Winter testing in driving simulators

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Preface

The project Winter testing in driving simulator (WinterSim) was a PhD student project carried out by the Swedish National Road and Transport Research Institute (VTI) within the ViP Driving Simulation Centre (www.vipsimulation.se).

The focus of the project was to enable a realistic winter simulation environment by studying the required components and suggesting improvements to the current common practice. Two main directions were studied, motion cueing and tire dynamics. WinterSim started in November 2014 and lasted for three years, ending in December 2016.

Findings from both research directions have been published in journals and at scientific conferences, and the project resulted in the licentiate thesis “Motion Perception and Tire Models for Winter Conditions in Driving Simulators” (Kusachov, 2016). This report summarises the thesis and the undertaken work, i.e. gives a short overall presentation of the project and the major findings.

The WinterSim project was funded up to a licentiate thesis through the ViP competence centre (i.e. by ViP partners and the Swedish Governmental Agency for Innovation Systems, VINNOVA), Test Site Sweden and the internal PhD student program at VTI.

The project was carried out by Artem Kusachov (PhD student) and Fredrik Bruzelius (project manager and supervisor of the PhD student), both at VTI.

Throughout the project several people have been involved in the work:

- Martin Fischer at DLR Germany
- Calle Sandberg and Max Boerboom at Volvo Car Corporation
- Niklas Fröjd and Leo Laine at AB Volvo (GTT)
- Mattias Hjort at VTI and
- Bengt Jacobson at Chalmers as the examiner for Artem Kusachov.

Gothenburg, June 2017

Fredrik Bruzelius
Quality review

As the report is a summary of the licentiate thesis and peer reviewed journal and conference papers the review for ViP was performed by the ViP Director Lena Nilsson on 23 January 2017. Fredrik Bruzelius has made alterations to the final manuscript of the report. The ViP Director Lena Nilsson examined and approved the report for publication on 5 December 2017.
Table of contents

Executive summary .................................................................................................................. 9

1. Introduction ......................................................................................................................... 11
   1.1. Aims ................................................................................................................................. 12
   1.2. Research questions ......................................................................................................... 12
   1.3. Limitations ...................................................................................................................... 13
   1.4. Project reports ............................................................................................................... 13
   1.5. Outline ............................................................................................................................ 14

2. Motion feedback .................................................................................................................... 15
   2.1. Importance of the yaw rotation ..................................................................................... 15
   2.2. Importance of the rotation centre .................................................................................. 17
   2.3. Pre-positioning .............................................................................................................. 19

3. Motion generation ................................................................................................................ 21
   3.1. Perception of tire characteristics .................................................................................. 21
   3.2. Modelling the tire-to-snow interaction ......................................................................... 23

4. Discussion and conclusion .................................................................................................. 29

References ............................................................................................................................... 31
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>MCA</td>
<td>Motion Cueing Algorithm</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
</tbody>
</table>
List of figures

Figure 1. Impact situation, the black car is the car driven by the test participants while the white car was programmed to hit the black car with a certain impact and position................................. 15

Figure 2. Displacement in the road coordinates during regular driving with (upper graph) and without (lower graph) yaw motion. Solid lines represent the average lateral displacements and shaded corridors the standard deviations. Dot-dashed lines represent the centre line of the road.............................. 16

Figure 3. Trajectories at and after the impact, with (blue) and without (red) yaw motion feedback. ... 17

Figure 4. Schematic picture of the momentary rotation centre. .............................................................. 17

Figure 5. Double lane change manoeuvre for high (top) and low (bottom) friction levels. .............. 18

Figure 6. Normalized lateral tire force \( \frac{F_y}{F_z} \) [N/N] as a function of slip \( \sigma_y \) [-] for three of the test tires and the reference tire. (Test tire 4 is not shown because it changes the dynamic properties.)............. 22

Figure 7. Self-aligning torque \( M_z \) [Nm] versus lateral slip \( \sigma_y \) [-] for the test and reference tires. ....... 23

Figure 8. Tire characteristics from measurements of a Nordic winter tire on a snow surface (Tire 1), a studded winter tire on wet asphalt (Tire 2), a summer tire on wet asphalt (Tire 3), and an up-scaled version of Tire 1 (Tire 1*), to illustrate the difference in shape between Tire 1 and Tire 2. ............ 24

Figure 9. Schematics of the double interaction brush model. ................................................................. 25

Figure 10. Suggested double interaction brush model (yellow) compared with parabolic (broken red) and uniform (broken green) single interaction brush models for a) an unstudded European winter tire, b) an unstudded Nordic winter tire and c) a studded tire................................................................. 26

Figure 11. Parameters of the double interaction model when fitted to the recorded data. Left column shows the variation in the parameters for one particular tire. Right column shows the variation of the parameters between the tested tires. Dotted – Nordic tire, dashed – studded tire, and solid – European tire................................................................. 27

Figure 12. Self-aligning torque. Double interaction brush model compared with two single interaction brush models.......................................................................................... 28
Winter testing in driving simulators

by Fredrik Bruzelius and Artem Kusachov

1Swedish National Road and Transport Research Institute (VTI)

Executive summary

Many traffic accidents are due to winter conditions like slippery roads and limited visibility. The road administrators put a lot of effort into snow removal and de-icing the roads, and the vehicle manufacturers have been working with functionality to support drivers in winter conditions for decades.

