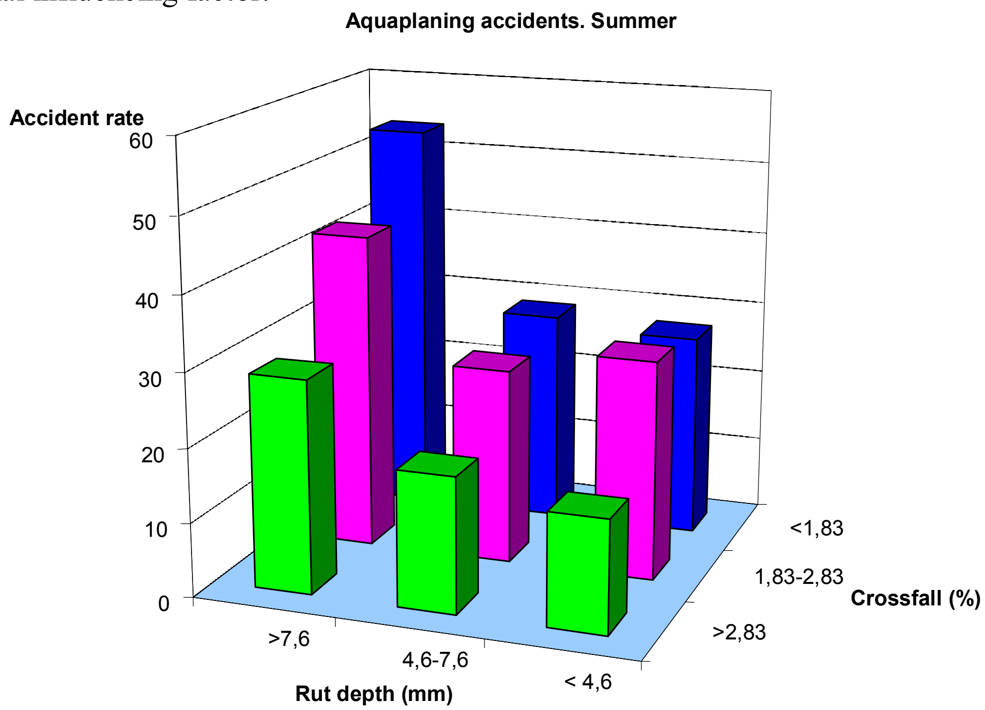


Figure 2.12. Aquaplaning accident rate at summertime for different classes of rut depth and crossfall. Accident rate is here defined as the amount of accidents per 100 million km travelled by a pair of vehicle axes. All precipitation classes. Figure taken from [22, p. 67].

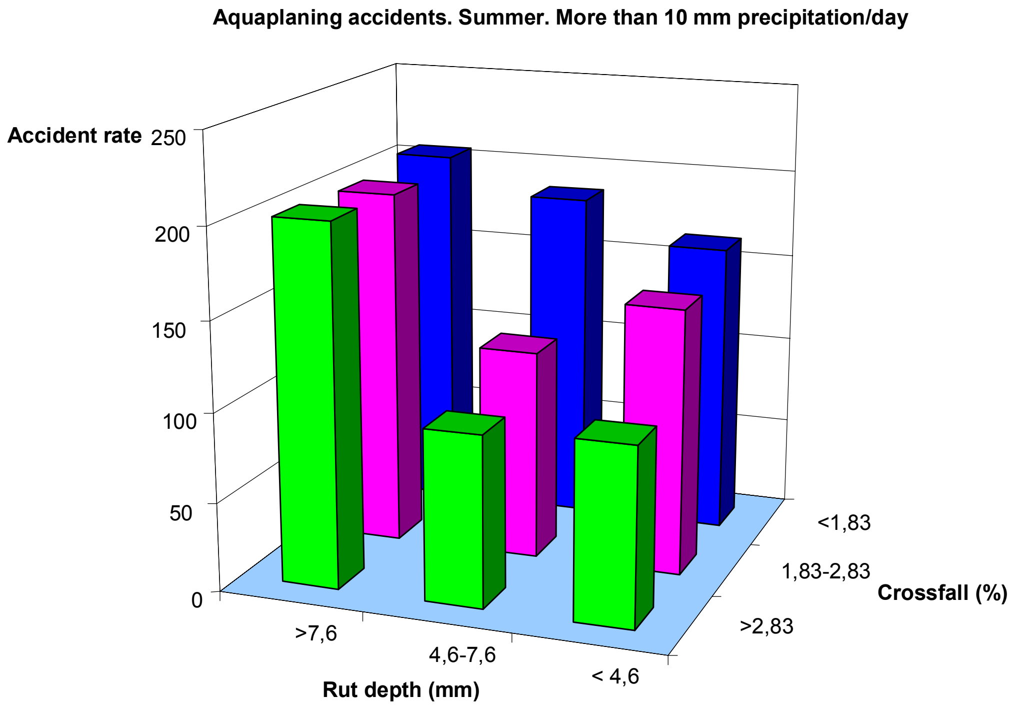


Figure 2.13. Aquaplaning accident rate at summertime for different classes of rut depth and crossfall at days with more than 10 mm precipitation. Accident rate is here defined as the amount of accidents per 100 million km travelled by a pair of vehicle axes. Figure taken from [22, p. 68].

In the year of 2000 an experimental study on an authentic road surface was carried out [33]. The study was conducted in order to find significant differences in performance between tyres of different widths. With a tyre tread depth of 4 mm and a water depth above the aggregates of about 7 mm, full dynamic aquaplaning was not accomplished even for speeds over 100 km/h. Partial aquaplaning however, caused an unacceptable low friction value. A result from the experiments was that, at least down to 4 mm tyre tread depth, the tyre width could not be concluded to be of significance for gripping power.

2.7.4 The Transportation Research Board

The Transportation Research Board (TRB) published a report in 1998 called *Improved Surface Drainage of Pavements: Final Report* [42]. In this a programme, known as the PAVDRN programme, for predicting water film thicknesses at certain points, is described (see also [17]). PAVDRN is based on a one-dimensional flow equation and includes parameters such as rain intensity, mean texture depth (MTD), velocity of flow and a variable called Manning's roughness coefficient. This means that the PAVDRN programme is relatively complex and takes flow theory into account. Its benefits are that it can calculate the water film thickness for certain circumstances and considers many parameters. The aim of this master's thesis is to create a simple model though, based on actual measurements of road surface characteristics.

Another report, [24], was published by the TRB in 1994. It discusses the safety issues of wet pavements in relation to the width of the road, crossfall and drainage. The work is built upon guidelines for a water depth of about 1 mm. No critical length of a pond is however stated.

In [18] the longest drainage path lengths for different mean texture depths, rainfall intensities and temperatures, respectively, are examined together with the aquaplaning speed. The results are presented in Table 2.2 below.

Table 2.2. Parameters affecting the longest drainage path length.

Examined value and range	***Aquaplaning speed***	***Longest drainage path length***
Rainfall intensity, 25-150 mm/h	77–105 km/h	3-20 m
Temperature, 0–30°C	77-98 km/h	3-20 m
Mean texture depth, 0.50-1.00 mm	98-160 km/h	2-9 m

This report also states some recommended ranges in mean texture depth for some pavement types.

2.7.5 The American Society for Testing and Materials

In 1981 a symposium on the contact problem between vehicle tyres and the road was held in Ohio, sponsored by the American Society for Testing and Materials (ASTM). In an article by Hayes et al., [16], results of tests with different tread design depths, speeds and type of ponds are presented. One outcome was that loss of contact with the pavement could occur at speeds in the range of 64 to 72 km/h in ponds of about 9 m length and 25 mm maximum depth. Loss of traction could however begin to occur at speeds as low as 32 km/h.

Another article resulting from the symposium is [5]. This article examines the test results and analyses of different tyre-pavement interactions concerning aquaplaning. A conclusion made is that 2.5 mm is a sufficient water depth for dynamic aquaplaning to occur. For small tread design depths (1.6 mm or less), water depths of 1.8 mm would however be dangerous. It is also interesting that when doubling the tyre pressure from 125 to 250 kPa the initial speed of aquaplaning is raised more than 16 km/h. The type of pavement is further discussed and it is stated that an increased texture depth decreases the risk of aquaplaning.

2.7.6 Miscellaneous

One of the first studies concerning the aquaplaning phenomenon was [12], carried out in Germany in 1967. The experiments were carried out using a rotating drum in which a test tyre was placed in a suspension device. By altering the water depths in the drum conclusions about aquaplaning on real roads were drawn. With the equipment used a bad friction was concluded to occur at 0.2 mm water depth. In comparison with more road similar conditions with water on the road, a bad correlation between drum data and "real" road was observed. To achieve the same friction coefficient a water depth of 1.5 mm would be needed on the road. Therefore, the drum tests should be considered inappropriate for determining the actual aquaplaning depth. Another German work based on experiments with similar equipment is [14].

During the same period of time work was carried out by the Road Research Laboratory in Great Britain. The English tests show that on smooth surfaces the aquaplaning speed is almost constant at a water film thickness of between 4 and 7 mm for the tyres studied [32].

According to traffic engineer John C. Glennon, aquaplaning could be expected for speeds over 70 km/h where water ponds have a depth of about 2.5 mm and a length of about 9 m as a general rule of thumb for rural highways [13].

3 Model Development

In this chapter, the subject of how to define a pond is discussed, followed by the development of a road and pond model.

3.1 Pond Considerations

When considering aquaplaning you have to work with some kind of definition of a risk pond. One thing that has to be taken into account is the extent of the water accumulation. Intuitively, the more time spent driving through a pond, the greater the risk for an aquaplaning accident. Maybe the length should be related to the speed in order to achieve a constant "drive-through-time". This means that at higher speeds a longer pond could be acceptable than at lower speeds. This assumption is the basis for the study [1] by Alm.

Another important issue is defining a pond as being dangerous depending upon how the underlying ground is drained. Two equally sized ponds should be considered as differently dangerous with respect to different kinds of texture. If the texture is high the risk for aquaplaning is reduced [15], [29].

There are four concepts that will have to be separated in order to be able to define a risk pond. These are:

- Rut depth
- Theoretical water depth
- Pond
- Risk pond

Rut depths are the depths made by heavy vehicles and wear caused by studded tyres in the wheel tracks. How they influence the water depth is further discussed in Subsection 3.1.1.

The theoretical water depth is measured in two dimensions according to Figure 3.1. It is the maximum depth that could be expected from a transverse profile. In this report the convention is that, when nothing else is stated, water depth means the thickness of the potential water layer as measured above the peaks of the texture.

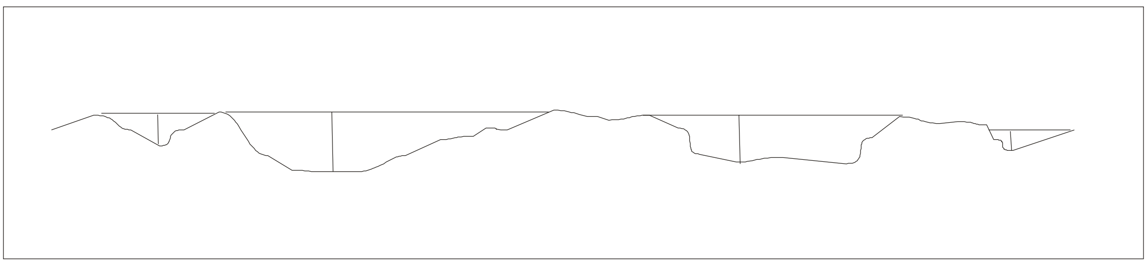


Figure 3.1. The theoretical water depth is measured perpendicular to the water surface. It is taken as the largest of the measured depths from a mean transverse profile.

A pond, in the sense used in this report, is any water accumulation on the road. It contains all possible kinds of holes where water can gather and is not specified in how deep or wide it has to be to be called a pond.

Risk ponds make up a subset of ponds. The subset should include all ponds where aquaplaning could be expected. How to define such a pond is analysed in Subsection 3.1.2.

3.1.1 The Influence of Rut Depth

At first sight, water depth and maximum rut depth seem to be strongly correlated. Rut depth, however, is measured according to the wire principle, as described in Subsection 2.5.3, and does not take crossfall into account. In Figure 3.2 the two concepts are further explained.

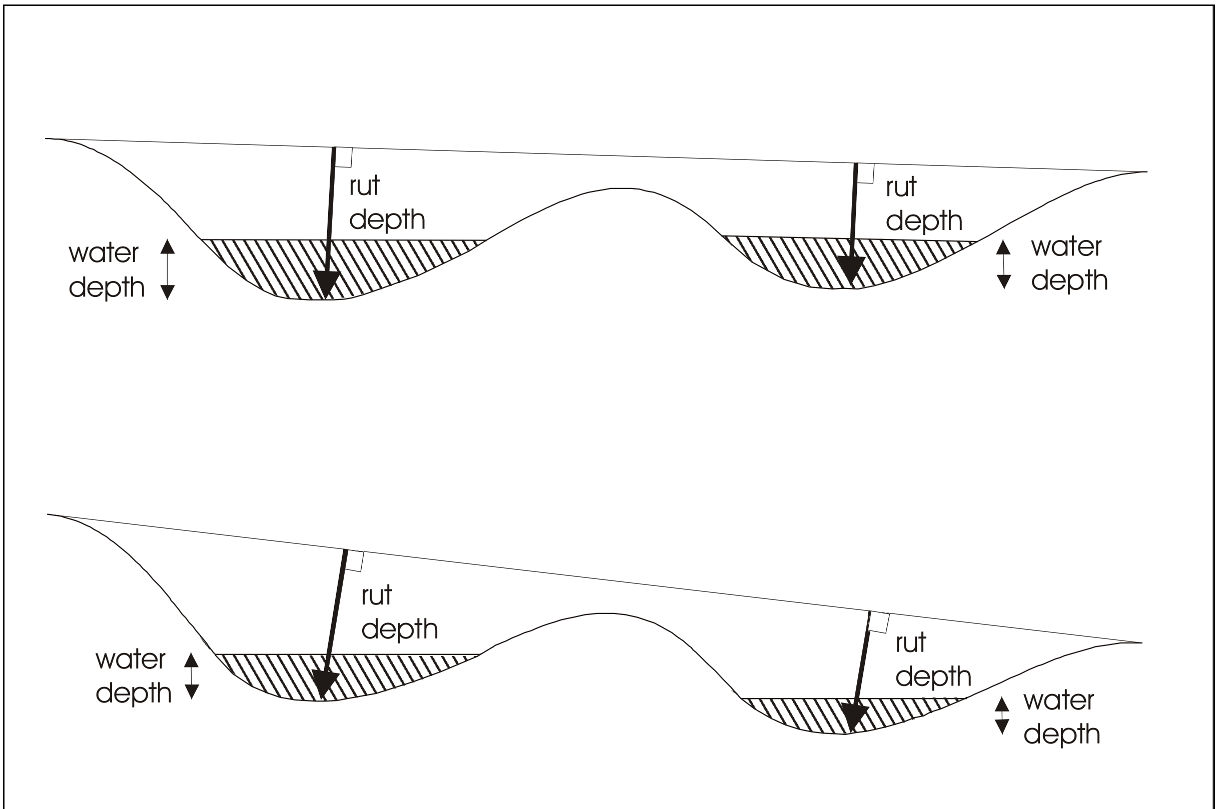


Figure 3.2. Rut depth and water depth, with (below) and without (above) crossfall. Rut depth is the same in both cases, whereas the water depth depends on the crossfall.

A study by the Department of Civil and Environmental Engineering at the University of Wisconsin-Madison in the USA [41] treated pavement rutting and safety consequences. Statistical analyses revealed that the accident rate was significantly increased for rut depths exceeding 7.6 mm. This value was also the water depth limit at which aquaplaning could occur, according to laboratory tests carried out.

3.1.2 Defining a Risk Pond

As stated in for example [25] water film thickness plays a major part in how the car will react considering braking safety, accelerating and the distances necessary for braking. Aquaplaning is said to be the result of friction decreasing between the tyres of the driving wheels and the road surface. Different friction for the left and the right pair of wheels could also be hazardous [20]. The SNRA consequently requires that the transverse friction should not vary more than 0.25 on paved roads [44]. This means that a general statement that a wide pond would be more dangerous than a narrow one cannot be made. In view of this, the width of a risk pond is seen as a minor issue and shall not be further regarded in this work.

In Section 2.6 some examples of risk ponds were regarded. Then again, there are numerous studies carried out which bring up the subject of aquaplaning. Most of them work with specific combinations of parameters that could lead to hazardous driving in wet weather. In Table 3.1 below, the factors contributing to aquaplaning as found in different literature sources are listed.

Table 3.1. Aquaplaning risk parameters from literature studies. f = full dynamic aquaplaning, p = partial aquaplaning. The last column reveals the basis for the figures in the source, using the following notation: E = Experiments, L = Literature studies, T = Theoretical considerations, S = Simulations, U = Unknown

Reference	***Water depth (mm)***	***Water length (m)***	***Speed (km/h)***	***Flow/Width (m^3/s/m)***	***Intensity (mm/h)***	***Basis***
[1]	4	20	72	-	-	T
[5]	2.5	-	Ca 65	-	--	L, T
[7]	2-5*	10-15	110	-	100	U
[8]	3	-	80	-	-	L
[11]	25(f) 9.5(p)	9	64	-	>13	L, E
[13]	2.5	9	70	-	-	U
[14]	3	-	100	-	-	S, E
[16]	25(f) 9.5(p)	9	64-72	-	-	E
[17]	1.3	6.66	90	0.00013	-	S, L, T
[17]	1.5	11.79	88	0.00023	-	S, L, T
[17]	1.6	16.39	86	0.00032	-	S, L, T
[18]	--	2-20	76-96	-	25-150	L, T
[19]	2.5	-	75	-	-	L
[19]	Ca 0.6	-	Ca 100	-	-	L
[20]	>10	-	80	-	-	S, L
[21]	1.3	-	120	-	-	L
[23]	2.5*	10	70	-	-	U
[24]	3	-	-	-	101.6	S, E
[31]	8	-	85-105	-	-	E
[36]	3.0	-	140	-	-	U
[41]	7.6	9.1	80	-	-	L
[43]	1-2	-	80-100	-	-	L

**Uncertainty about how the water depth is measured.*

The aim of this master's thesis is to discover risk ponds. Therefore, the interesting parameters are not a certain crossfall at a certain speed or flow and so forth, but the characteristics of the road concerning holes. It is a fact that drivers do not always follow the speed limit and the wheel tracks. When overtaking for example, speed is increased and the ruts are left. Therefore, the analysis should consider all available road geometry data to see where water has a possibility to accumulate.