Many issues of driving in winter conditions originate in drivers’ behaviours such as risk taking and lack of awareness. Studying drivers’ behaviour in winter conditions in general, and the effect of various countermeasures of the vehicle, would increase the understanding of the underlying mechanisms and could possibly be used to reduce the accident risks. Motion-base driving simulators are tools frequently used for driving behaviour research. However, the validity of the results of such studies depends to a large extent on the realism of the simulation. The purpose of this project was to study winter simulation with the aim to improve the realism of simulator driving in winter conditions.

Driving in winter is in many ways different from driving in summer. The difference can to a considerable extent be explained by the tire-to-road interaction. Winter driving is typically characterized by softer motion and slower development of tire forces. In the present project two aspects of the motion have been studied, the motion feedback in the simulator and models for tire-to-snow behaviour.

Vehicle motion during winter driving is characterized by large vehicle body slip angles and the associated yaw motions. Thus, understanding the importance of yaw motion feedback is essential to simulate winter conditions. A study was designed to investigate the impact that lack of yaw motion will have on the driver, and if it alters his driving behaviour. It was found that the yaw motion alters the driving behaviour, implying that it contains vital information for a wide range of driving situations. A second study was carried out to investigate if the rotation centre, which is a consequence of the yaw and lateral motions, can be used to present valuable information about the vehicle state to the driver. Indicative results suggest that the rotation centre of the motion is valuable to the driver, but further studies are needed. The softer and slower motions of winter driving suggest that pre-positioning of the simulator’s motion platform could be performed to improve the motion envelope. A third implementation study performed in the project suggests this.

The main differences in the force generation of tires between asphalt and snow surfaces are due to the friction levels and the shearable properties of snow. These differences are of importance for the driver’s perception in driving simulators, which was confirmed by an experiment where some basic tire characteristics were tested and described by expert drivers. The results from the study suggested that tyre property testing could be performed in motion-base driving simulators. To perform this study a simple tire model was developed that includes the snow shearing properties of the surface. The developed model was validated towards test track measurements of tire forces. It enables predicting the aligning torque of the tire, given the characteristics of the lateral force. This is a strong point of such models and makes them very useable in driving simulation applications.
1. Introduction

Many traffic accidents are caused by situations related to winter conditions such as snowy or icy roads, black ice, limited visibility etc. (see for example Wallman & Åström, 2001; Andreescu & Frost, 1998). Both road administrations and vehicle original equipment manufacturers (OEMs) spend significant resources to reduce the risk of such events (Norrman et al., 2001; Lie et al., 2005; Lie et al., 2006). Also, many issues related to driving in winter conditions stem from driving behaviour such as risk-taking, lack of driving skills and awareness (Leviäkangas, 1998; Evans, 1996). Thus, studying driving behaviour in winter conditions in general and as reactions to specific winter related phenomena is a step towards reducing the traffic accident risk.

Studying driving behaviour in general is hard in real traffic due to lack of control of the environment. Winter conditions add additional uncontrollable parameters to the environment such as temperature, road surface changes etc. Driving simulators are convenient tools for studying interaction between driver and vehicle in certain traffic situations. They offer a completely controlled environment with very high repeatability. However, the (ecological) validity of the environment provided by the driving simulator can be questionable, implying that validity of studies performed in simulators can be questioned. It is desirable to understand the consequences of a simulated environment and to improve the validity in general.

The development of hardware capabilities reduces the constraints on graphics, sound and motion cues and allows for increased simulation realism and consequently improved validity. To improve the simulated environment, it is however required to understand the limitations of driving simulators and how the difference between driving in winter conditions compared to driving in summer conditions can be presented in the simulator.

To improve the ecological validity of winter conditions in driving simulators, it is important to understand the difference to summer conditions. There are many studies that involve driving in winter conditions (see for example Parker et al., 2009; Peltola et al., 2000; Markkula et al., 2013; Wallman 1997). In these studies, a commonly used approach to create a winter-driving environment in the simulator is to scale down the friction coefficient and present snow and ice in the graphical environment. However, the difference in real life is substantially more complex.

Driving in winter conditions is typically characterized by moderate accelerations, changes in motion and vibration due to different road surfaces, more pronounced yawing motion due to higher slips and usually lower driving speeds compared to the dry summer-like condition. The main difference in motion between winter and summer driving, experienced by drivers, originates from the tire-to-road interaction. The characterization of this interaction goes far beyond the coefficient of friction, and for real vehicle driving subtle differences can be perceived even by non-expert drivers.

This project focused on two aspects of the motion feedback, the presentation and the generation of motion in a driving simulator. One of the most fundamental limitations of motion-base driving simulators is their inability to present the motion feedback correctly to the driver. Various trade-offs are required to create a sensation of motion. Presenting motion originating from winter driving requires an additional set of trade-offs that needs to be investigated. In this project, the focus has been on the yawing motion and on the possibility to utilize the fact of relatively low accelerations to increase the motion envelop.

The generation of motion is largely determined by the properties of the tire-to-road interaction. This is particularly true for the planar motions. The interaction is complex but is typically described by simple mathematical models (see for example in Svendenius, 2003) relating the motion of the tire (slip) to the force and aligning torque generation. These models can be used to describe various surfaces and road conditions and could potentially be used to create winter-like conditions in a driving simulator.
1.1. Aims

The main aim of this project was to create a knowledge base for a winter simulation environment to be used in driving simulators for various human factors and vehicle systems studies. Such a test environment would be a strong complement to test-track testing and field operational tests. It would make it possible to further improve the efficiency of simulator studies in terms of time and cost by performing winter-driving tests in this context. Generally, driving simulators provide a test environment that:

- Has high repeatability, which is not the case for field testing with changing weather conditions, etc.
- Is capable of testing ideas as well as costly or non-realized features and properties in an early stage of development.
- Can be used in scenarios that are not suitable for test tracks due to, for example, high risks.

The validity of studies in general, and particularly of studies in a winter-condition setting, is dependent on the ecological validity of the simulation. The project focused on investigating how to improve the ecological validity of the simulation. The ecological validity of the simulation is determined by the validity of the components of the simulation, i.e. of the visual presentation, the sound, the steering wheel torque, and the motion feedback from the motion platform. All these components are important and contribute to the overall validity. However, this project focused on the motion, particularly the presentation of motion by the motion platform and the generation of motion, by studying the tire-to-road interaction.

1.2. Research questions

The overall question addressed in the reported work was how to improve the ecological validity of winter-driving simulation with respect to motion. This rather general question was broken down into more specific questions which were addressed in the separate studies conducted in the project. These specific questions are listed below with capital letters in brackets referring to the resulting publications listed in sub-chapter 1.4 below.

1. How important is the yaw motion in driving simulators and how does it affect the driving behaviour and perception? [E]
2. What is the impact of a correct representation of the rotation centre in driving simulators? [F]
3. Can pre-positioning be utilized to improve the linear motion envelop of the motion platform? [F]
4. How are different characteristics of the tire-to-road interaction perceived by the driver? [B]
5. Can tire-on-snow behaviour be captured in a simple mathematical model with few parameters with meaningful interpretation? [A]

The first two questions were derived from the fact that for winter driving on slippery road surfaces it is common to be close to the limit of forces, i.e. to large vehicle slip angles. This is felt in real vehicle driving by non-expert drivers and is often used in the driving style of experienced drivers. For driving simulators, it is of interest to investigate how important the yaw motion feedback is. Given that it is of importance, it is further of interest to understand if the yaw motion can be used to inform the driver about the current state of the vehicle and whether the slip of the vehicle is high. One way of presenting this is through the rotation centre, which could potentially be presented correctly in motion-base simulators.

The third question is connected to the fact that winter driving typically results in low accelerations. This could be utilized by moving the motion platform in position for an upcoming event. This would enlarge the motion envelope and the possibility to generate a more correct representation of the motion and consequently improve the ecological validity.
The last two questions focused on the generation of the motion and the tire-to-road interaction. This interaction can be perceived strongly in day-to-day driving and is accentuated for slippery winter surfaces. Question 4 addressed how well the interaction can be represented in a driving simulator and is a first step to determine the focus and further efforts of modelling and motion cueing. Question 5 picked one of the tire-to-surface characteristics and created a simple model, which is useable in driving simulators.

1.3. Limitations

The reported research considered planar motion of the simulated vehicle on snow surfaces and the presentation of this motion in the driving simulator. It is reasonable to assume that other factors, like vibrations and sound specific to the winter surrounding and corresponding visual environment, also contribute to creating a more realistic winter-driving sensation. These aspects are not considered in the present project.

The current research was conducted in the passenger cars context. Some of the findings may be applicable to heavy trucks as well, like the perception of yaw motion and the rotation centre. However, heavy trucks were not explicitly covered in this research.

Finally, all the driver-in-the-loop experiments were conducted in the advanced driving simulator Sim IV at VTI1. The generality of the conclusions might be affected by the specific construction and setup of this simulator. Thus, it would be beneficial to repeat some of the experiments at different simulator facilities.

1.4. Project reports

The project has reported its progress through publications in scientific conference proceedings and journals throughout the project time. These publications are listed below and referred to in the remainder of this report by the corresponding capital letter.


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1.5. Outline

The outline of this report is that the following two chapters deal with motion feedback and motion generation through the tire-to-road interaction. These chapters will give a brief background and summarize the publications listed in sub-chapter 1.4. For a more complete description of the separate studies, the reader is advised to the corresponding publications. A discussion chapter summarizing the overall findings ends the report.
2. Motion feedback

The motion cueing algorithm (MCA) maintains a certain balance between actuated degrees of freedom (DOFs) since it is impossible to actuate all of them to a full scope. This balance may be adjusted from experiment to experiment depending on what kind of driving is expected or what sort of reaction is studied. In this research, the motion cueing was studied from a winter-driving simulation perspective. Since perceived vehicle motion in winter conditions is different from that in summer driving, the balance may need to be shifted to increase the realism of the winter-driving simulation.

Driving in winter conditions is characterized by lower friction and sometimes varying friction levels. The lower friction levels imply that the vehicle is closer to slide under normal driving conditions. Therefore, more extensive yaw velocity as well as over- and under-steering situations will occur. This makes studying yaw motion feedback particularly interesting in a context of winter driving in the simulator. Two studies investigating the importance of correct yaw motion in the motion feedback of a driving simulator were performed in this project and are presented below.