As seen in the studies above, many sources indicate a very small water depth as being dangerous. There are several reasons why a total trust in the values found should not prevail, though. One of them is that many of the studies base their figures on work carried out by others. Even more crucial is the fact that almost none of the studies are based on experiments under actual road surface conditions. There are trials with rotating drums ([12], [14]) and experiments with tyres travelling in basins ([31]) but data from real road surface tests is mostly lacking. The Federal Highway Administration is however one of the few organizations that conducted tests in ponds of standing water following a rainfall ([11], [16]). In consideration of this, the default risk depth chosen for the model in Section 3.4 was 10 mm.

On basis of the values found for the longitudinal extension of a risk pond, which were about 10 m, this was taken as the lower limit for the risk pond model.

3.1.3 Risk Pond Classification

One of the goals of this work is to create a pond index. Table 3.2 shows an indication of how to categorize a pond depending on its depth and length. When crossfall is not included, then the theoretical water depth from the mean transverse profiles was exceeding 10 mm on less than one percent of 2260 km of main roads [28]. In view of the fact that aquaplaning accidents are relatively rare, a limitation of 10 mm depth for a high risk pond should therefore not be an overstatement. Since crossfall is also contributing to water runoff, the actual hazardous areas found would be even less. An alternative approach considered is to create a pond index on a scale from zero to ten. When scrutinizing the available literature and considering the discrete steps that would have to be present, a pond index of that kind is however regarded as too difficult to produce and too uncertain if produced.

Table 3.2. Risk pond indication table.

	Low risk	***Medium risk***	***High risk***
Depth D, Length L	D<8 mm **or** L<8 m	(8≤D<10 mm **and** L≥8 m) **or** (D≥8 mm **and** 8≤L<10 m)	D≥10 mm **and** L≥10 m

3.2 Road Model

A first step in most tasks based on data from road surface surveying would be to create a model of the road. In this section first a method to create a model based on hilliness for every 20 m part of the road is presented. It gives an idea of how to combine measured data to create a three-dimensional model. In the next subsection a model based on longitudinal profiles for every decimetre is described.

3.2.1 Road Model Based on Hilliness

To get a fairly correct (but of course rough) model of the road surface in three dimensions, the mean transverse profile should be rotated to account for the crossfall. Thereafter, the different rotated transverse profiles should be put in a sequence with different values of the hilliness. This means that the curvature of the road is neglected. With the three measures mentioned, a three-dimensional model is possible to create.

Since the mean transverse profiles should be properly adjusted according to the crossfall, the question of how much the length of the rotated profile thereby is affected arises. Considering the standard crossfall of the roads in Sweden, which is -2.5% [39], the difference in width between the mean transverse profile and its projection when rotated with the crossfall can be calculated. It could for instance be done using the following formula, with notation taken from Figure 3.3:

$$\cos\alpha = \frac{x}{l} \Rightarrow x = l \cdot \cos\alpha \qquad (3.1)$$

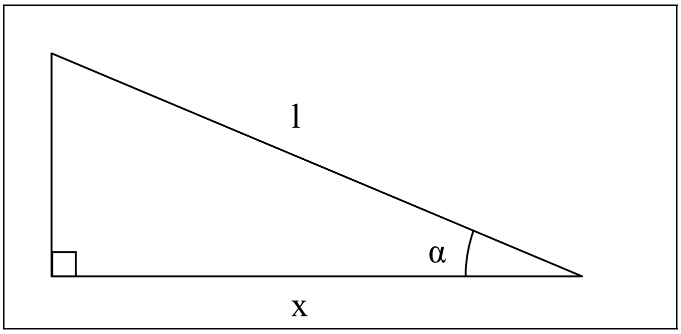


Figure 3.3. Crossfall angle α, rotated mean transverse profile width l and projected width x.

With $\tan\alpha = 2.5\% \Rightarrow \alpha = \arctan\left(2.5 \cdot 10^{-2}\right)$ [radians], the projected width x becomes 0.9997 times the original width. Since the measuring width of the Laser RST is 3.2 m, this implies a reduction of 1 mm. Keeping this in mind, the width effect of rotating the mean transverse profile can be neglected.

To implement the model above, some geometrical considerations were made. Since the crossfall should be added to the model, the height of the mean profile will alter. See Figure 3.4.

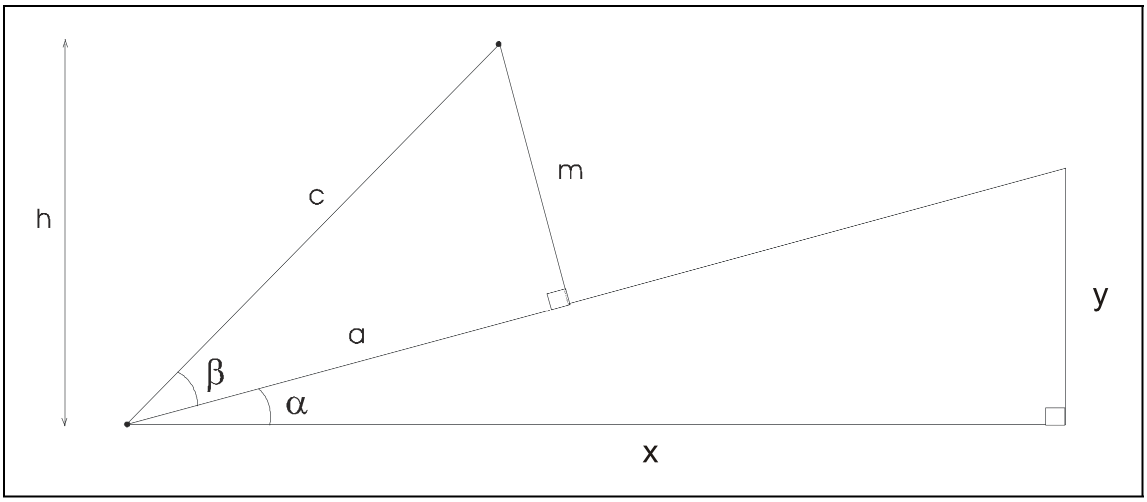


Figure 3.4. The resulting height (h) is calculated from the crossfall angle (α), the relative distance from measurement point number 0 to the current measurement point (a) and the height (m) of the measured point perpendicular to the mean transverse profile. The crossfall is defined as tan(α) = y/x.

With notation taken from the figure, the height m, which is appropriate for the mean transverse profile, should be modified to the correct height h, which includes crossfall. The distance a is a known distance between laser number 0 and the current laser.

To begin with, the angle β is calculated.

$$\tan\beta = \frac{m}{a} \Rightarrow \beta = \arctan\left(\frac{m}{a}\right) \tag{3.2}$$

The distance *c* to the current measurement point is thereafter achieved.

$$\sin\beta = \frac{m}{c} \Rightarrow c = \frac{m}{\sin\beta} \tag{3.3}$$

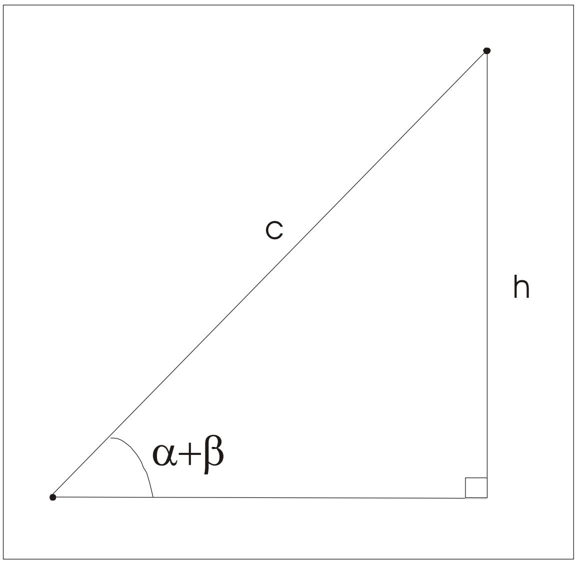


Figure 3.5. The resulting height h is easily calculated from the angle (α+β) and the distance c between measurement point number 0 and the current measurement point.

The angle α is obtained from

$$\alpha = \arctan\left(\frac{y}{x}\right) \tag{3.4}$$

Finally the resulting height *h* can be determined (see Figure 3.5).

$$\sin(\alpha+\beta) = \frac{h}{c} \Rightarrow h = c \cdot \sin(\alpha+\beta) \tag{3.5}$$

3.2.2 Road Model Based on Longitudinal Profiles

The accelerometers are continuously drifting, which results in an accumulation of the measured longitudinal profiles. To get data of an appropriate form, the profiles must be filtered. A comparison including filtered profiles containing wavelengths up to at least 60 m made by the VTI in 1990 [35] shows a good agreement between road profiles measured by the Laser RST and profiles from levelling. Therefore, 60 m is chosen as an appropriate wavelength upon which to filter the longitudinal profiles.

Following below is an algorithm implemented in the function `Roadmodel`, which creates a three-dimensional model of the road. Input data are the longitudinal profiles in left and right wheel track for each decimetre and the mean transverse profiles and crossfall as mean values over 20 m sections. The left and right longitudinal profiles correspond to the left and right wheel track in the mean transverse profiles.

1. High pass filter the longitudinal profiles with a third order Butterworth filter
2. Find the midpoints for every 20 m interval of the left longitudinal profile and calculate the mutual relationships for their intermediate points
3. Fixate the mean transverse profiles at the midpoints for every 20 m interval of the right longitudinal profile and turn them according to the crossfall
4. Calculate the resulting midpoint values for the left wheel track
5. Raise/lower the midpoints of the left longitudinal profile according to step 4. and let the intermediate values in the profile follow, according to the mutual relations in step 2. (See Figure 3.6. and Figure 3.7.)
6. Interpolate the mean transverse profiles in every decimetre
7. Calculate new crossfall angles for each interpolated mean transverse profile by comparing the height relationship partly between the longitudinal profiles and partly for left and right wheel track in the mean transverse profile
8. Calculate the height values for each decimetre in measurement points 0-16 from:
   - right longitudinal profile
   - height relations in the interpolated mean transverse profiles
   - new crossfall angles

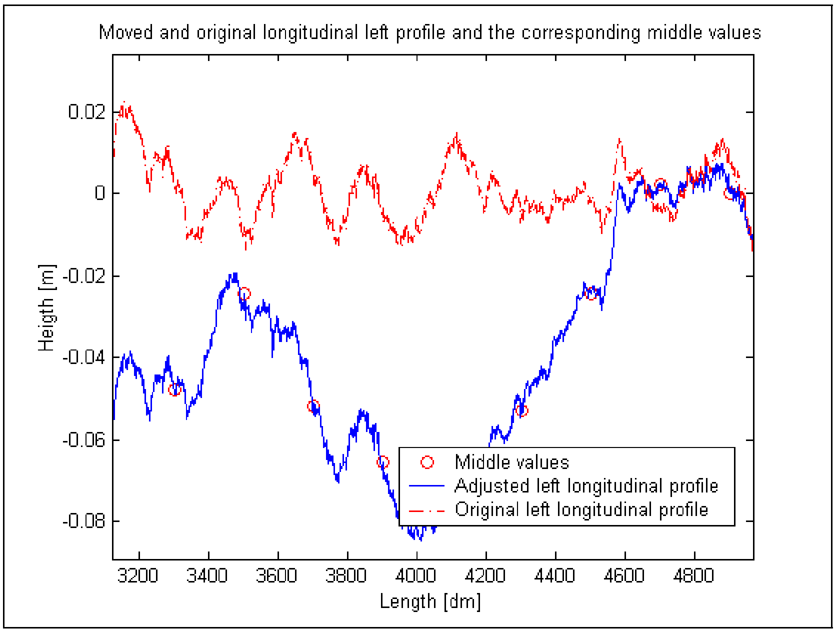


Figure 3.6. Visualization of step 4 in the algorithm above. The left longitudinal profile before (upper curve) and after (lower curve) being moved according to the midpoint values calculated in step 4, indicated by circles.

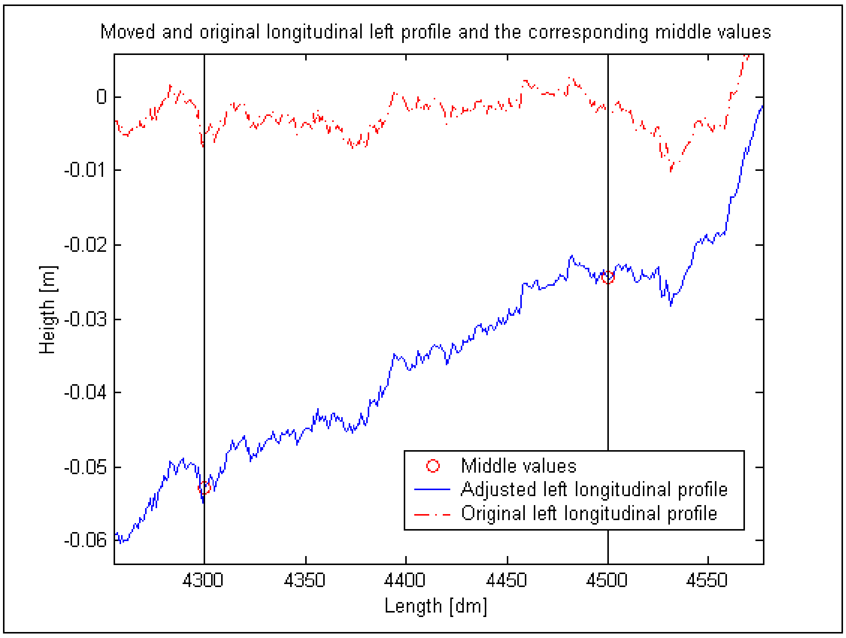


Figure 3.7. Enlargement of an area in Figure 3.6.

The outputs of the algorithm are three matrices:

- One that contains the travelled distance from zero for each point
- One that contains the distance from laser number zero for each point
- One that contains every point's resulting height in relation to a zero level defined by the right longitudinal profile

This three-dimensional model of the road from road surface data is created to resemble the road as far as possible, without being too complicated. Since the algorithm generates a general model of the road, it has a wide range of application. It can be used in every area where road surface data in a simple model is enough for the given purpose (to achieve the goals wanted). An example of this could be finding local irregularities.

3.3 Pond Model

The task to detect parts of the examined road which are in the risk zone considering aquaplaning could be satisfactorily accomplished using the three-dimensional model described above. Reasoning concludes that a prerequisite of aquaplaning is that there is a possibility that water can assemble on the road. As a consequence, finding the maximum water depths at every measurement point of the road would be of great importance. This was done by first creating a depth-algorithm, which works separately across and along the road, and then by combining the resulting depths for the complete road.

The depth-algorithm takes as input a vector containing the interesting heights. Figure 3.8 below shows how the algorithm works. The main steps are the following:

- Starting with the first value, a search for the closest higher value in the remaining part of the vector is conducted
- The intermediate depths are calculated
- When a higher value cannot be found, a search for the maximum value in the rest of the vector is carried out and the intermediate depths are calculated

Using this algorithm, all theoretical depths are being stored in an output vector.

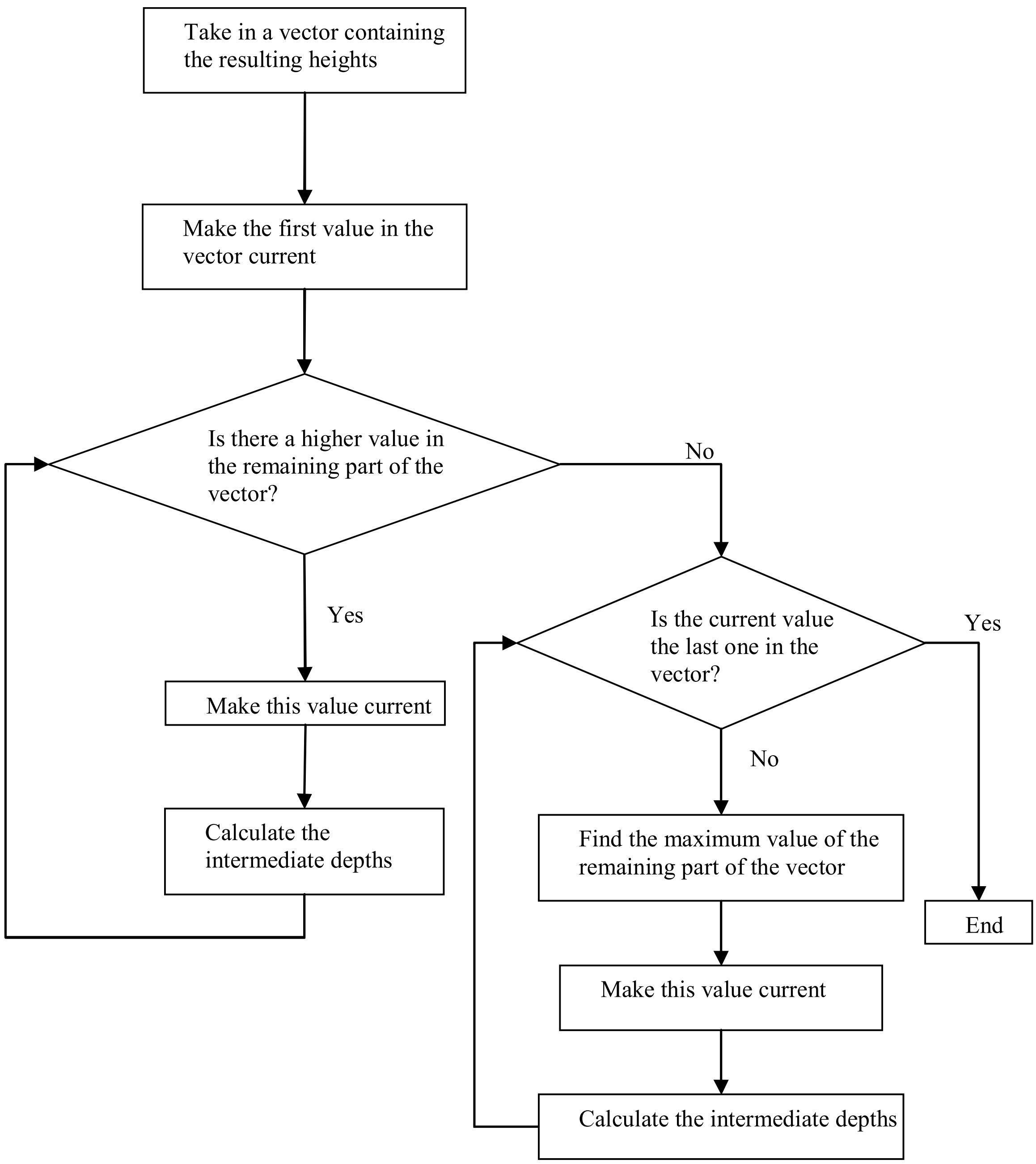


Figure 3.8. Flow chart showing the algorithm for calculating theoretical water depths for each profile from the heights.