Typical winter road surfaces, like snow and ice, have substantially lower friction levels than typical summer road surfaces like asphalt or gravel. The lower friction of the tire-to-road interaction results in lower accelerations of the vehicle. Actuating translational motion, such as longitudinal and lateral accelerations, in the motion platform of a driving simulator has been studied extensively (see for example Jamson, 2010 and references therein). Lower absolute values of the planar accelerations of a vehicle driven on for example snow or ice roads imply that the accelerations are sustained for a longer period compared to higher accelerations. A way to utilize lower and more sustained accelerations is to use pre-positioning of the motion platform. A strategy for this and a study of its effect is presented below.

2.1. Importance of the yaw rotation

To investigate the importance of yaw motion feedback for the driving behaviour a user study was set up. The study is summarised below, and a more detailed description of the set-up and findings can be found in publication [E]. The study was conducted in collaboration with another project, and therefore the experimental conditions and set-up were a compromise between the two projects. Due to this, the study was done on simulated dry asphalt and the scenario was an impact situation with another vehicle, see Figure 1.

![Figure 1. Impact situation, the black car is the car driven by the test participants while the white car was programmed to hit the black car with a certain impact and position.](image-url)
The scenario admitted studying three separate driving conditions; normal driving prior to the impact, reaction to the impact, and post-impact driving with high slips and yaw motion. The motion feedback to the drivers was given through the standard motion cueing algorithm used in the VTI Sim IV driving simulator\(^2\). (Fischer et al., 2011). To study the influence of feedback, the yaw motion of the platform was presented to one group of drivers while it was removed for another group. Driver inputs were recorded to measure objective driving behaviour and questionnaires were used to measure subjectively experienced driving behaviour.

The questionnaire answers could not show any statistically significant difference between the yaw motion group and the non-yaw motion group. However, the objective measures showed a noticeable difference. For example, in the normal driving part of the study, the group with yaw motion drove closer to the centre line of the road compared to the non-yaw motion group, see Figure 2. On average the difference was approximately 0.2 meters, which should be considered large given the width of the lane. A possible interpretation could be that drivers with the yaw motion feedback found it easier to control the vehicle and focus on the oncoming traffic.

![Figure 2. Displacement in the road coordinates during regular driving with (upper graph) and without (lower graph) yaw motion. Solid lines represent the average lateral displacements and shaded corridors the standard deviations. Dot-dashed lines represent the centre line of the road.](image)

Concerning the impact and the evasive manoeuvring after it (see Figure 3) it could be observed that the group with yaw motion feedback tended to steer less and settle the yaw motion faster than the group without the yaw motion feedback.

Thus, the findings of the study strongly suggest that an absence of yaw motion leads to changes in driving behaviour.

2.2. Importance of the rotation centre

The first study suggested that absence of yaw motion feedback alters the driving behaviour compared to when yaw motion feedback is present. This finding raised the question whether the yaw motion feedback could be used to inform the driver about the current state of the vehicle and how the vehicle is sliding. Therefore, another study was set up specifically to study a strategy to inform the driver about the vehicle state. This study is briefly described here together with the general findings. In publication [D] the study is described in more detail.

\[ \mathbf{r} = \left( -\frac{v_y}{\omega_z}, \frac{v_x}{\omega_z}, 0 \right) \]

where \( \omega_z \) is the yaw rate, and \( v_x \) and \( v_y \) are the longitudinal and lateral speeds in the vehicle coordinate system respectively. The lateral component of the quantity \( \mathbf{r} \) is closely related to the turning radius of the vehicle. These are typically so large that they cannot be presented in the motion platform of a driving simulator. The longitudinal component of the rotation centre is, on the other hand, located at the rear wheels for low-speed manoeuvring and is moving forward as the speed increases. The distance is also changed when the body slip angle is changed. Hence, the rotation centre could be a candidate to be used to inform the driver about the vehicle state in a motion-base driving simulator. Some observations about
the longitudinal component could be drawn; it is singular when the vehicle have a zero-yaw rate and it gives a relation between the lateral speed and the yaw rate of the vehicle.

The singularity implies that the quantity \( r \) is not defined in certain situations, like straight driving or when the rotation of the vehicle is changing. Hence, the rotation centre cannot be used directly in a motion cueing algorithm. Actuating a correct rotation centre in the motion platform implies that the fraction between the lateral speed and the yaw motion of the cabin needs to be respected. Thus, for a motion cueing algorithm the lateral speed (or acceleration) channel needs to be treated in the same manner as the yaw rate channel, such that the fraction between them remains the same. Operations that respect this are linear scaling and filtering of major frequency components. It should be noted that classical motion cueing algorithms (see for example Fischer et al., 2011) will not respect and preserve the rotation centre of the vehicle in the motion feedback.

A study was set up to investigate if the information in the rotation centre could be used by the drivers to manoeuvre the simulated vehicle better. Of particular interest was the driving capabilities when the vehicle is close to its handling capabilities, i.e. in situations with high slip angles. As a comparison, a motion feedback was derived that gives a correct rotation centre when driving far from the handling limit. This steady state rotation centre was derived using a simple single-track model and linear tire models according to,

\[
\frac{v_y}{\omega_x} = b - \frac{v_x^2}{C g}
\]

where \( b \) is the distance from the centre of gravity to the rear wheels and \( C \) is the linear stiffness of the tires. The motion feedback for the correct rotation centre (1) was a scaling and gentle high-pass filtering of the yaw rate and the lateral speed, while the lateral speed was given by the expression above for the simplified comparison case (2).

The test participants drove two sets of manoeuvres defined by cone tracks for a high-friction and a low-friction surface, respectively (see Figure 5). The speed was gradually increased as the participants managed to complete the cone tracks without touching the cones and was used as an objective performance measure. A questionnaire was used to measure the test participants’ subjective impressions.

**Figure 5. Double lane change manoeuvre for high (top) and low (bottom) friction levels.**
Only subtle differences between the different ways to present the rotation centre could be observed. The answers to the questionnaire showed that the correct rotation centre was favoured as informative of the vehicle state, but the difference to the baseline rotation centre was not statistically significant. Obtained differences in the objective performance measures were also very subtle, but measurable.

An explanation of the unexpectedly small differences between the two conditions is likely to be found in the experimental set-up with the used manoeuvres being very hard. It turned out that positioning of the vehicle in the entrance corridor of cones was a non-trivial driving task in the simulator due to mismatches in the visual presentation. This together with the fact that the conditions were close to identical for vehicles driving far from the handling limit gave a very subtle difference in the results. An easier driving task that had forced the vehicle into limit handling would have been preferred. Also, a condition more different from the correct rotation centre should have been used, for example a motion cueing closer to common practice.

There is much more to investigate, dispute the weak indications of difference and the importance of a correctly presented rotation centre in the motion platform. The presented work is novel in incorporating vehicle dynamics in the motion cueing and connecting two motion channels to each other in the motion cueing algorithm. A similar study was made at Volvo Cars’ facility but focusing on the rate of change of the rotation centre as a guidance in the tuning of a conventional motion cueing algorithm. In a smaller study on vehicle perception the results of this approach were positive.

2.3. Pre-positioning

Faster accelerations are typically represented by a linear motion of the platform while slower or maintained accelerations are presented by tilt coordination (see for example Fischer et al., 2011). Tilt coordination is a technique to use the gravitational field and tilt the driver without him noticing (see for example Groen & Bless, 2004). The result is that a maintained sensation of acceleration can be presented without hitting boundaries of the motion platform. However, it is very hard to actuate the tilt without the driver noticing, which leads to false cues and potentially nausea and simulator sickness. It is not uncommon that tilt coordination is not used at all and sustained accelerations are not presented at all, often referred to as onset motion cueing. It is hence desirable to use the linear motion capabilities of the motion platform as much as possible. It is also therefore some platforms have a large linear stroke.\(^3\)

Given the platform limitations, it is desirable to utilize the linear stroke to a maximum to show as much as possible of the vehicle acceleration. Common practice in motion cueing algorithms is to return the platform to a central position after a simulated acceleration. In this work, publication \([F]\), strategies were developed to position the platform off-centre before the simulated acceleration to enlarge the linear motion.

Such a pre-positioning of the motion platform is possible because upcoming events can be predicted in a driving simulator. For the longitudinal case the acceleration capability of the simulated vehicle is decreasing with increasing speed. Hence, for high speeds it makes sense to develop a strategy that positions the motion platform to be ready for braking manoeuvres by moving the return position towards the front of the linear stroke. For the lateral case, the combination of speed and upcoming curvature can be used to estimate the future lateral acceleration. Based on this, the return position of

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The University of Leeds Driving Simulator (UoLDS), http://www.uolds.leeds.ac.uk/ [accessed 2014-05-10].
the motion platform can be moved in the opposite direction of the curve with a magnitude dependent on the upcoming lateral acceleration.

The movement of the return position needs to be performed under the perception threshold to avoid introducing false cues. There is always a risk that the driver still will notice this motion. Other risks are due to errors in the estimate of the upcoming event and that the pre-positioning can make the available stroke shorter in some situations like for example unexpected steering activities.

A pre-positioning algorithm was developed in publication [F] based on the present speed and the upcoming curvature. Benefits of the proposed algorithm was illustrated by off-line simulations and a user study. The simulations showed that, with pre-positioning the amount of acceleration presented by an x-y sled system can be increased by up to 25% in longitudinal direction and 53% in lateral direction. The comparative user study, with and without pre-positioning, included 12 test participants and indicated that perceived realism is rated higher with pre-positioning.
3. Motion generation

In real driving, the motion of a vehicle is ultimately determined by the driver, the propulsion/braking system and the physical limitations of the tire-to-road surface interaction. Driving in winter conditions, i.e. on slippery surfaces like snow and ice are, compared to summer-condition driving, closer to the limit of what the tire-to-surface interaction can generate in terms of forces. The closeness to the limit is present in normal day-to-day driving for snow and ice roads. This means that the tire-to-road interaction needs to be considered in more detail in simulation of winter conditions compared to simulation of summer conditions.