As an example, the case in Figure 3.9 can be considered:

Input heights: [0 -1 -2 1 3 2 4 2 3 1 2 0 2 -1 1 2 3]

Output depths: [0 1 2 0 0 1 0 1 0 2 1 3 1 4 2 1 0]

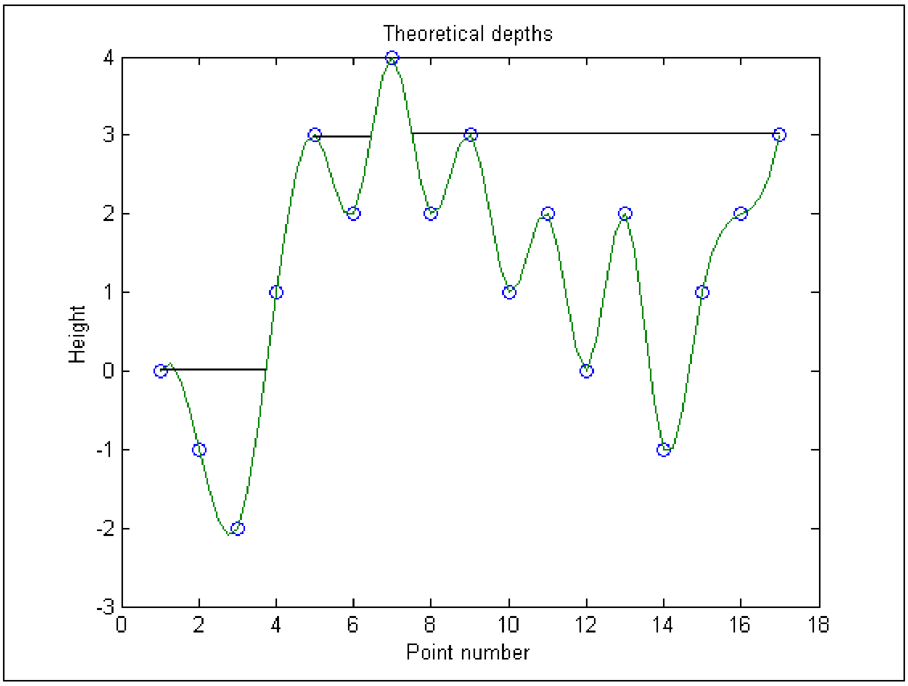


Figure 3.9. A plot of the vector in the example with straight lines corresponding to a possible water surface.

The depth vector contains the largest depth possible at each point, resulting from an infinite amount of water.

To achieve a two-dimensional depth two matrices are at first created using the depth-algorithm. Both contain the theoretical water depths at each point, but one with respect to the width (transverse profiles) and the other with respect to the length of the road (longitudinal profiles). To get the resulting depths the smallest values, comparing the two matrices, are collected in a third matrix. Thereby, this matrix contains the theoretically possible depths. Figure 3.10 shows as an example the possible ponds of a certain road, as seen from above.

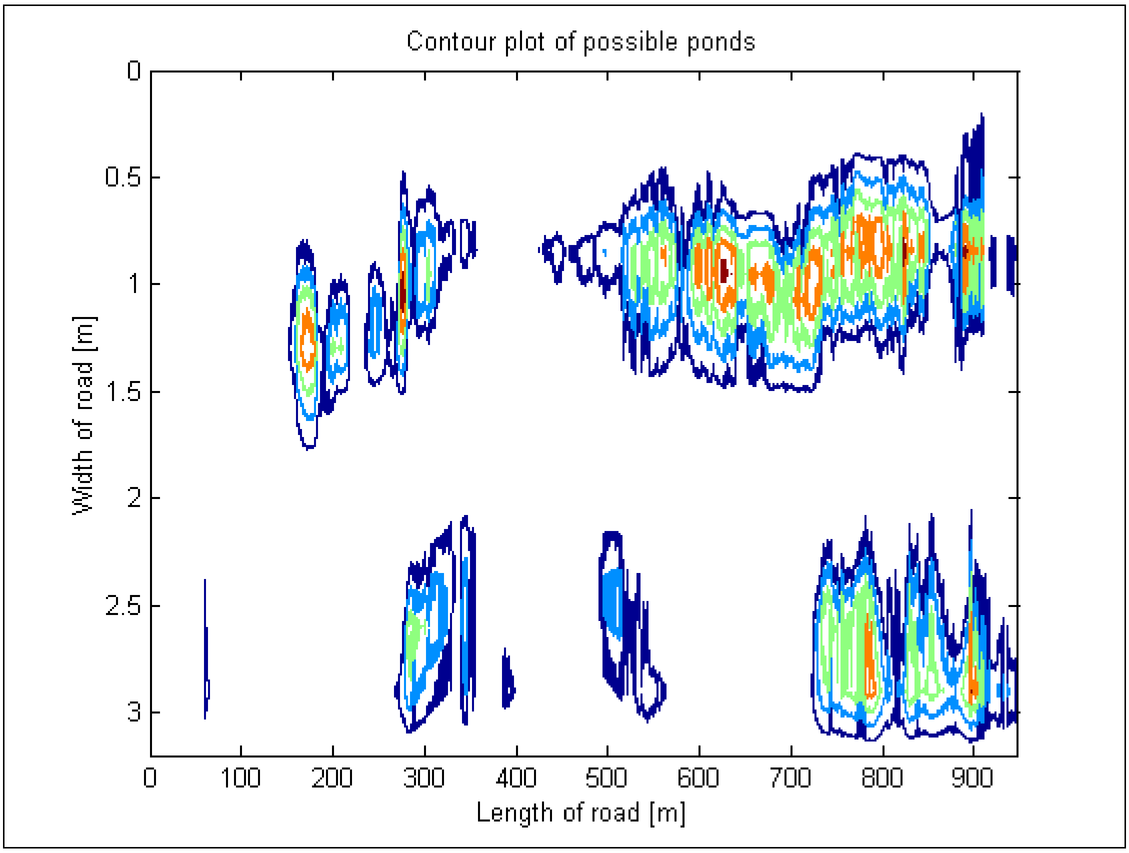


Figure 3.10. A contour plot of the depths of a section of road 63.

A problem connected to treating data in the way previously described is the case where a ditch is directed diagonally along the road. In the ideal case, the water would find its way out at both ends of the ditch and therefore not create a pond. Because the algorithm handles the relationships between the heights in the lane-way direction and across the lane, separately, the free ends are not taken into account and a pond is found. See left hand side of Figure 3.11. A comparable problem is a channel in form of a half-ring, where the water is able to flow out at the openings. A part of the channel will, however, be indicated as containing water. See right hand side of Figure 3.11. Similar problem ponds can be observed, but none of them is here regarded as crucial, because these special cases are highly unlikely to occur.

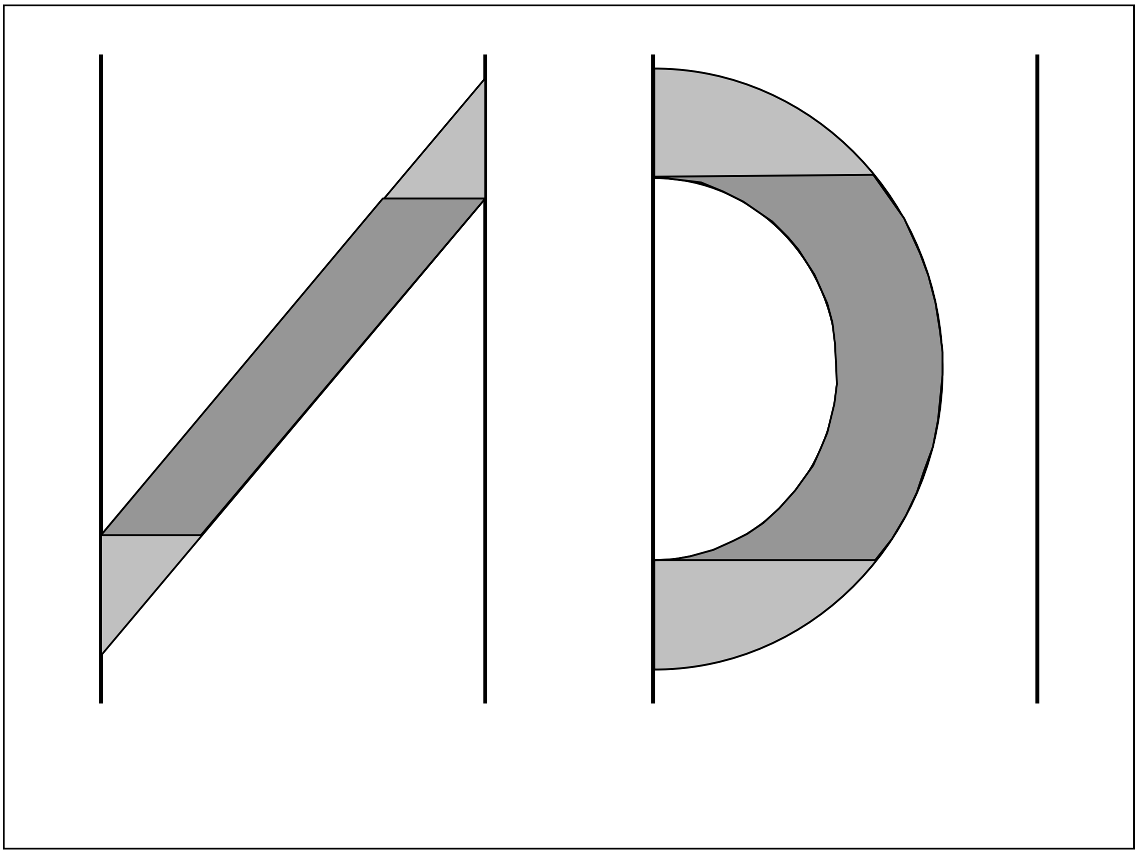


Figure 3.11. Two special cases that are treated as ponds by the depth-algorithm: A diagonal ditch stretching over the entire road lane (left) and a half-ring shaped channel (right). The darker areas in the figures are treated as ponds by the algorithm.

3.4 Combined Model

The resulting algorithm first uses the road model-algorithm on the input data. Then the pond model-algorithm is applied on the data from the road model. After the two-dimensional depths have been computed, only those equal to or exceeding a certain risk depth limit are kept. From these, only depths that together create a continuous length in the longitudinal direction equal to or exceeding a particular risk length limit are maintained. In the implementation made here, risk depth and risk length are factors that can be arbitrarily adjusted. (The default values used are 10 mm pond risk depth and 10 m pond risk length.) The percentage of hazardous parts (i.e. ponds classified as constituting a high risk in Subsection 3.1.3, if nothing else specified) out of the measured road is computed, and the start- and endpoints for possible risk ponds on the distance are shown.

A drawback on the combined model is that it does not handle all directions simultaneously. A pond exceeding the risk length limit, but that for instance is rotated diagonally (see the example in Figure 3.12), is not regarded as being a pond by the algorithm. This is because the longitudinal and transverse road profiles are treated separately, as mentioned above.

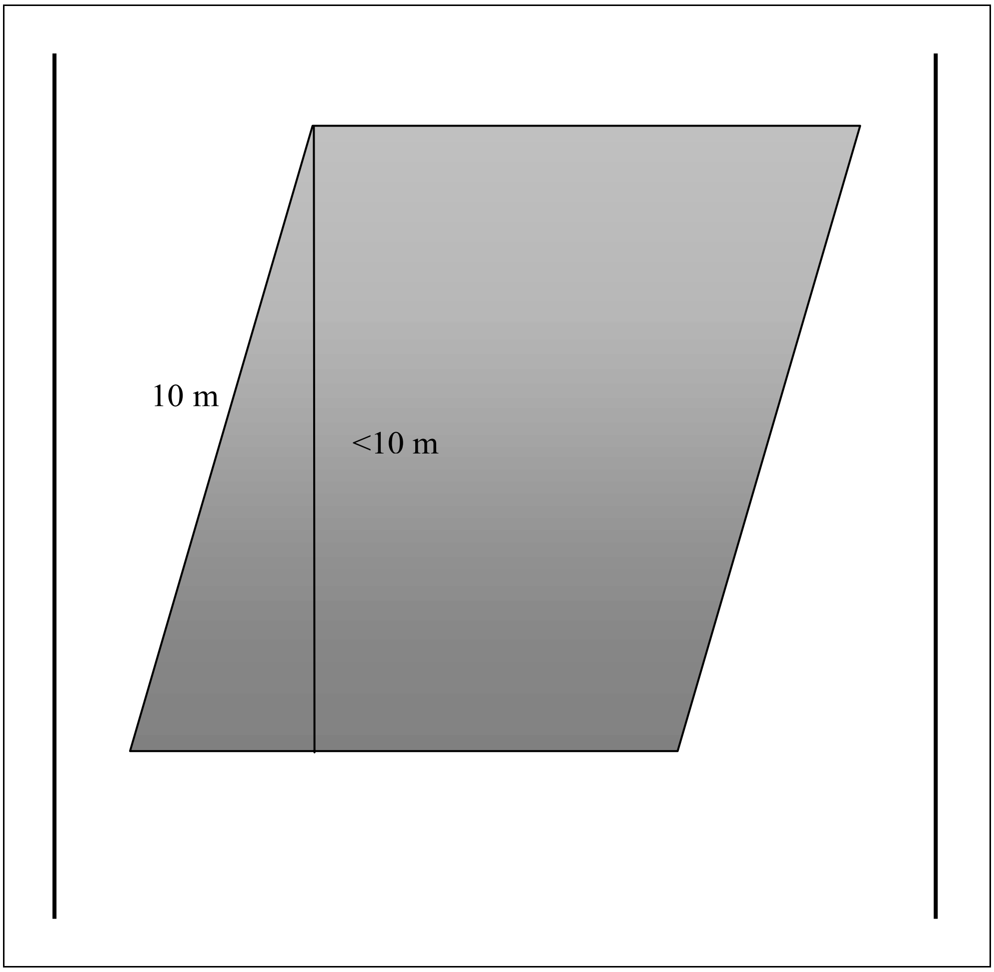


Figure 3.12. The diagonal water accumulation of length 10 m is not detected by the pond model since the length in the longitudinal direction is less than 10 m.

4 Validation

In this chapter, the models are validated. A validation on artificial road surfaces is made for the pond model, followed by a visual validation on real ponds. In Section 4.3 some tests are carried out to see how consistent the models are to change of parameters.

4.1 Validation of the Pond Model on Synthetic Road Profiles

To see if the model works satisfactorily some synthetic road profiles were created and tested. The parameters that were altered in these were rut depth, crossfall and longitudinal profile. In the following the roads are presented together with a contour plot of the resulting water depths, if existing. To begin with, the case of a totally plane road is examined. In the next cases, first rut depth and then slopes at the ends are further added to the road. Subsequently, a plane road with a rectangular shaped hole in the middle is studied, followed by observations of roads with, in order, crossfall only, crossfall and continuous rut depth, crossfall and rut depth holes. Finally a road of container shape and a road with an irregular hole in the middle are scrutinized. It must however be emphasized that the synthetic roads in the examples are extremely improbable in reality. This is a fact, since road surface data in this section is stylistically adjusted in order to illustrate the characteristics of the pond model. To demonstrate certain features of the model, the extension of the road is sometimes chosen very small. All properties are given in metres except for crossfall, which is given in hundredths of percent.

A totally plane road

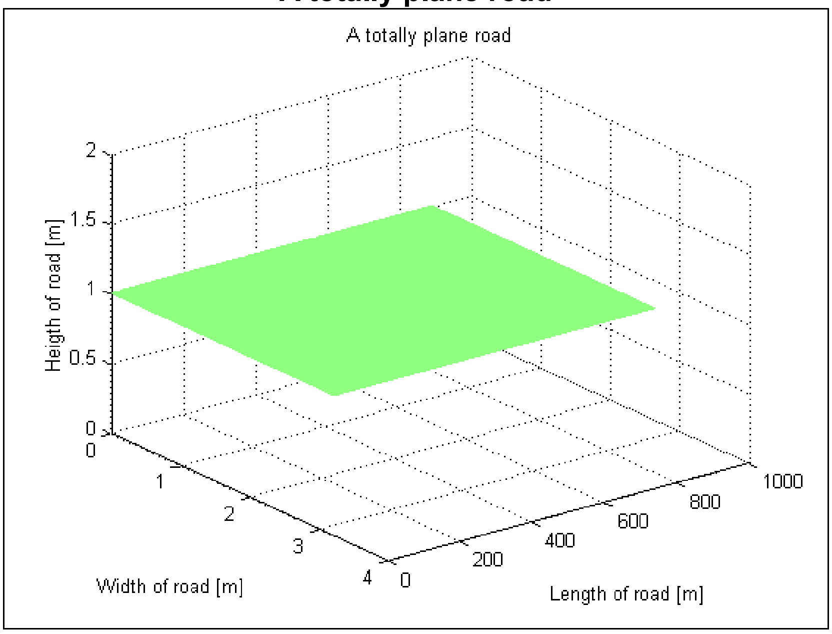


Figure 4.1. Example of a totally plane road with equal heights at 1 m.

The road in Figure 4.1 is totally plane and all water is theoretically supposed to float off it. When applying the algorithm an easy validation shows that no depths are at hand for this road.

A plane profiled road with constant rut depth

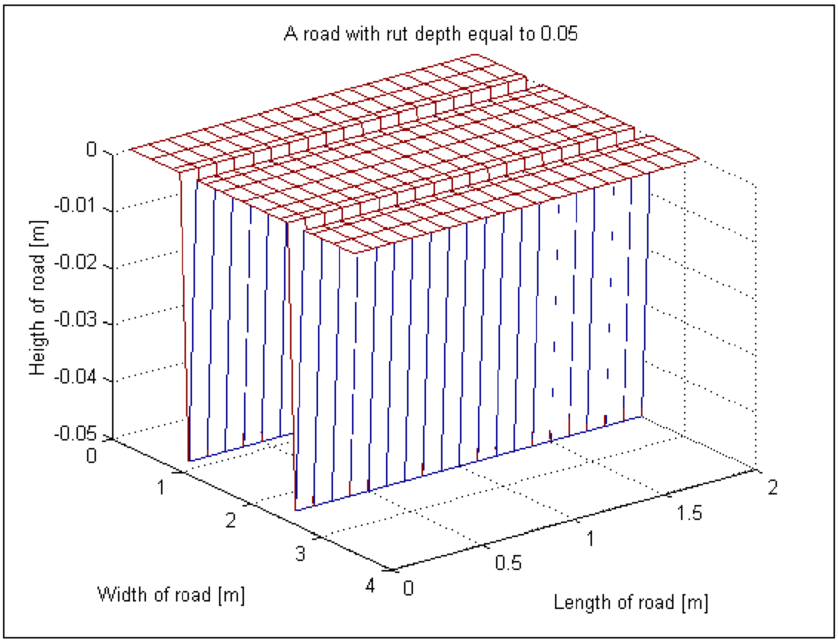


Figure 4.2. Example of a road with crossfall equal to zero and rut depth equal to 0.05 in both ruts.

Also the road in Figure 4.2 results in no water depths, because the water has a way out at both ends of the road.

A road with constant rut depth and slopes at both ends

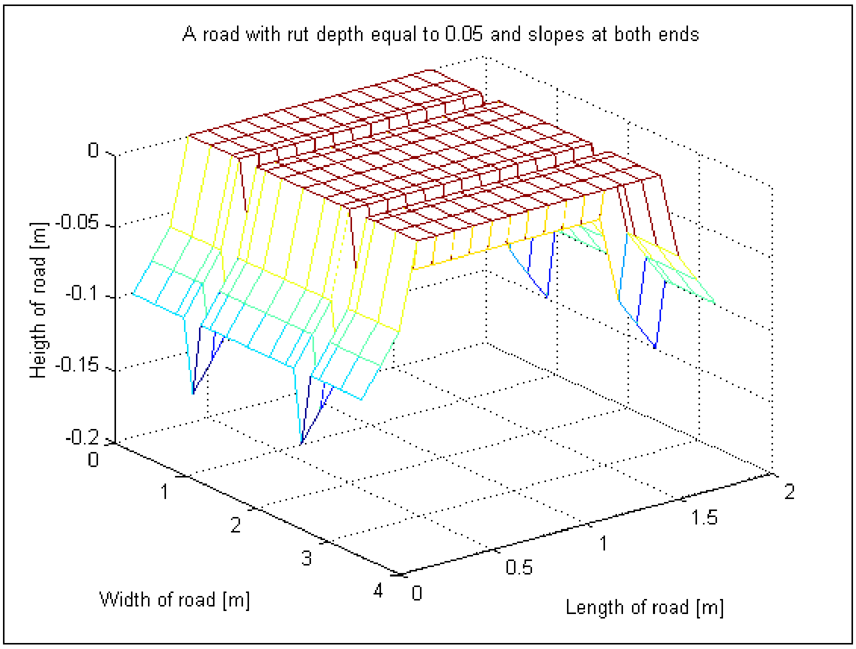


Figure 4.3. Example of a road with rut depth equal to 0.05 and slopes at both ends.

The road in Figure 4.3 cannot hold any water since there is nothing preventing the water from leaving the construction. Accordingly, there are no resulting theoretical water depths.

Plane road with rectangular shaped hole in the middle

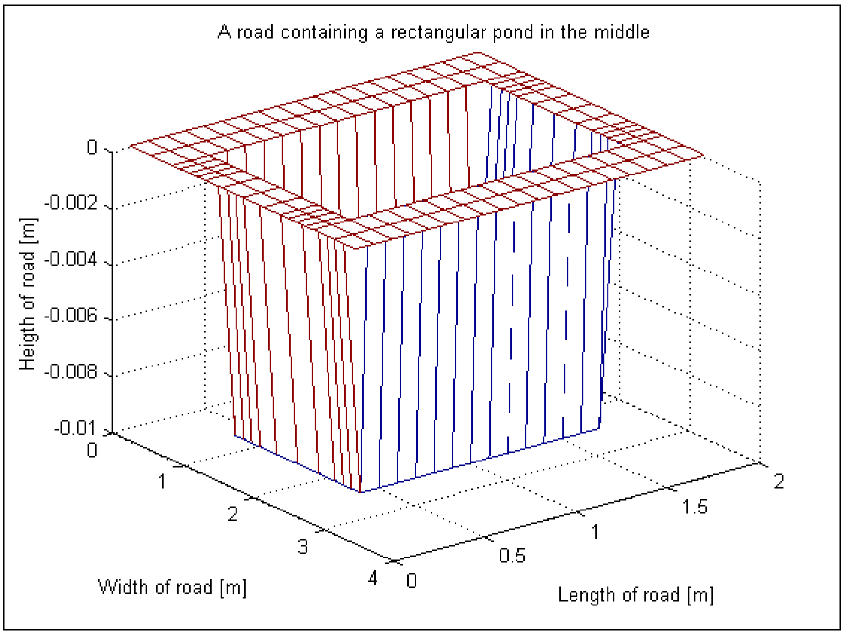


Figure 4.4. Example of a road with crossfall and longitudinal grade equal to zero but with a 1 cm deep hole of rectangular shape in the middle.

Logically, there is no way for water to escape from the rectangular hole in Figure 4.4 and many water depths of the same magnitude are detected. These are shown in the contour plot in Figure 4.5 below. The contour plots in this section seem to have chamfered edges, which is due to interpolating phenomena in MATLAB.

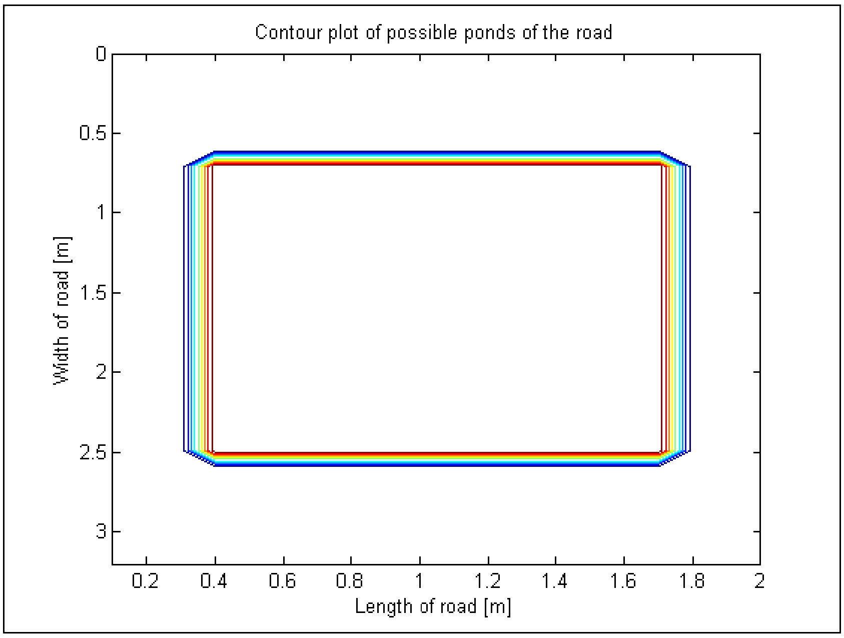


Figure 4.5. The resulting contour plot of the possible depths from the road in Figure 4.4.

Road with crossfall only

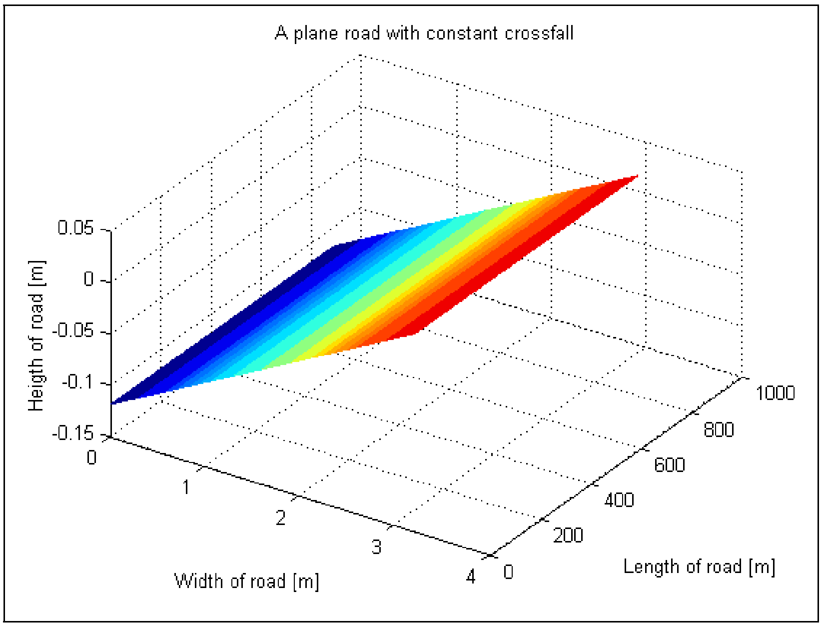


Figure 4.6. Example of a plane road with crossfall equal to 0.05.

This road is not considered to hold any water, as the implementation is made in the programme. Therefore, no water depths are found. In reality one should however keep in mind that Figure 4.6 only reflects one road-way and that the characteristics of the left side of the road could be of great importance for water accumulating.

Road with constant crossfall and rut depth

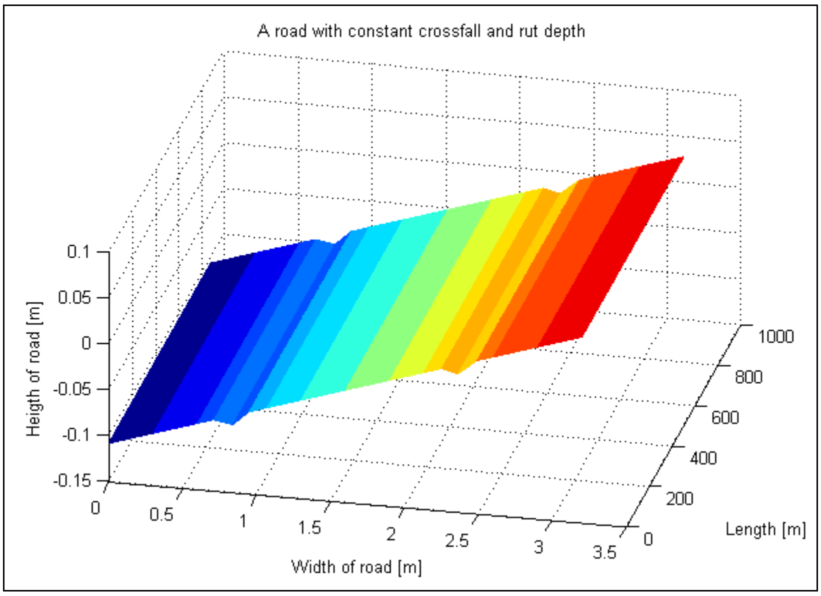


Figure 4.7. Example of a road with crossfall equal to 0.05 and rut depth equal to 0.01.

Since the road in Figure 4.7 has free ends, potential amounts of water can find their way out without difficulty.

Road with constant crossfall and rut depth in the middle

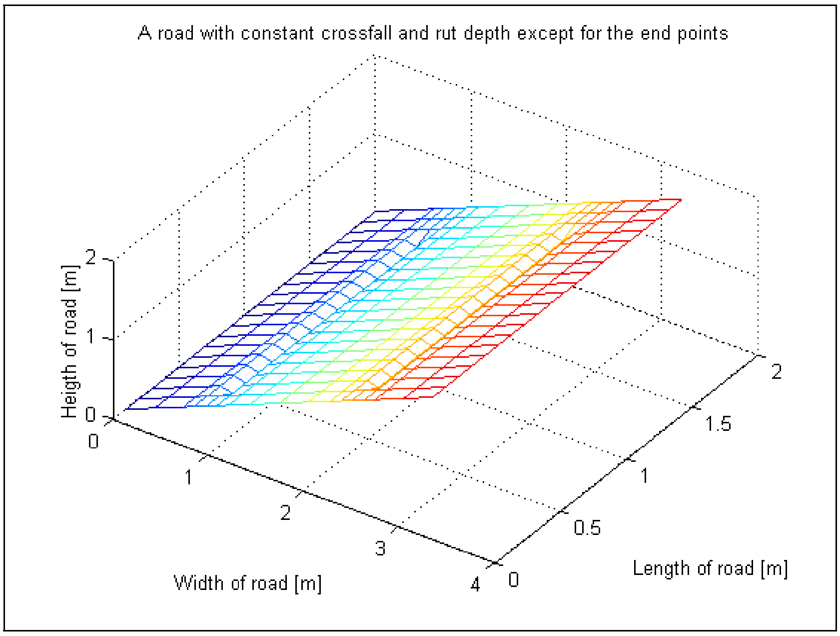


Figure 4.8. Example of a road with rut depths in the middle and constant crossfall.

The road in Figure 4.8 should assemble some water in the ruts, which is shown in the contour plot in Figure 4.9 below.

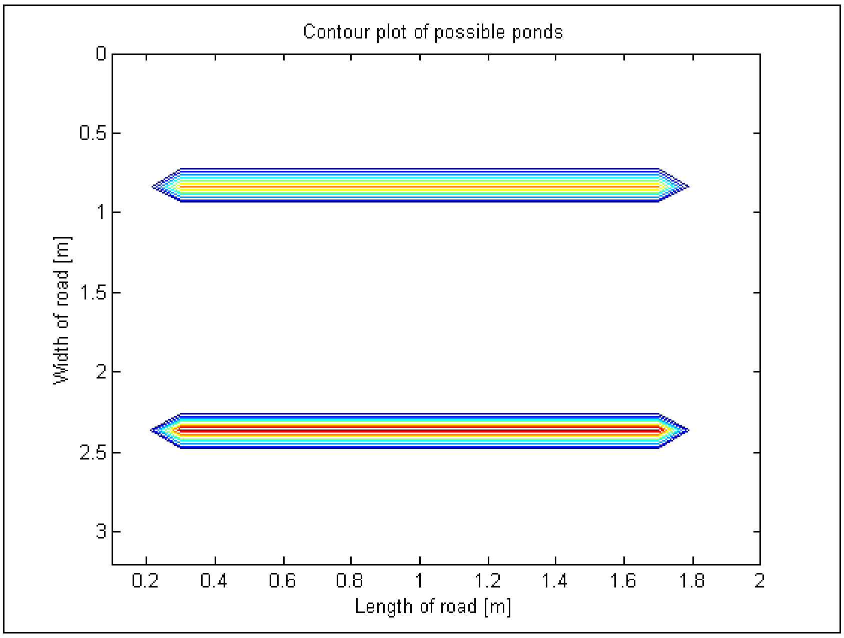


Figure 4.9. The resulting contour plot of the possible depths from the road in Figure 4.8.

Road of container shape

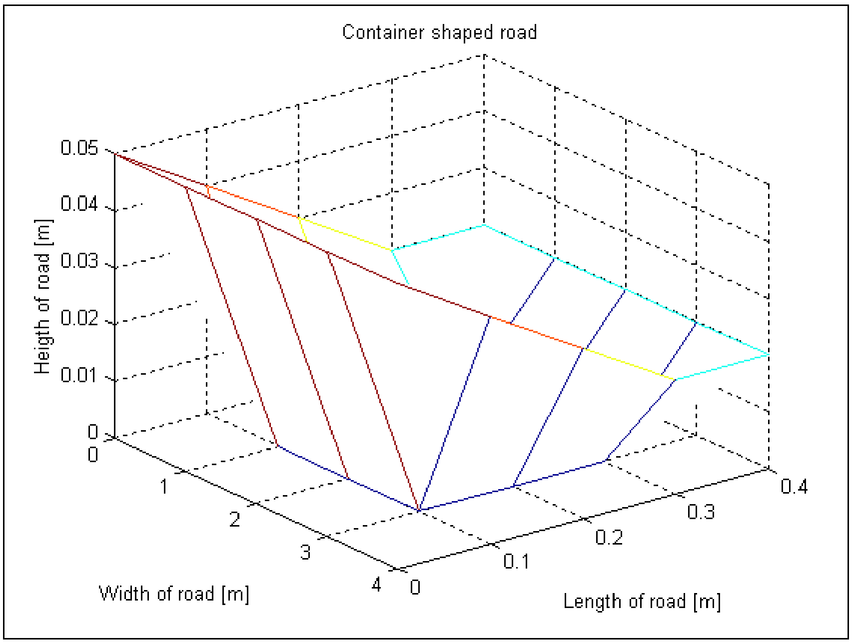


Figure 4.10. Example of a road of container shape.

Figure 4.10 shows a road with altering longitudinal grade and a hole in the middle. The programme calculates the theoretical water depths and shows them according to Figure 4.11. Note that the grid is sparser in Figure 4.10 than in, for example, Figure 4.8. This illustrates that the algorithm can handle smaller amount of lasers than the default number of 17.

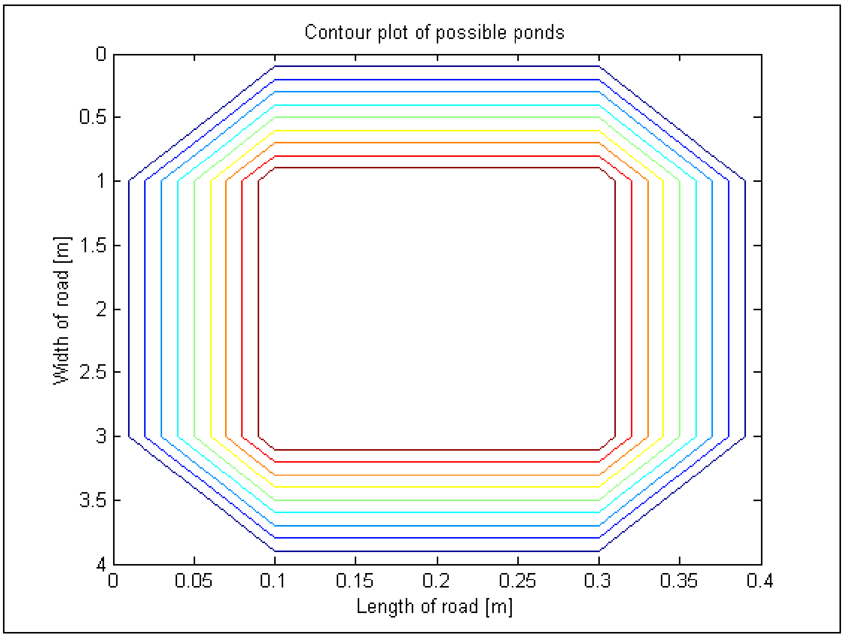


Figure 4.11. The resulting contour plot of the possible depths from the road in Figure 4.10.