Closeness to the limit of force extraction of the tire-to-road interaction in winter road driving, on for example ice or snow, is something that is very much perceived by normal non-expert drivers. Sensing the state of the tire force extraction is crucial for safe winter driving, and experienced drivers can use the perceived closeness information in their decision making while driving, i.e. for preventing sliding or understeering. Properties of the tire-to-road interaction is hence of interest to study. In this project two studies were conducted on tire-to-road interaction; modelling of tire-to-snow interaction and a user study on how tire characteristics are perceived in a driving simulator.

3.1. Perception of tire characteristics

The forces generated by the tire depend on many factors, such as the road surface properties, tire tread pattern, stiffness, tire type etc. Most of these factors are perceived by the driver in a real vehicle. It is, however, not clear how this complex interaction contributes to the perception of motion and what parts of it that are of importance.

Ideally, it would be desirable to study these characteristics one by one to understand their significance for the perception of motion. Individual tire-road-interaction characteristics cannot be studied in isolation due to the inherited nature of rubber, tire design and the properties of the road surface. However, a driving simulator could potentially be used to study these characteristics in isolation.

Publication [A] presents a study investigating the perception of some fundamental characteristics of the tire-to-road interaction, described by mathematical tire models. An experiment was set up as a tire test with four test tires and one reference tire. The experiment was a first attempt to study perception of tire characteristics in a driving simulator. Hence, the focus was on how the different tires were perceived in general rather than quantifying differences. This was also why a qualitative assessment with eight professional and expert test drivers was undertaken. Furthermore, no detailed instructions were given to the test drivers except to drive as they do in a real car when they are testing tires. A questionnaire with some basic questions was answered by the test drivers, but the main focus in the study was on “what they felt” when driving, described in their own words.

In a driving simulator, the tire model describes the tire-to-road interaction and includes the tire and road surface characteristics. The tire model used here was a brush tire model with only a few parameters (see for example Svendenius, 2003), the tread stiffness and friction coefficient at stiction and sliding. The major dynamics experienced in the tire with respect to motion is due to the carcass deflection. To model the carcass, motion degrees of freedom in the lateral and longitudinal directions were introduced with stiffnesses and dampings of the carcass.
Figure 6. Normalized lateral tire force $F_y/F_z \ [N/N]$ as a function of slip $\sigma_y \ [-]$ for three of the test tires and the reference tire. (Test tire 4 is not shown because it changes the dynamic properties.)

The four test tires all represent a change of one characteristic corresponding to a parameter value in the model, see Figure 6 and the descriptions below.

Test tire 1. **The tread stiffness** is the initial slope of the slip/force curve. It is represented by the tread stiffness parameter $C$. The value was changed from the nominal 30 to 20. This is one of the most important characteristics that affects the vehicle trajectory.

Test tire 2. **The smooth transition** is the characteristic typically seen for snow and gravel. It was represented by the dual interaction and with two sets of stiffnesses and friction levels for these interactions. The stiffnesses were 28.5 and 1.5 and the friction levels were 0.47 and 0.23.

Test tire 3. **The pronounced peak** was represented by a stiction friction $\mu_s$ that is higher than the sliding friction $\mu_k$. The stiction friction was changed from 0.7 to 1 and the sliding friction from 0.7 to 0.6. Such tire behaviour can be noticed on certain surfaces, for example wet asphalt.

Test tire 4. **The carcass stiffness** can represent different carcass designs as well as different inflation pressures. Here it was represented by a change in the corresponding parameter $C_{cy}$ from a nominal value of 80 to 10. This corresponds to a relaxation length of 0.375 meters for the nominal case and 3 meters for the test tire. It should be noticed that this change cannot be visualized in Figure 6 as it gives rise to a change of the dynamic properties of the tire. Figure 6 only visualizes the steady state properties.

It should be noticed that the friction coefficient at stiction was not altered, it was set to 0.7 for all the test tires. The value was a compromise between the capabilities of the motion platform and getting noticeable force differences at high utilization levels. The friction coefficient is the parameter most often used to characterize different surfaces, and the perception of the friction characteristic could be considered well known through numerous studies in driving simulators.

The tire characteristics affect the slip-to-force generation according to Figure 6. These forces will affect the trajectory of the vehicle and could be perceived by the driver. The tire characteristics will also affect the generation of aligning torque around the vertical axis of the tire. This torque is transmitted through the steering system up to the steering wheel. The aligning torque of the tires, felt in the steering wheel, also contributes to the overall sensation of the tire-to-road interaction. The
aligning torque versus slip for the tested tires is depicted in Figure 7, and described by similar models as the forces.

![Figure 7. Self-aligning torque $M_z \text{[Nm]}$ versus lateral slip $\sigma_y \text{[\%]}$ for the test and reference tires.](image)

From the tire test, it can be concluded that the different tire characteristics were perceived with different intensity. For example, the change in tire tread stiffness was distinctly noticeable by all the test drivers. Many of them directly named the tread stiffness as a possible difference between the test tire and the reference tire. This is an indication that tread stiffness is directly perceived and may be used to represent different tires and/or surfaces in the simulator.