Road with irregular hole in the middle

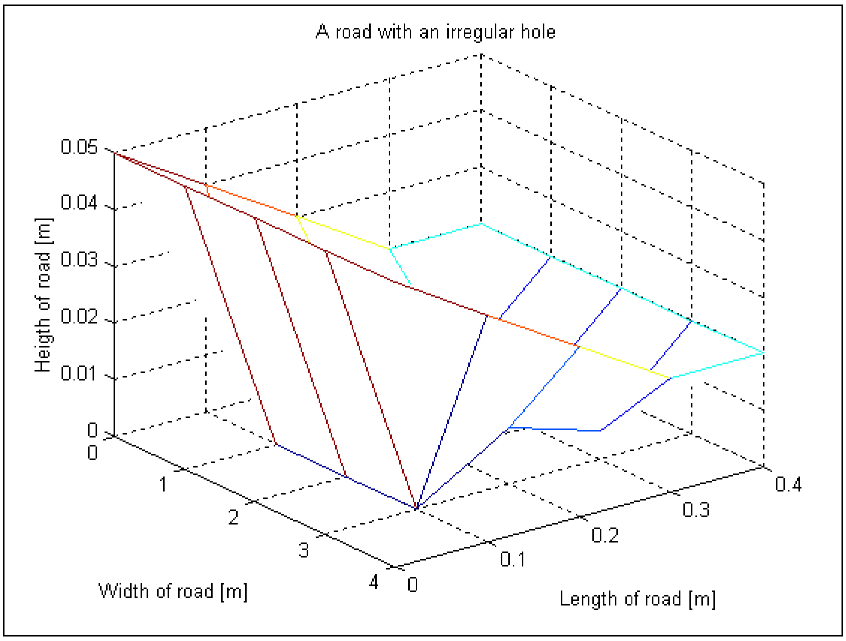


Figure 4.12. Example of a road with an irregular hole in the middle.

The road in Figure 4.12 has an irregular hole shape in the middle and the algorithm should therefore result in different water depths over the road. This can be seen in the contour plot in Figure 4.13.

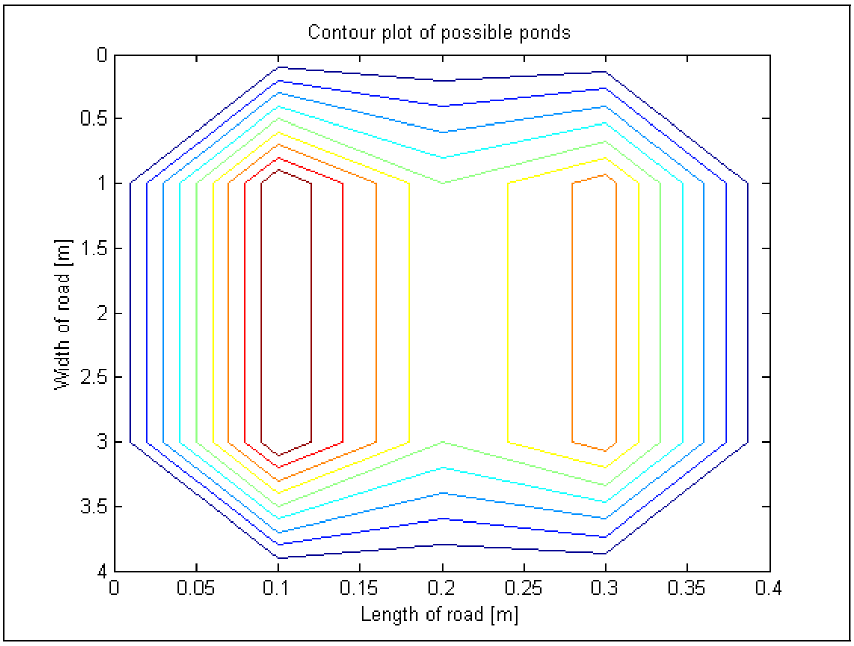


Figure 4.13. The resulting contour plot of the possible depths from the road in Figure 4.12.

4.2 Visual Validation of the Models

With the aid of an attached video camera on the Laser RST in combination with road surface monitoring an attempt to validate the accomplished pond model, based upon the road model, was made. The appropriate weather chosen for filming was during a heavy rainfall, when the ruts could be expected to be filled as much as possible, in accordance with assumptions made when constructing the model.

There is an uncertainty about how the lasers react in wet weather, i.e. at which surface the beams are reflected; at the water surface or the interesting road surface. As a consequence, data was collected twice: first when filming in rainy weather and then at a later time when the road was dry. The dry weather data was used for creating the models and the filmed road sections were then compared with the graphical output from the programme.

Except for the aforementioned parameters that are not included in the data, there are other things contributing to the unreliability of the validation. Among these is the fact that the person conducting the data collection (the author of this thesis) was not trained for it. Therefore, the road sections were possibly not correctly handled which could lead to incorrectness when searching for correspondence between authentic road features and the ones for the modelled road.

When watching the filmed road and comparing it to the contour plots of the possible ponds from the programme, some conclusions could be drawn. Because the contour plots could not be arbitrarily well linked to the filmed sequences, the visual validation could however not be more than roughly made. Nevertheless, it was seen that the water accumulations on the authentic road were extended more than calculated in the pond model. A major discovery was that water in slopes does not find its way down the hill immediately, but is remaining on the road, at least for as long as the rainfall continues. This implies that flow theory would be useful when developing the model.

Comparing sections of 1000 m road data with the filmed parts, the correspondence was regarded as reasonable. It seems that when the left part of the road is filled with water to a wider extent than the right part, this is also the case in the model. However, many long extended water accumulations were missed by the programme. One presumable reason is that they were situated at slopes and therefore considered to flow down the road. Another possibility is that due to the heavy rainfall the ruts in the road were filled with water at the same rate as it was flowing down the slope. The result from this would therefore be a continuous accumulation of water.

At the last part of the filming, the camera lens was partly covered with rain drops so the quality of the tape was somewhat decreased. Due to the human factor, the observations made could of course not be said to be correct, but the modelled possible ponds and the filmed ones would however seem to correspond relatively well.

4.3 Robustness of the Models

To see if the models could be trusted concerning how they will work on different road parts and when changing certain parameters, some test runs were carried out, see Appendix A. They contain different road sections from roads in Mälardalen. The test runs show that, in general, the pond model is more time-consuming than the road model. Another major characteristic is that the longer a road section is, the more time is needed to create the models. The relation between length and time is not linear, though.

When changing the risk depth parameter to a larger value than the default, the percentage of risk ponds was clearly reduced. An additional increase of the risk length totally eliminated the risk ponds of the particular road part in the example.

For testing if the results would be constant even when using other types of filters, a change of the filtering of the longitudinal profiles was also carried out. The filter normally used is a third order Butterworth high pass filter. Replacing it with a third order Chebyshew-filter of type I yielded significantly the same result. A third order Chebyshew-filter of type II instead found more risk ponds, but still in about the same distance. Finally changing the Butterworth-filter to a high pass filter of second order produced substantially the same results as the third order.

5 Discussion and Conclusions

This chapter discusses the advantages and disadvantages of the models, conclusions from this master's thesis and suggestions about future work.

5.1 Model Discussion

For long road sections the calculations in the programme, especially in the pond model, are slow. It must be emphasized that the models are created in a laboratory environment and that the focus is set on completing a working model and not on execution speed at this point.

How well the road model works in reality must be proven with extensive reference measurements, which would be a too large subject to include in this master's thesis. On one hand, the model ought to be quite good because it considers parameters collected from the roads on a basis of 17 points on a 3.2 m width and the longitudinal profiles are determined for each decimetre. On the other hand, the mean transverse profile and crossfall are taken as an average value over a length of 20 m. The width is not the real width of the road lane, but the one measured with the survey vehicle. Additionally, the longitudinal profiles are high pass filtered and the left profile is afterwards adjusted in relation to the right in accordance with the mean transverse profile and crossfall. The system would otherwise be over-determined.

There is a need for an initializing distance in order to settle the filter used. Every road section between crossings (links) is treated separately, which means that this distance will have to be eliminated for each section. This implies that the reliability for short road sections is low.

The pond model, on the other hand, seems to work satisfactorily considering the validation with artificial inputs from the road model. Hazardous areas are being correctly detected on the synthetic roads. Visual validation with the aid of a video camera showed that the programme was not able to detect all ponds on the road, a fact that might be due to insufficient data from the road model.

A major advantage of using MATLAB is that the code is generally considered easy to understand intuitively. Testing different kinds of parameters is thus made quite simply.

Summing up, the pond model seems to work well assuming that the data from the road model is correct. There are, however, some special cases that are treated incorrectly. (See Figure 3.11.) These are not very interesting for the purposes of this work, though. The flexibility of determining the limits for depth and length of risk ponds increases the value of the programme. Considering that only areas where a major risk could occur should be detected, the fact that the programme does not discover every pond might not be very significant.

5.2 Conclusions

Two models have been created from road surface data as it is being collected today. Supplementary research is however desirable for further improvement.

The road model is adaptable to a larger number of lasers and smaller intervals for the longitudinal profiles. Many parameters have however been omitted and should, if required, be included when developing the model. Combining hilliness with longitudinal profiles may, for instance, lead to a better description of the road. A drawback is that the model is based on filtered longitudinal profiles, where the filtering may change the characteristics.

The limit values for depth and length in the pond model may be arbitrarily adjusted. A weakness is though, that only the *longitudinal* length is considered. If the pond would be diagonally placed on the road, then the pond model would not be able to detect it, unless it also stretches at least 10 m in the longitudinal direction. (See Figure 3.12.)

When a more continuous transverse profile is being collected, the width might also be an important parameter to examine. The pond model seems to work properly, considering the validation on synthetic road profiles. This assumption is reasonably realistic, since the roads in this validation were stylistically adjusted in order to show how the pond model would respond to certain characteristics of the road.

The final summary of the development of the work can be contained in a simple flow chart, see Figure 5.1 below. The left part of the chart shows in some major steps how the work has been accomplished, whereas the right part includes some alternative areas of use for the road model, and some possible fields of application for the pond model.

The dashed box contains some possible alternative fields of application for the road model. It could be developed to be used for discovering unevenness in a three-dimensional model of the road, as well as for searching areas where precipitation will be remaining on a road after snow clearance. The output from the model could also be used as a road geometry data supplier for road simulators.

When detection of risk ponds is a fact, the local road maintenance keepers could use this information to take action and prevent possible accidents. The pond model could also be used for gaining an overview over the performance of the pavement management systems. Another possibility is that the pond model could form the basis for a future measure of hazardous road sections. Exactly how it could be constructed is however something that must be investigated.

5.3 Future Improvement

Further research on the aquaplaning phenomenon is needed to fully examine the problem. Most references listed in this report have their basis on experiments in a fixed environment or under not road-like conditions. Their aim has often been to compare certain types of tyres with respect to tyre tread depth, width or pattern design. The experiments have been performed at different speeds and on different grounds, but not on actual roads. Therefore, no greater confidence in the results obtained should prevail until more thorough tests have been carried out on real roads. Work that needs to be done in the future is relating actual water film thickness on the road surface and the extent of a hazardous water accumulation with the potential of aquaplaning.

As stated in Section 1.8 there are different ways of approaching the problem of aquaplaning on roads. By validating ponds against authentic aquaplaning accidents, a valid risk water depth could be found. A prerequisite for this is a more scrutinized average adjustment where measurements are being performed at every water-related road accident. A more detailed localization and a qualified classification of accident cause would be desirable.

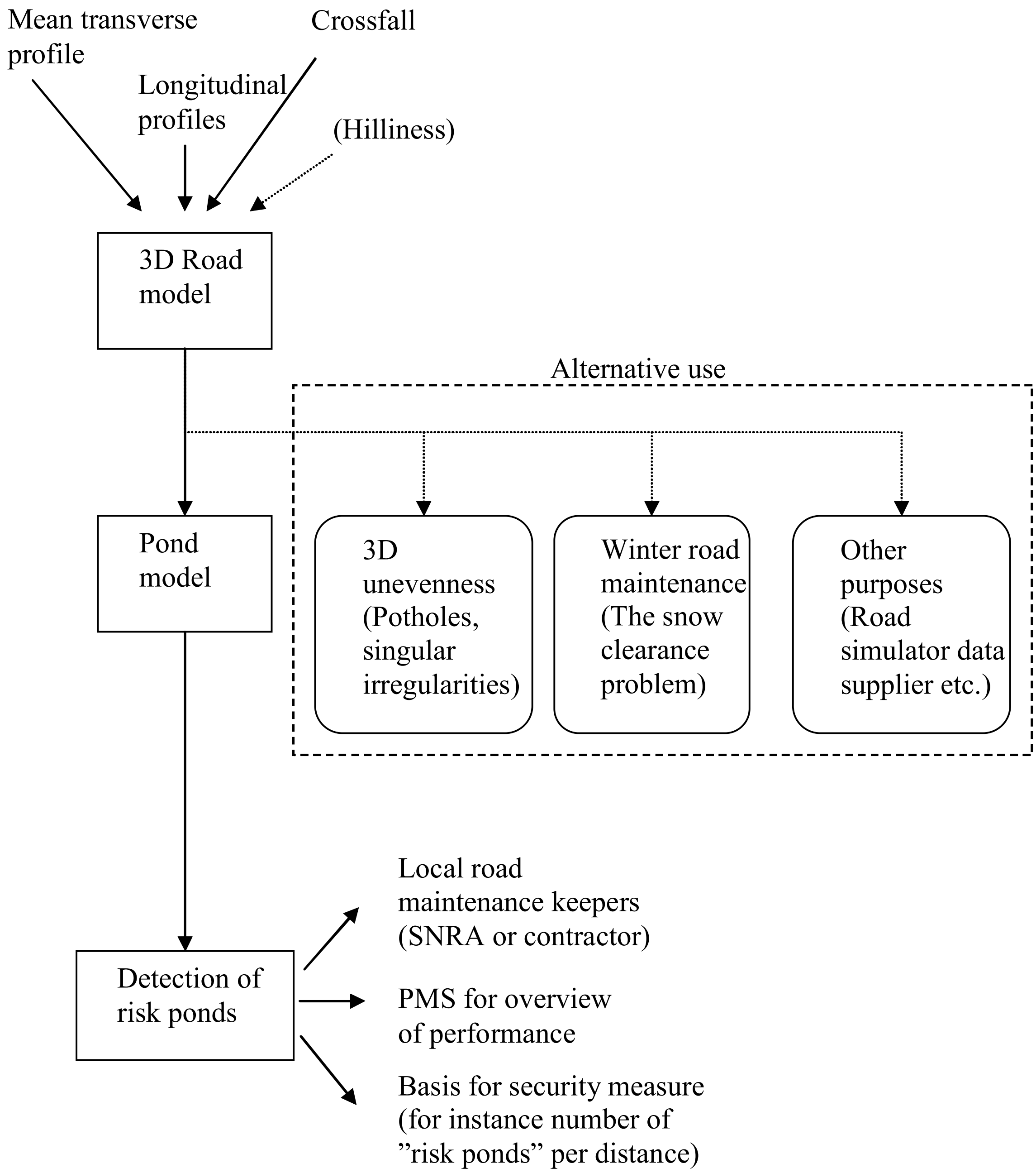


Figure 5.1. Flow chart showing the main steps in the progress of the work, some alternative fields of application for the road model, and for whom and what purposes the pond model may be of interest.

A recommendation when developing the model further is to examine the longitudinal profiles more carefully. It might be better to use only one of the profiles instead of both of them, as implemented today. This has not been investigated in this master's thesis but would be of interest to study. Another thought is that relating the left and right longitudinal profile could be done in some different way than done here.

Higher demands on the measurement method would also be advantageous. Intuitively, if the sampled data were averaged over smaller intervals than the prevailing 20 m sections, the correspondence between the models and the actual road would improve. Collecting data at a higher rate should also contribute to a more road-like model. An essentially continuous transverse or longitudinal profile would of course be of enormous use, but would on the other hand be very hard and memory consuming to accomplish. An increased number of measurement points in the laser beam could however improve data collection.

Below some suggestions for improving measurements and use are made:

- Denser collection of lateral road surface data (for instance by using 39 lasers)
- Denser collection of transverse profiles and crossfall (collecting all data for each decimetre would be desirable)
- Easier access of data from the PMS by keeping relevant data on the same place (to make this programme work in the production)
- Spreading the programme tool to the SNRA regions for local planning and use on “problem roads”

The models in this master’s thesis were created using MATLAB version 6.1. In order to enable a high performance with faster computations another programming language could be useful. Porting the code to for instance the programming language C++ could be a way to achieve a shorter execution time. This could also improve the possibilities for handling the data directly after collection.

6 References

[1] Alm, Lars-Olof (1995), *Bedömning av risk för vattenplaning med hjälp av LRST-data – redovisning av litteraturstudie.* Internal investigation ordered by Vägverket, unpublished report.

[2] Anderson, Per-Anders (1988), "Swedish Experience of Drained Asphalt Concrete 1975-1985" in *Pre-Conference Proceedings 3rd IRF Middle East Regional Meeting: Towards Better Road Performance.* Riyadh, Saudi Arabia.

[3] Arnberg, Peter W. (1985), *The Laser Road Surface Tester (RST).* VTI särtryck 102. Klintland Grafiska, Linköping. ISSN 0347-6049.

[4] Arnberg, Peter W., Burke, Michael W., Magnusson, Georg, Oberholtzer, Roger, Råhs, Knut & Sjögren, Leif (1991), *The Laser RST: Current Status.* Linköping: Statens väg- och transportforskningsinstitut (VTI).

[5] Balmer, G. G. & Gallaway, B. M. (1983), "Pavement Design and Controls for Minimizing Automotive Hydroplaning and Increasing Traction" in *Frictional Interaction of Tire and Pavement*, ASTM STP 793, Meyer, W. E. & Walter, J. D., Eds., American Society for Testing and Materials, pp. 167-190.

[6] Black, George W. Jr. & Jackson, Lawrence E. (2000), "Pavement Surface Water Phenomena and Traffic Safety" in *ITE Journal. 2002/02.* Institute of Transportation Engineers, Washington, D.C., pp. 32-37. ISSN 0162-8178.

[7] Domenichini, Lorenzo & La Torre, Francesca (1996), "Relationship Between Friction, Surface Characteristics and Rain Intensities to Evaluate Roadway Safety" in *International Forum on Road Safety Research.* VTI konferens, No. 5A:2, pp. 147-161. Statens väg- och transportforskningsinstitut, Linköping.