For the smooth transition tire, the difference was not clearly identified by the test drivers. Many of them described driving with this tire similarly to what could be expected from driving on snow or gravel. However, the experience may have been an effect of perceiving a lower friction coefficient rather than the smooth transition described by the tire model. The pronounced peak was not sensed at all by the test drivers as they did not reach tire forces where the difference compared to the reference tire is noticeable. Concerning the carcass stiffness, some test divers identified the slower response of the weaker carcass tire while some commented that the vehicle felt easier to control. An explanation could be personal preferences for finding it easier to control a vehicle with slower response in combination with the latencies that exist in a driving simulator.

3.2. Modelling the tire-to-snow interaction

In a driving simulator the vehicle response to the environment and the driver’s input is determined by real-time executing mathematical models. For the tire-to-road interaction this is described by a relationship between the relative motion between the road surface and the tire contact patch (the slip), and the force and torque generated in this contact patch. The various tire characteristics described in sub-chapter 3.1 above originate from either the tire, the road or a combination of both.

For tires on snow surfaces, it has been observed from measurements that the shape of the curve describing the slip-force relation differs from the corresponding curve shape for tires on asphalt (see for example Svendenius, 2007; Hjort & Eriksson, 2016; Hjort & Ericsson, 2015 and Figure 8). The difference can be described as a softer transition between the initial linear part and the saturated tire force part for tires on snow. The results of the user study reported in sub-chapter 3.1 above show that this difference can be perceived by drivers in a driving simulator. Hence, there is a need to describe this tire on snow characteristic in a mathematical model.
A commonly used approach to derive these types of tire models is via curve fitting of measured data. The most common model using the curve-fitting approach is the well-known Magic Formula Tire model (see for example Bakker et al., 1989). The problem with this approach is that the parameters of the model do not have an intuitive physical interpretation and it is unclear what consequences a change of a parameter will have. It is also unclear what the behaviour of the model will be like outside the domain where the model has been fitted.

A different approach is to use physically motivated assumptions to derive a model. Models of this kind may range from very complex models considering many aspects of the interaction down to very simple models that only consider the most fundamental properties contributing to the force and torque generation (see for example Pacejka, 2006). Model complexity is closely related to the number of model parameters, ease of use, and computational effort. Hence, it is most often desirable to have as simple models as possible.

For snowy roads there are no models available in the literature that are based on physical assumptions and simple enough to be suitable for use in driving simulators. In publication [B] such a model is derived based on the brush model theory (see for example Pacejka, 2006). A common assumption in brush models is that the surface the tire is interacting with is solid and does not move when the tire is rolling over it. This assumption is of course violated when driving on snow. Part of the snow surface will stick to the tire and the interaction between the tire and the surface will not only be a tire-to-snow interaction but also an interaction between the stuck snow and the snow on the road. Therefore, a double interaction model was derived with the hypothesis that the main difference seen in the measurement could be described by this second interaction. A schematic picture of the assumption is shown in Figure 9.

Figure 8. Tire characteristics from measurements of a Nordic winter tire on a snow surface (Tire 1), a studded winter tire on wet asphalt (Tire 2), a summer tire on wet asphalt (Tire 3), and an up-scaled version of Tire 1 (Tire 1*), to illustrate the difference in shape between Tire 1 and Tire 2.
To fit the brush model theory framework some additional assumptions were made to the standard assumptions of the framework (see for example Svendenius, 2003):

1. There is an interaction between the snow surface and the packed snow occupying the voids between tread blocks. This interaction is the main contribution to the differences in tire behaviour on snow and on a solid surface.

2. The interaction between the snow in the voids and the snow surface can be modelled using elastic bristles.

3. The areas of packed snow and rubber are symmetrically distributed in the lateral direction on the tire surface so that there is no additional moment generated around the vertical axis, see Figure 9.

4. The movement of the “snow” bristles is independent of the movement of the “rubber” bristles.

The derived model was fitted to test data recorded in another project (Hjort & Ericsson, 2016; Hjort & Ericsson, 2015) with the purpose to illustrate the performance of the model and to test the hypotheses and assumptions made in the derivations. The data was recorded for three tire categories (unstudded winter tires designed for European conditions, unstudded winter tires designed for Nordic conditions, and studded tires) using a mobile test rig on a packed snow surface. Data from nine different tires in each category was used in this study. A sample showing the performance of one tire from each category can be seen in Figure 10 below. The suggested double interaction model is plotted together with the recorded data and two models based on standard assumptions (i.e. solid surface, uniform and parabolic pressure distributions). As can be seen in Figure 10 the suggested model outperforms the other models in terms of fitting the data for all three categories and both directions (lateral and longitudinal). The model’s ability to fit the data was not specific to the tire examples shown in Figure 10, but was a common result for all the 27 included tires.
Figure 10. Suggested double interaction brush model (yellow) compared with parabolic (broken red) and uniform (broken green) single interaction brush models for a) an unstudded European winter tire, b) an unstudded Nordic winter tire and c) a studded tire.
The ability to fit the recorded data is a fundamental property of the model. However, the model was derived under assumptions and hypotheses that can be tested using the measurements. The parameter values of the double interaction model fitted to the recorded data are plotted in Figure 11. The plots in the right column show how the parameters vary between the different test tires. It could be observed that the variation in stiffnesses between the tires vary for the stiffnesses originating from the rubber-to-snow surface interaction, while the stiffness originating from the snow-to-snow surface interaction does not vary to the same extent. This could be interpreted as an indication of confirmation of the assumption that snow is the major contribution. The variation between tires is well known and the tread pattern contributes to differences in both stiffness and friction (C and μ in Figure 11).