[8] Donald, Gavin S., Heaton, Brian S. & Francis, Chris L. (1996), *Potential for Hydroplaning on High Speed Roads.* International Symposium on Pavement Surface Characteristics. ARRB Transport Research LTD, Victoria, Australia.

[9] *Facts about the Swedish National Road Administration, Roads and Traffic* (2002). Publication 2002:55E. Vägverket. ISSN 1401-9612.

[10] *FAS Asfaltbok* (1995). Föreningen för Asfaltbeläggningar i Sverige. Stockholm. ISBN 91-971916-2-0.

[11] Gallaway, B. M., Ivey, D. L., Hayes, D., Ledbetter, W. B., Olson, R. M., Woods, D. L. & Schiller, R. F. Jr. (1979), *Pavement and Geometric Design Criteria for Minimizing Hydroplaning*. Texas Transportation Institute. Report No. FHWA-RD-79-31.

[12] Gengenbach, Werner (1967), *Das Verhalten von Kraftfahrzeugreifen auf Trockener und Insbesondere Nasser Fahrbahn – Experimentelle Untersuchungen auf Prüfstand und Straße.* Fakultät für Maschinenbau und Verfahrenstechnik der Universität Karlsruhe, Karlsruhe, Germany.

[13] Glennon, John C. (2003), *Hydroplaning – The Trouble With Highway Cross Slope.* http://www.johncglennon.com/papers.cfm?PaperID=8 (Acc. 2003-02-23).

[14] Gnadler, Rolf, Unrau, Hans-Joachim, Fischlein, Hartmut & Frey, Michael (1996), "Teil IV – Ermittlung von Reifenkennlinien für veränderliche Wasserfilmdicken" in *Wasserabfluss von unebenen Fahrbahnoberflächen*, Forschung Strassenbau und Strassenverkehrstechnik, pp. 271-354. Bundesministerium für Verkehr, Bonn. ISDN 0228-7 66 91 23.

[15] Gothié, Michel, Parry, Tony & Roe, Peter (2001), "The relative influence of the parameters affecting road surface friction" in *Friction Potential and Safety: Prediction of Handling Behaviour*, pp. 27-48, International Colloquium on Vehicle-Tyre-Road Interaction. VERT, Florence.

[16] Hayes, G. G., Ivey, D. L. & Gallaway, B. M. (1983), "Hydroplaning, Hydrodynamic Drag, and Vehicle Stability" in *Frictional Interaction of Tire and Pavement*, ASTM STP 793, W. E. Meyer & J. D. Walter, Eds., American Society for Testing and Materials, pp. 151-166.

[17] Heubner, Richard Scott, Anderson, David A., Warner, John C. & Reed, Joseph R. (1997), "PAVDRN – Computer Model for Predicting Water Film Thickness and Potential for Hydroplaning on New and Reconditioned Pavements" in *Transportation Research Record No. 1599: Roadside Safety Features and Other General Design Issues*, Transportation Research Board, National Research Council, Washington, D.C., pp. 128-131. ISSN 0361-1981. ISBN 0-309-06170-9.

[18] Heubner, Richard Scott, Anderson, David A. & Warner, John C. (1999), *Proposed Design Guidelines for Reducing Hydroplaning on New and Rehabilitated Pavements.* NCHRP Research Results Digest. Transportation Research Board, Washington, DC.

[19] Heubner, R. Scott, Reed, Joseph R. & Henry, John J. (1986), "Criteria for Predicting Hydroplaning Potential" in *Journal of Transportation Engineering*, ASCE, Vol. 112, No. 5, pp. 549-553. ISSN 0733-947X.

[20] Hight, P. V., Fugger, T. F., Marcosky, J. & Varat, M. (1994), "Asymmetric Water Drag on Vehicle Trajectory and Human" in *Safety and the Automobile. Selected Papers from Autotech '93, 16-19 November 1993.* Mechanical Engineering Publications, Suffolk, United Kingdom, pp. 71-80.

[21] Hofer, Dieter (1989), "Entscheidungshilfe zur Beurteilung kritischer Bereiche der Strassenoberflächenentwässerung" in *Strasse und Autobahn. 1989:1.* Kirschbaum Verlag, Bonn, pp. 65-75.

[22] Ihs, Anita, Velin, Hans & Wiklund, Mats (2002), *Vägytans inverkan på trafiksäkerheten. Data från 1992-1998.* VTI meddelande 909-2002. Statens väg- och transportforskningsinstitut, Linköping. ISSN 0347-6049.

[23] Joelsson, Christian & Nilsson, Tomas (1998), *Vatten på väg* Master's Thesis 25 1998, Examensarbete Lunds Tekniska Högskola.
ISRN LUTVDG/TVVB/EX-5025/--SE/1998/86.

[24] Khan, A. M., Bacchus, A. & Holtz, N. M. (1994), "Multilane Highway Design Crossfall and Drainage Issues" in *Transportation Research Record No. 1471: Recent Research on Hydraulics and Hydrology*, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C., pp. 1-9. ISSN 0361-1981. ISBN 0-309-06104-0.

[25] Lamberti, Renato (1995), "Safety Problems Related to Runoff of Rainwater on Road Paving" in *Road Safety in Europe and Strategic Highway Research Program (SHRP).* VTI konferens, No. 2A:4, pp. 137-150.

[26] Lang, Johan, Vägverket, Personal Communications (January 2003).

[27] Lewis, Andrew E., Chase, Steven B. & Lee, K. Wayne (1994), "Correlation of Pavement Surface Texture to Hydraulic Roughness" in *Transportation Research Record No. 1471: Recent Research on Hydraulics and Hydrology*, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C., pp. 10-17. ISSN 0361-1981. ISBN 0-309-06104-0.

[28] Lundberg, Thomas, Statens väg- och transportforskningsinstitut, Personal Communications (May 2003).

[29] Mounce, John M. & Bartoskewitz, Richard T. (1993), "Hydroplaning and Roadway Tort Liability" in *Transportation Research Record No. 1401: Highway and Traffic Safety and Accident Research, Management and Issues*, Transportation Research Board, National Research Council, Washington, D.C., pp. 117-124. ISSN 0361-1981. ISBN 0-309-05474-5.

[30] Nationalföreningen för Trafiksäkerhetens Främjande, *NTF Konsument – Däck.* http://www.ntf.se/konsument/default.asp?RecID=10105 (Acc. 2003-04-10).

[31] Nilsson, A. & Ohlsson, E. (1970), *Vattenplaningsförsök 1967-1969. Undersökningar rörande möjlig bromsverkan för bilhjul på vägbanor med vattenskikt av olika tjocklek.* Stockholm. Statens Väginstitut. Specialrapport 85.

[32] Nordström, O. & Lucas, J. (1971), *PIARC Technical Committee on Slipperiness Prague Report 1971 Chapter 3 - Effect of the Thickness of the Water Film on Skid Resistance.* Särtryck.

[33] Nordström, Olle & Åström, Henrik (2000), *Däckbreddens betydelse för vattenplaningsrisk.* VTI PM 2002-08-28, unpublished material.

[34] Ohlsson, Evert (1979), *Friktionsmätning på rullbanor och vägar.* VTI rapport Nr 177. Statens väg- och trafikinstitut, Linköping. ISSN 0347-6030.

[35] Palmkvist, Göran & Magnusson, Georg (1990), *Validering av längsprofilmätare ingående i mätfordonet Laser RST.* VTI notat TF 53-04. Statens väg- och trafikinstitut, Linköping.

[36] Ridha, Raouf A. (1989), "Wet Performance and Aquaplaning of Tires" in *Proceedings of the International Symposium: Road Development and Safety.* Institut National De Recherche Routiere, Luxembourg, pp. 196-215.

[37] Sjögren, Leif, Lundberg, Thomas & Andrén, Peter (2002), *Nya mått; ett underlag för en utvecklingsstrategi inom området vägytemätningar.* VTI notat 23-2002. Statens väg- och transportforskningsinstitut, Linköping.

[38] Sjögren, Leif (2002), *Road surface measuring in Sweden 2002.* Statens väg- och transportforskningsinstitut, Linköping. Publication 2000:65E.

[39] Sjögren, Leif, Statens väg- och transportforskningsinstitut, Personal Communications (January-September 2003).

[40] *Skid Resistance* (1972), Highway Research Board, Washington, D.C. ISBN 0-309-02024-7.

[41] Start, Marc R., Kim, Jeong & Berg, William D. (1996), "Development of Safety-Based Guidelines for Treatment of Pavement Rutting" in *Proceedings of the Conference Road Safety in Europe and Strategic Highway Research Program (SHRP).* VTI konferens, No. 4A:5, pp. 79-98.

[42] Transportation Research Board (1998), NCHRP Web Doc 16, *Improved Surface Drainage of Pavements: Final Report*. National Academy Press. http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+1-29 (Acc. 2003-02-24).

[43] Tromp, Jan (1989), "Ruts and Waves in the Road Surface" in *Proceedings of the International Symposium: Road Development and Safety.* Institut National De Recherche Routiere, Luxembourg, pp. 124-132.

[44] Vägverket (2000), *Allmän teknisk beskrivning för vägkonstruktion.* VV Publ. 2000:111 ATB Väg, Section A4. ISSN 1401-9612. Vägverket, Borlänge.

[45] Vägverket, *Frågor och svar – Däck: Vilket mönsterdjup ska däcken ha?* http://www.vv.se/faq/fordon/dack/monster.htm (Acc. 2003-04-10).

[46] Vägverket (1994), *Mätning av tvärfall med mätbil.* (VV MB 109:1994) http://www.vv.se/publ_blank/bokhylla/ATB/atb_vag/Publikationer/MB109/frfootno.htm (Acc. 2003-04-22).

[47] Vägverket (2002), *Vägteknik Uppdrag.* http://www.vv.se/publ_blank/bokhylla/ATB/atb_vag/Vagteknik-uppdrag.htm (Acc. 2003-06-25).

[48] Wågberg, Lars-Göran (2001), *I valet & kvalet – Handbok för val av beläggningsåtgärd.* Svenska Kommunförbundet, Stockholm. ISBN 91-7289-009-6.

[49] Wågberg, Lars-Göran, Statens väg- och transportforskningsinstitut, Personal Communications (April 2003).

Appendices

A Programme Examples

The ponding programme works on variables in a workspace defined by the user. To execute properly, the variables in the workspace must be named and ordered according to the following:

The variables `profL` and `profR` should contain the longitudinal profiles for each decimetre in the left and right wheel track, respectively.

A matrix called `Roaddata` must be created in the workspace. Column number 5 of it should contain the crossfall in percent, according to the surface line method, for every 20 m section of the road. The columns numbered 7 to 21 should contain the mean transverse profiles for every 20 m section of the road for laser points number 1 to 15 (numbered from left to right in the direction of travelling, starting with 0 for a total of 17 lasers), respectively. See Table A.1.

Table A.1. Specification of the columns of the matrix `Roaddata`. The columns marked with an "x" may have arbitrary content since they are not used by the programme.

Column number																				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
x	x	x	x	Crossfall in percent, according to the surface line method	x	Mean transverse profile for laser point number 1	Mean transverse profile for laser point number 2	Mean transverse profile for laser point number 3	Mean transverse profile for laser point number 4	Mean transverse profile for laser point number 5	Mean transverse profile for laser point number 6	Mean transverse profile for laser point number 7	Mean transverse profile for laser point number 8	Mean transverse profile for laser point number 9	Mean transverse profile for laser point number 10	Mean transverse profile for laser point number 11	Mean transverse profile for laser point number 12	Mean transverse profile for laser point number 13	Mean transverse profile for laser point number 14	Mean transverse profile for laser point number 15

After having defined and saved a workspace, the programme `ponding` should be easy to use. There are three possible output parameters and three possible input parameters. As a user, you can choose how many of the outputs you are interested in, but will always be shown the graphs from the models.

Basically, the programme is run by executing the following line in MATLAB:

```
>>[percent, startpoint, endpoint] = ponding(workspacename, riskdepth,...
risklength);
```

The possible input parameters are:

`workspacename`: the name of the workspace, within quotation marks (must always be specified)

`riskdepth`: the smallest value for the desired pond depth in metres (optional, default value 0.01)

`risklength`: the smallest value for the desired longitudinal pond length in metres (optional, default value 10)

The possible output parameters are:

`percent`: the percentage of the current road section that is considered hazardous by the programme

`startpoint`: if there are any risk ponds this parameter shows at which distance in metres a dangerous road section starts

`endpoint`: if there are any risk ponds this parameter shows at which distance in metres a dangerous road section ends

The following pages in this appendix show some examples of how to use the programme.

Road part 41160:

In this example, the outputs of a function call using only the name of the workspace (here ws41160) are shown. Figure A.1 show the road part in three dimensions, followed by contour plots of the road part; as seen from above (Figure A.2), showing all possible ponds (Figure A.3), showing the possible risk depth ponds (Figure A.4) and finally showing the risk depth ponds (Figure A.5).

```
>> [percent,startpoint,endpoint]=ponding('ws41160')

The road model needed about 2 min and 48 sec calculation time
The pond model needed about 6 min and 38 sec calculation time

    Startpoints: [3031 8895]
      Endpoints: [3045 8907]

0.0180 percent of a total road section length of 11876 m was
considered hazardous.

percent =

    0.0180


startpoint =

        3031         8895


endpoint =

        3045         8907

>>
```

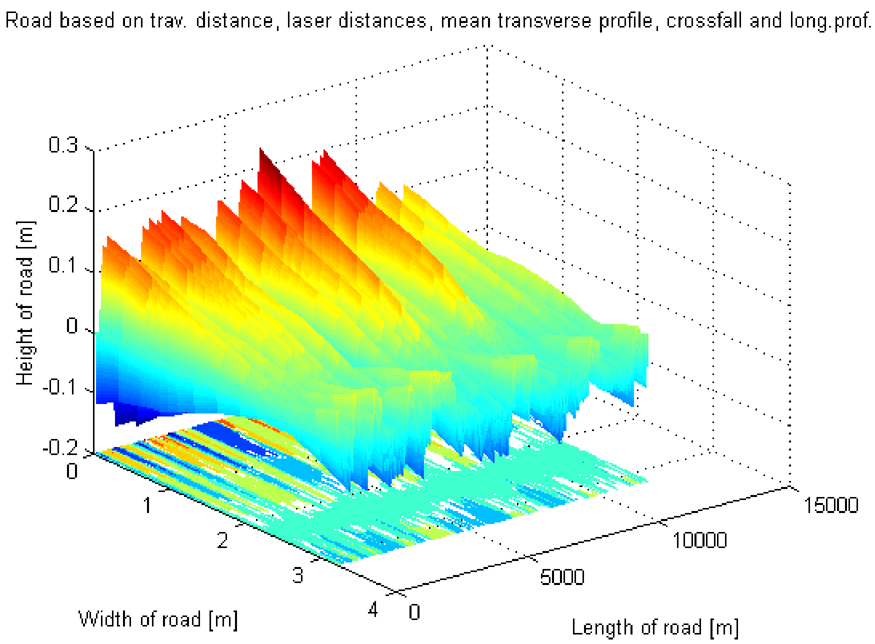


Figure A.1. Three-dimensional model of the road part 41160.

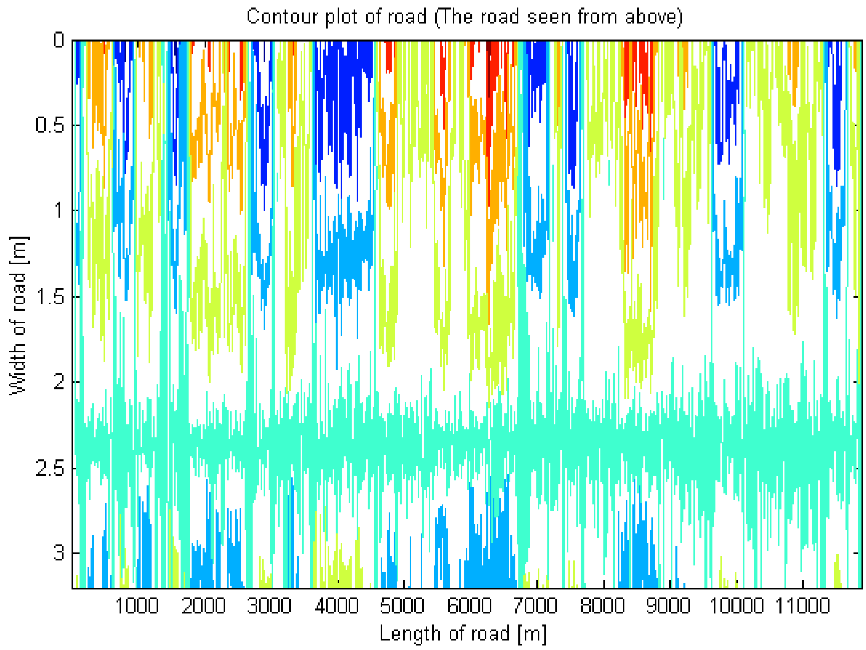


Figure A.2. Contour plot of the road part 41160.

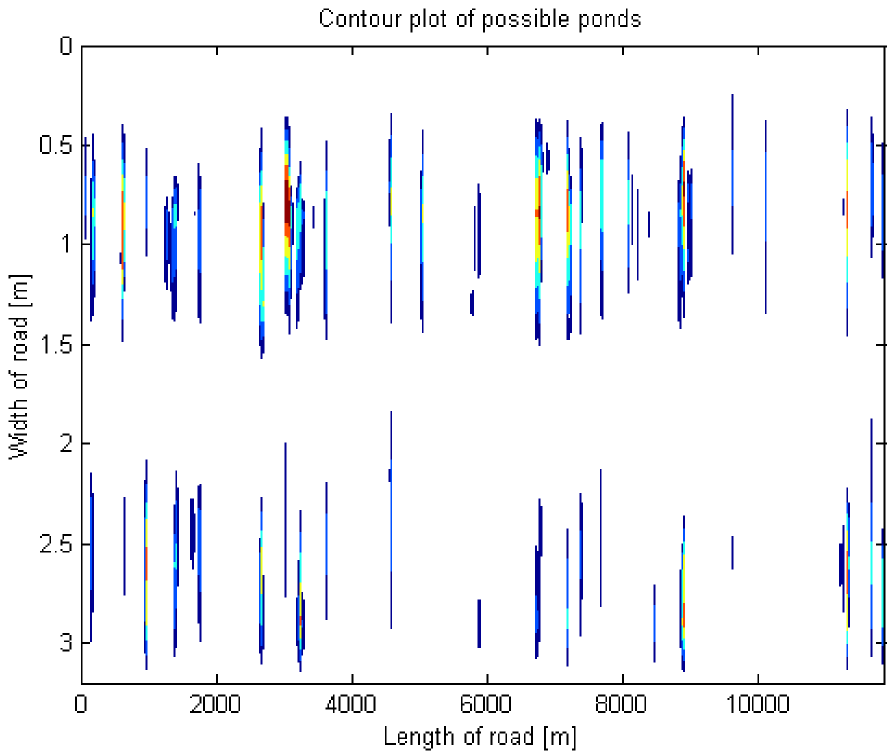


Figure A.3. Contour plot of possible ponds of the road part 41160.