Figure 11. Parameters of the double interaction model when fitted to the recorded data. Left column shows the variation in the parameters for one particular tire. Right column shows the variation of the parameters between the tested tires. Dotted – Nordic tire, dashed – studded tire, and solid – European tire.

The self-aligning torque of the tire is very important in driving simulators as it determines most of the torque felt in the steering wheel. Hence, predicting and describing this torque from the tires is essential for the tire model. The suggested double interaction model was derived for this aligning torque and fitted to recorded torque data. Figure 12 shows such a fit to measured data. The measurements are inheritably noisier than the force data and exposed to disturbances from the measurement rig. Hence, only curve originating from an averaged measurement set was used here. As Figure 12 shows, the suggested double interaction model again can fit the data better than the two single interaction models based on standard assumptions. However, a major difference to the force plots (Figure 10 above) is how the parameters have been obtained. The torque measurements are contaminated with torques originating from the measurement rig (friction and mechanic trails) which are added to the measured
torque. These effects are hard to compensate by direct measurements on the rig. Hence, the effects were modelled, and the parameters were fitted to the data and added to torque from the suggested tire model. The parameters of the tire model were given from the fitting of the corresponding forces. Hence, the model enables predicting the aligning torque based on the force measurements and the fit to these. This shows the true strength of the model approach, i.e. that the parameters have a physical interpretation and that the model can predict behaviour outside the domain where it has been fitted to measured data.

Figure 12. Self-aligning torque. Double interaction brush model compared with two single interaction brush models.
4. Discussion and conclusion

The current project has studied some aspects of motion of vehicles driving on winter roads (snow or ice) and how to handle these aspects in driving simulators. The aspects can be divided into presentation of motion and generation of motion.

The presentation of motion in a driving simulator is limited by the capabilities of the motion platform of the simulator. There is often a trade-off between motions to actuate, and it is of vital importance for the ecological validity of the simulation to understand the importance of each motion. For winter driving the yawing motion is of particular interest as it contains information regarding the vehicle’s state. A study in this project showed that this is also true for driving simulators. The study quantified the differences in driving behaviour when driving with and without yaw motion.

The yaw motion cannot be actuated one to one with the real motion. Trade-offs are needed that consider the limitations of the motion platform. Typical restrictions of the actuated yaw motion are no low-frequent motions and limited amplitudes. Given the importance of yaw motion, a study was carried out to investigate a strategy to express the yaw motion in terms of the momentary rotation centre of the simulated vehicle. Even though the study showed weak improvements of the drivers’ performance, the result suggested that the strategy could be beneficial for presenting relevant vehicle states such as body slip angle. The result could also be used as a guidance for tuning of the motion presentation of driving simulators through the connection between the yaw and lateral motions.

The low accelerations of winter driving could be used to more efficiently pre-position the motion platform for upcoming and expected events. The main benefit of pre-positioning is that a longer stroke of the motion can be used, which can be considered a relaxation of the platform limitations. A simple strategy was designed utilizing the vehicle speed and upcoming road curvatures to pre-position the motion platform. A study carried out in the project suggested that significant improvement of the linear stroke could be made with a minimum risk of false cues.

The generation of motion is, besides the driver’s input, to a large extent determined by the properties of the tire-to-road interaction. The low tire forces and closeness to sliding in normal winter driving make this interaction even more relevant to study. The perception of the characteristics of the interaction between the winter road and the tire is well known and experienced drivers can use the information to adapt their driving style. It is however not clear what components and characteristics that are of importance. A driving simulator study was carried out to study the perception of tire-to-road interaction characteristics. The expert drivers participating in the study suggested that many characteristics are of importance for the perception and that they can be presented in motion-base driving simulators. Consequently, tire models for driving simulators need to capture a certain level of details, far beyond the coefficient of friction.

The importance of the tire characteristics in driving simulators in general, and for simulating driving on slippery winter road surfaces like snow and ice in particular, implies the need for tire models able to capture major characteristics. However, there are no available tire models that meet the requirements of simplicity, real-time performance and ease of use. Hence, a model for tire-to-snow surface interaction was developed, and validation by test track measurements suggested that the model is capable of accurately represent the important characteristics of both the force and the aligning torque.

The work undertaken, and results obtained in this project can be used to improve the realism and ecological validity of simulations of driving on winter road surfaces in driving simulators. The project focus has been on some aspects of the presentation and generation of motion in driving simulators. Other aspects of the motion, such as vertical dynamics induced by the road surface, will likely be of major importance for the validity of winter road driving simulation. The visual and audible simulations are also likely to be of vital importance to the overall perception in this context.
References


ViP is a joint initiative for development and application of driving simulator methodology with a focus on the interaction between humans and technology (driver and vehicle and/or traffic environment). ViP aims at unifying the extended but distributed Swedish competence in the field of transport related real-time simulation by building and using a common simulator platform for extended co-operation, competence development and knowledge transfer. Thereby strengthen Swedish competitiveness and support prospective and efficient (costs, lead times) innovation and product development by enabling to explore and assess future vehicle and infrastructure solutions already today.