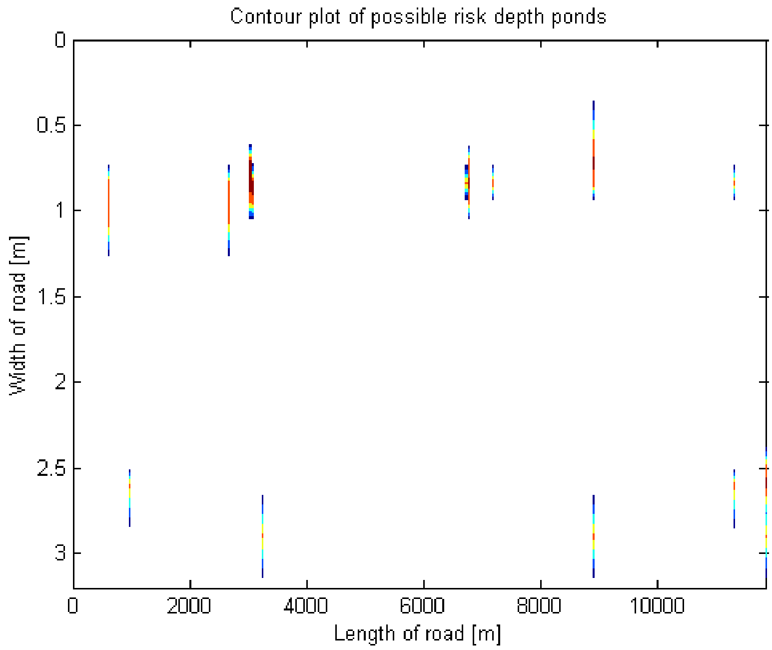


Figure A.4. Contour plot of the ponds of the road part 41160 exceeding the (default) risk depth limit.

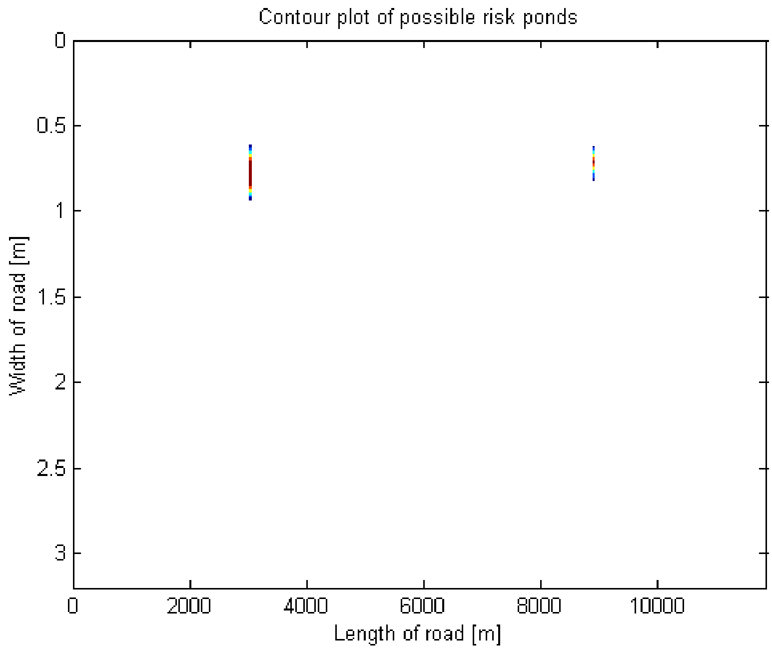


Figure A.5. Contour plot of the ponds of the road part 41160 exceeding the limits of both risk depth and risk length. Because the limits are not specified by the user, the default risk depth and length are used, i.e. 10 mm and 10 m, respectively.

Road part 41149:

The following example shows a case where no risk ponds are found. Figure A.6-Figure A.9 treats the road part 41149 in the same way as Figure A.1-Figure A.4 treats the road part 41160 in the previous example. As seen from the percent value (`percent = 0` below) not any of the possible ponds are exceeding the default risk limits. Actually, no possible pond exceeds the risk depth limit of 10 mm (see Figure A.9).

```
>> [percent,startpoint,endpoint]=ponding('ws41149')

The road model needed about 0 min and 16 sec calculation time
The pond model needed about 0 min and 18 sec calculation time

0 percent of a total road section length of 1330.2 m was
considered hazardous.


percent =

     0


startpoint =

   Empty matrix: 0-by-1


endpoint =

   Empty matrix: 0-by-1

>>
```

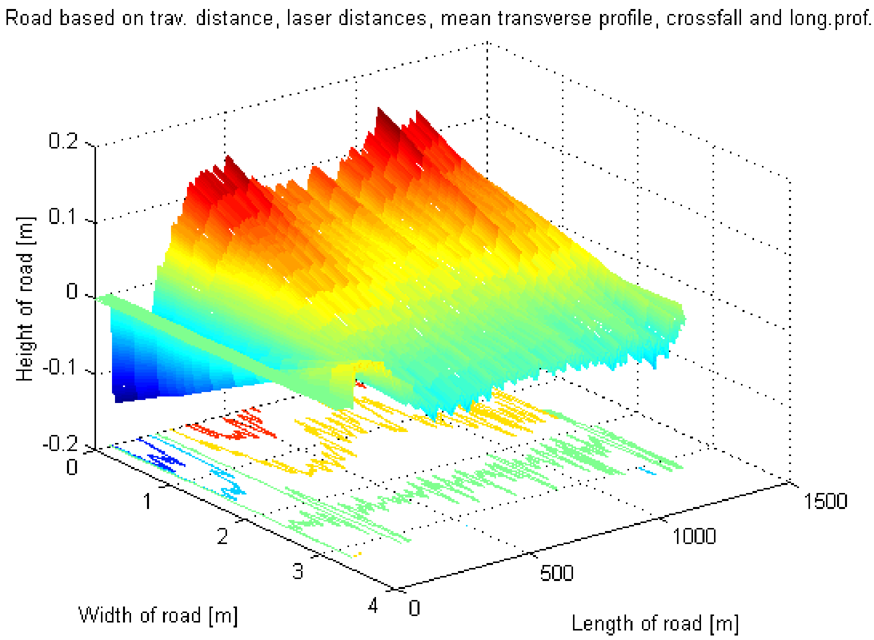


Figure A.6. Three-dimensional model of the road part 41149.

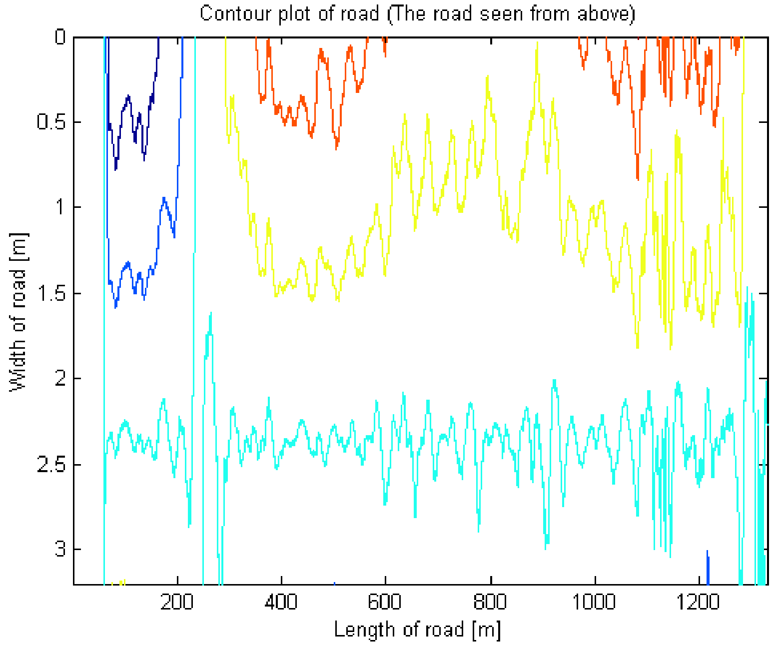


Figure A.7. Contour plot of the road part 41149.

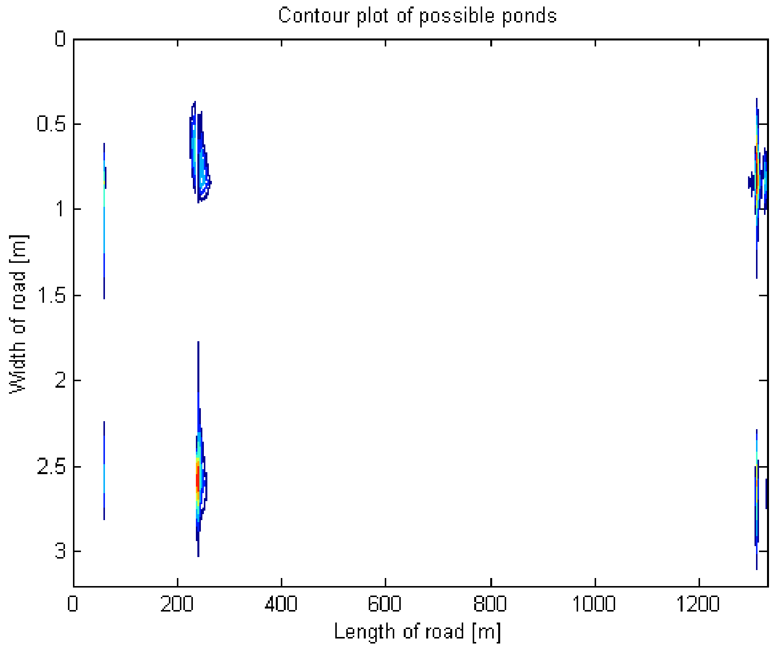


Figure A.8. Contour plot of possible ponds of the road part 41149.

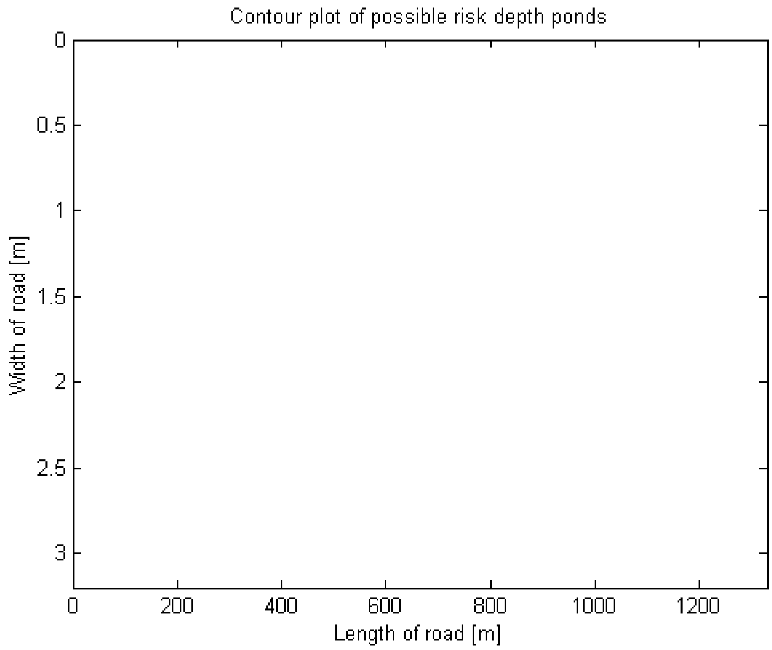


Figure A.9. Contour plot of the ponds of the road part 41149 exceeding the (default) risk depth limit.

Road part 40854:

The road part 40854 is in the following dealt with in different ways. At first, the programme is run on the road part using the default values for risk ponds (10 mm depth and 10 m length). See Figure A.10-Figure A.14. Thereafter a risk depth of 20 mm and a risk length of 20 m are specified. Figure A.15-Figure A.17 show contour plots of possible ponds, possible risk depth ponds, and possible risk ponds, according to these specifications, respectively. Next, only the risk depth (20 mm) is stated and the default risk length of 10 m is again used. See Figure A.18-Figure A.20. The last examples show how robust the model is. First the butterworth-filter is changed to a chebyshew-filter of type I and type II, respectively, and then the order of the butterworth-filter is changed.

Running the programme with default values yields:

```
[percent,startpoint,endpoint]=ponding('ws40854')

The road model needed about 0 min and 3 sec calculation time
The pond model needed about 0 min and 9 sec calculation time

2.8771 percent of a total road section length of 459.2 m was
considered hazardous.

    Startpoints: 329
      Endpoints: 398


percent =

    2.8771


startpoint =

   329


endpoint =

   398

>>
```

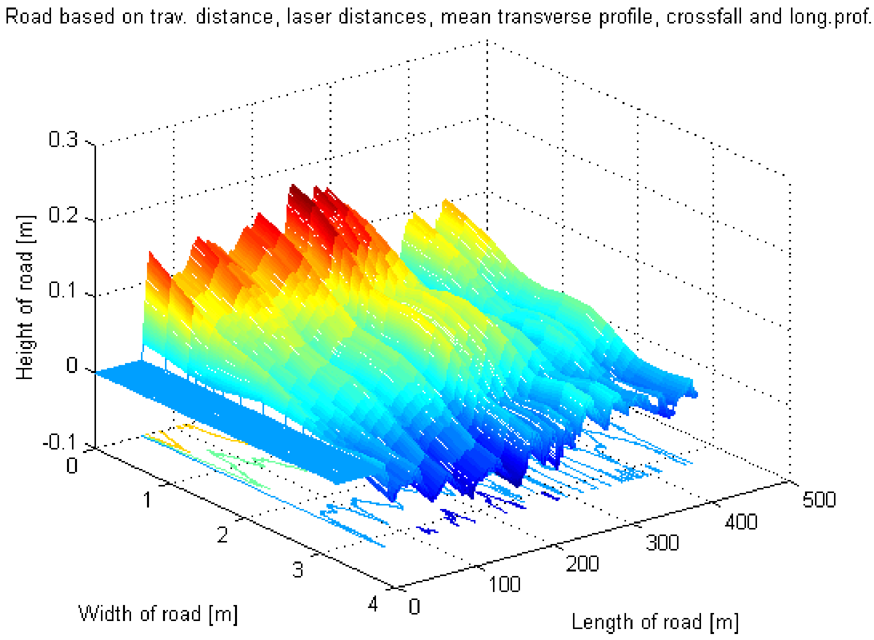


Figure A.10. Three-dimensional model of the road part 40854.

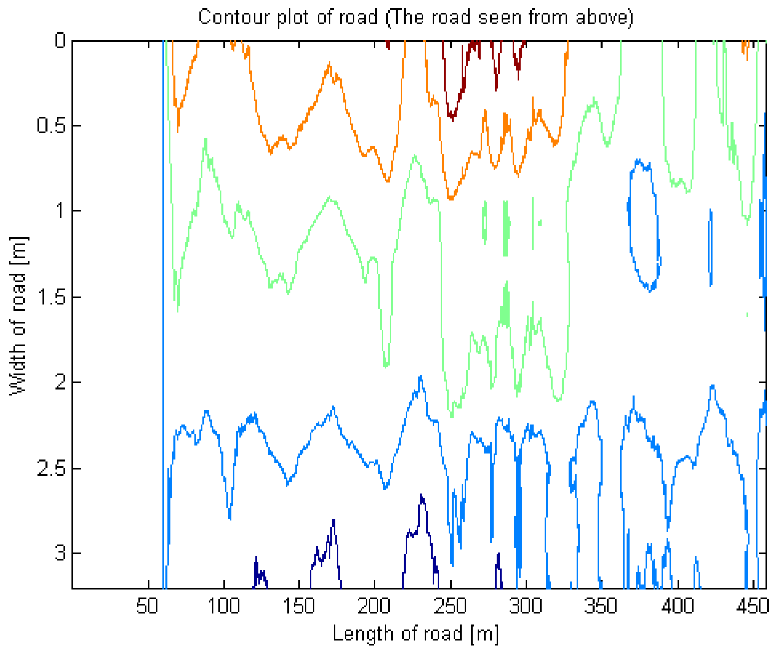


Figure A.11. Contour plot of the road part 40854.

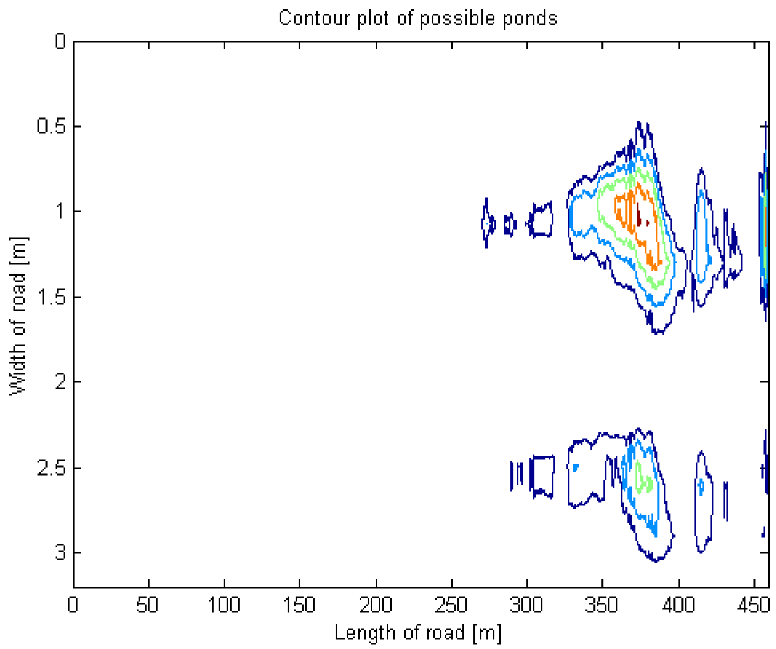


Figure A.12. Contour plot of possible ponds of the road part 40854.

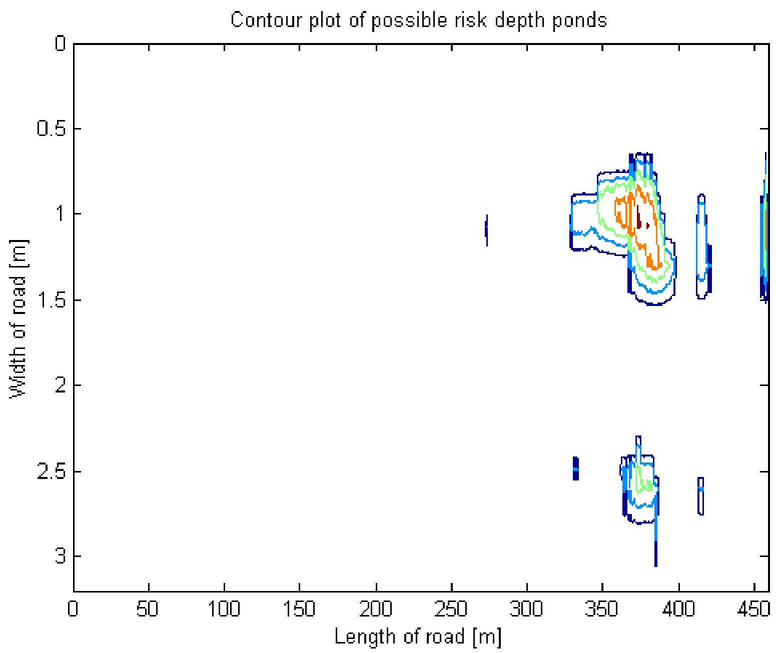


Figure A.13. Contour plot of the ponds of the road part 40854 exceeding the (default) risk depth limit.

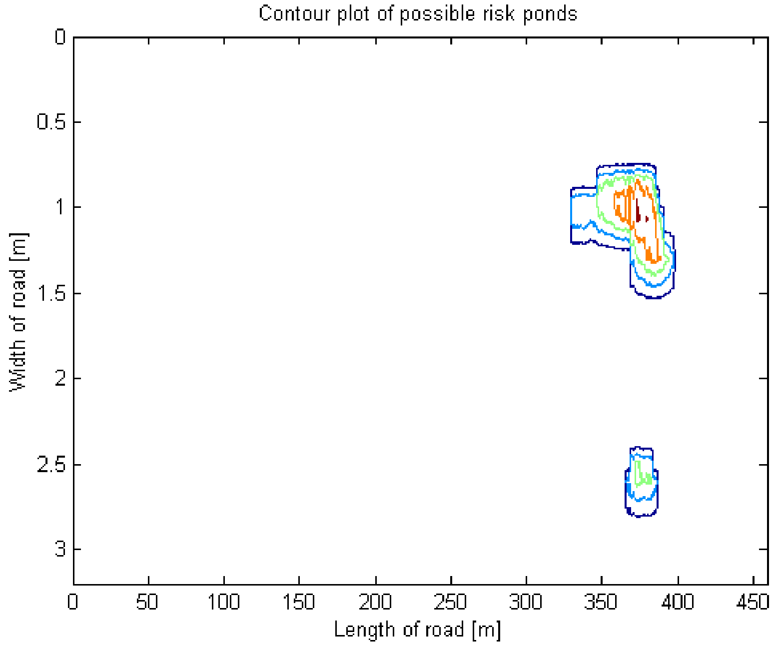


Figure A.14. Contour plot of the ponds of the road part 40854 exceeding the limits of both risk depth and risk length. Because the limits are not specified by the user, the default risk depth and length are used, i.e. 10 mm and 10 m, respectively.

The function call below specifies a risk depth of 20 mm (written as 0.02) and a risk length of 20 m for a risk pond.

```
>> [percent,startpoint,endpoint]=ponding('ws40854',0.02,20);

The road model needed about 0 min and 3 sec calculation time
The pond model needed about 0 min and 9 sec calculation time

0 percent of a total road section length of 459.2 m was
considered hazardous.

>>
```

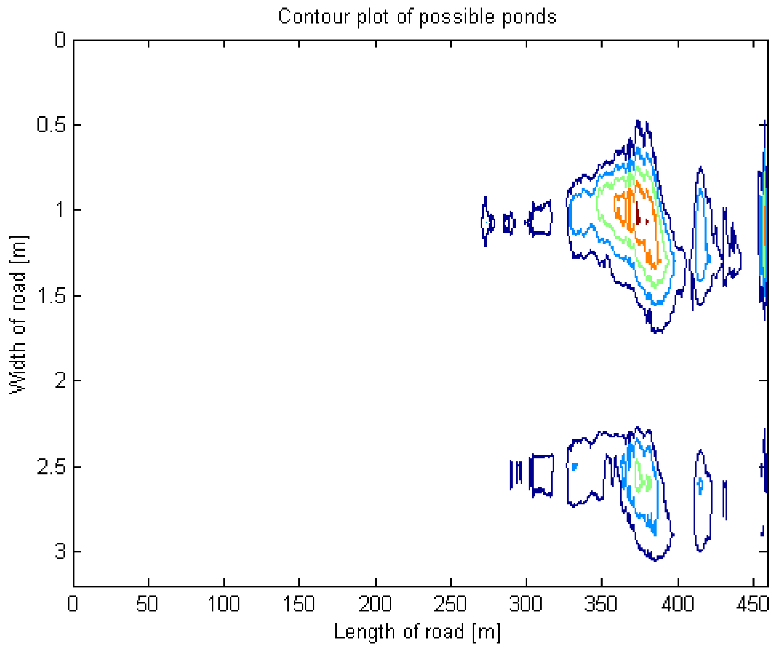


Figure A.15. Contour plot of possible ponds of the road part 40854.

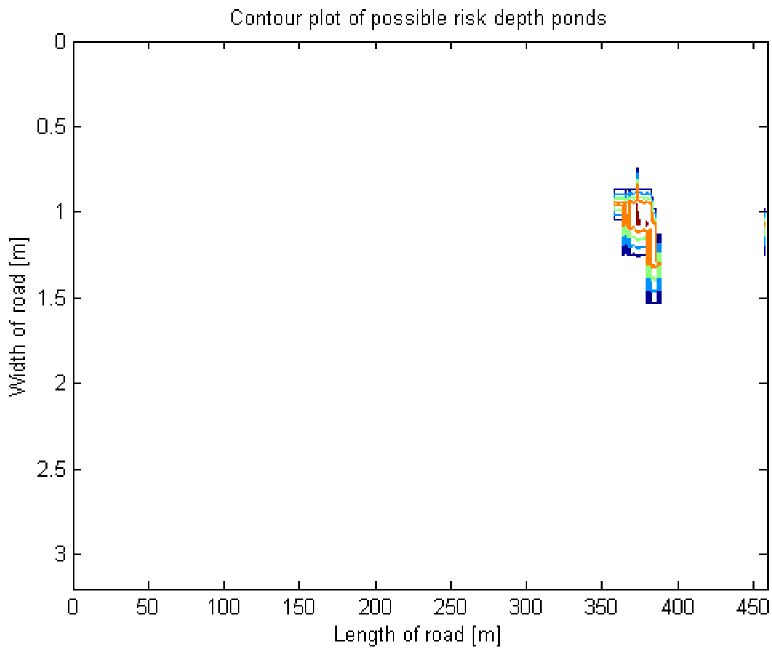


Figure A.16. Contour plot of the ponds of the road part 40854 exceeding the risk depth limit, here specified to 20 mm.

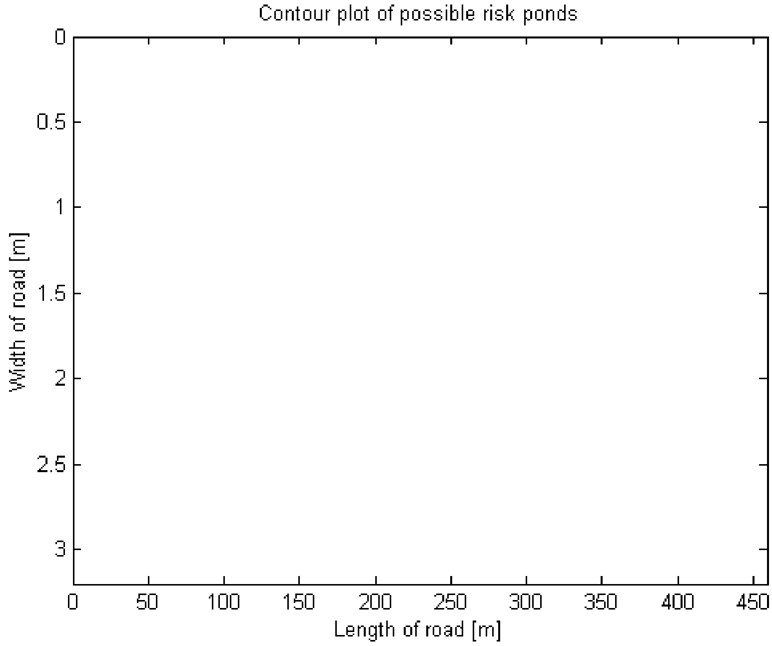


Figure A.17. Contour plot of the ponds of the road part 40854 exceeding the limits of both risk depth (here 20 mm) and risk length (here 20 m).

Specifying only the risk depth (20 mm) yields:

```
[percent,startpoint,endpoint]=ponding('ws40854',0.02);

The road model needed about 0 min and 3 sec calculation time
The pond model needed about 0 min and 9 sec calculation time

0.40352 percent of a total road section length of 459.2 m was
considered hazardous.

    Startpoints: 368
      Endpoints: 386

>>
```

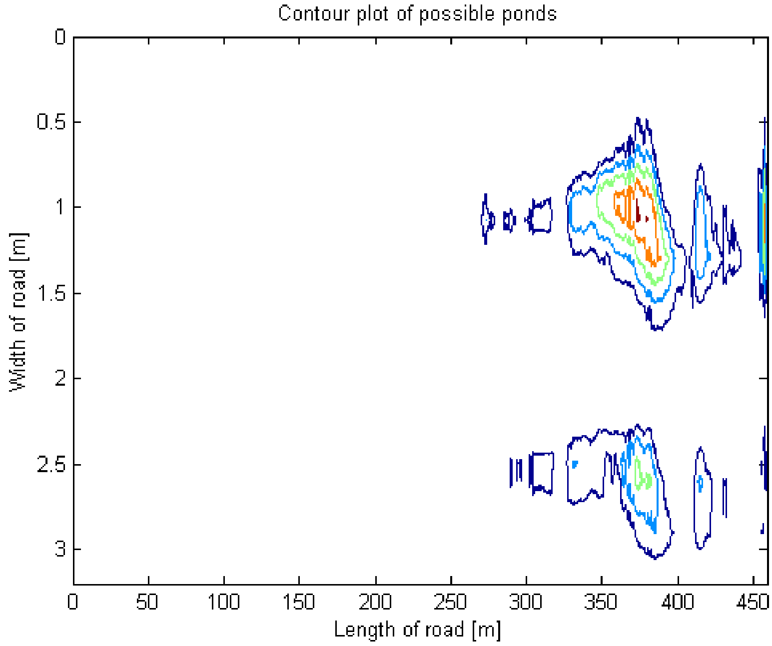


Figure A.18. Contour plot of possible ponds of the road part 40854.

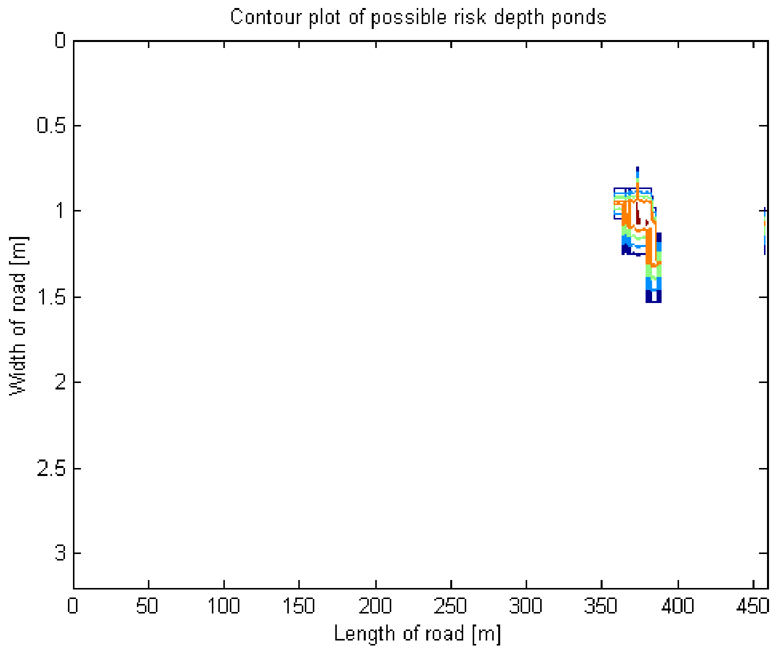


Figure A. 19. Contour plot of the ponds of the road part 40854 exceeding the risk depth limit, here specified to 20 mm.

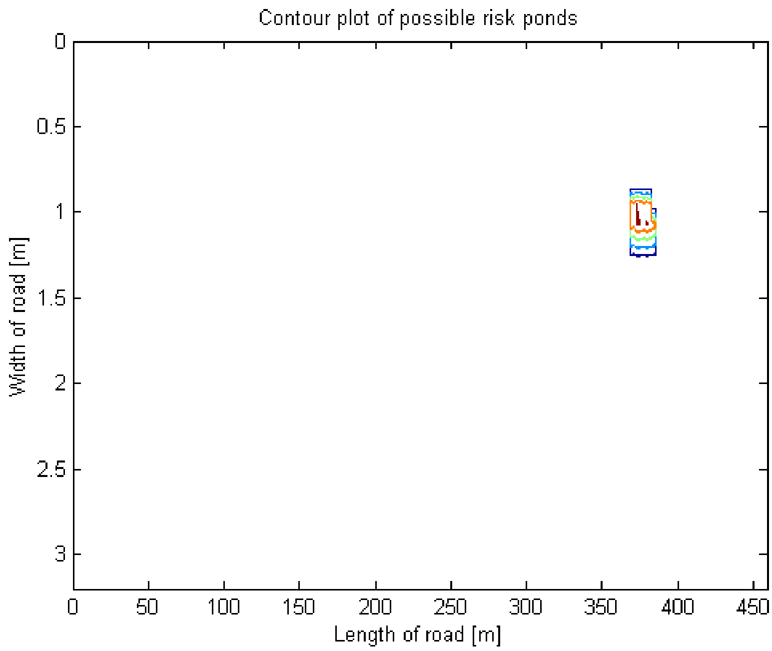


Figure A.20. Contour plot of the ponds of the road part 40854 exceeding the limits of both risk depth (here 20 mm) and risk length (here the default value 10 m is used).

When changing the default third order butterworth-filter to a third order chebyshew1-filter, the following result is achieved:

```
[percent,startpoint,endpoint]=ponding('ws40854');

The road model needed about 0 min and 5 sec calculation time
The pond model needed about 0 min and 10 sec calculation time

2.8707 percent of a total road section length of 459.2 m was
considered hazardous.

    Startpoints: 330
      Endpoints: 398

>>
```

Changing the filtering to a third order chebyshew2-filter yields:

```
[percent,startpoint,endpoint]=ponding('ws40854');

The road model needed about 0 min and 3 sec calculation time
The pond model needed about 0 min and 9 sec calculation time

2.5466 percent of a total road section length of 459.2 m was
considered hazardous.

    Startpoints: 330
      Endpoints: 400

>>
```

Changing to a second order butterworth-filter, does not affect the result much either:

```
[percent,startpoint,endpoint]=ponding('ws40854');
```

```
The road model needed about 0 min and 4 sec calculation time
The pond model needed about 0 min and 10 sec calculation time

2.8758 percent of a total road section length of 459.2 m was
considered hazardous.

    Startpoints: 329
      Endpoints: 398

>>
```

B Glossary

AADT, Annual Average Daily Traffic *ÅDT, årsdygnstrafik*
The estimate of typical daily traffic on a road segment for all days of the week, over the period of one year

ABD *dränerande asfaltbetong*
Porous asphalt

Aquaplaning speed *vattenplaningshastighet*
The speed at which aquaplaning is initiated

Asperities *skrovligheter*
The tops of aggregate particles that are exposed on the surface of the pavement

Average adjustment *haveriutredning*
Investigation carried out to find the cause of a vehicle accident

Chamfer *fasa av*
To cut off the edge or corner of

Chippings *chipsten, pågrus*
A stone material used by surface treatment

Crossfall *tvärfall*
A measure of the transverse slope of the road

Dense-graded *tätt graderad*
The asphalt does not contain many cavities

IRI, International Roughness Index *IRI*
The longitudinal unevenness of a road as experienced by the driver of a standardized car at a speed of 80 km/h

Laser RST, Laser Road Surface Tester *Laser RST*
A survey vehicle using laser measurement technique

Levelling *lantmäterimätning, avvägning*
To measure the different elevations of a specified or limited area of land with the aid of a spirit level

Link *länk*
The road part between two crossings

Longest drainage path length *längsta dräneringssträckan*
For a given section of pavement, the longest distance on that section that a drop of water must flow in order to exit the pavement

Mean transverse profile *medeltvärprofil*
The transverse profile of the road, taken as an average value over 20 m

MTD, Mean texture depth *medeltexturdjup*
Half of the peak-to-peak value of the texture on the average

Open-graded *öppet graderad*
The asphalt contains many cavities

Pavement *överbyggnad*
The part of a road that is above the formation

Pond *vattenpöl*
A water accumulation on the road

Porous asphalt *dränerande asfaltbetong*
Extremely open-graded asphalt

Pothole *potthål*
Bowl-shaped hollows in the roadway

Road base *bärlager*
The layer that spreads weight on the road

Rut depth *spårdjup*
A measure of transversal unevenness

SNRA *Vägverket*
The Swedish National Road Administration

Spirit level *vattenpass*
An instrument for ascertaining whether a surface is horizontal, vertical, or at a 45° angle, consisting essentially of an encased, liquid-filled tube containing an air bubble that moves to a centre window when the instrument is set on an even plane

Subbase *förstärkningslager*
A layer between the ground and the road base that should spread weight on the road, but with lower requirements than on the road base

Towed recording device *mätvagn*
A device towed to a vehicle used for measuring

VTI *Statens väg- och transportforskningsinstitut*
The Swedish National Road and Transport Research Institute