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IN MACHINE AND VEHICLE SYSTEMS

Motion Perception and Tire Models for Winter Conditions in Driving Simulators

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Abstract

Many traffic accidents happen due to winter conditions, like slippery roads and limited visibility. The road administrators put a lot of effort into snow removal and deicing the roads. The vehicle manufacturers have been working with functionality to support drivers in winter conditions (studded tires, ABS, ESC, etc.) for decades.

Many issues with driving in winter condition originate in drivers' behaviors, such as risk taking and lack of awareness. By studying drivers' behavior in winter condition in general and, the effect of various countermeasures of the vehicle, it is possible to reduce accident risks. Motion base driving simulators are commonly used tools for driver behavior research. The validity of the results of such studies depends on a large extent on the realism of the simulation. The aim of this research is to improve the realism of the driving in winter condition in driving simulators.

Driving in winter conditions is in many ways different from driving in summer conditions. The difference originates mostly from differences in the tire to road interaction. Winter condition driving is typically characterized by softer motion and softer development of tire forces. With a focus on motion, two aspects have been studied: the motion feedback in the simulator and tire models for tire to snow behavior.

Vehicle motion during winter driving is characterized by large yaw motions. It is shown through an experimental study that yaw motion feedback in the driving simulator is valuable for the perception of motion. Furthermore, a correct representation of the momentary center of rotation in the simulator can be important to the driver as it contains information on the vehicle state.

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 driver's perception in driving simulators, which was confirmed by a subjective experiment. A physically based model was derived for tire behavior on snow and validated with real life measurements.

It can be concluded that the there is a difference between driving in summer and winter conditions in terms of vehicle yaw motion and tire to road interaction. Conducted studies showed that these differences can be represented in the motion base driving simulator. Representing these difference increases the realism of the winter driving simulations.

Keywords: winter conditions, motion perception, tire model, winter driving simulation, vehicle dynamics

Acknowledgements

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Artem Kusachov

Göteborg, November 2016

List of appended papers

Paper A. A. Kusachov, F. Bruzelius and X. Xie, *The Importance of Yaw Motion Feedback in Driving Simulators*, in International Symposium on Dynamics of Vehicles on Road and Tracks, Graz, 2015

Paper B. A. Kusachov, F. Bruzelius, B. Augusto and M. Fischer, *The Importance of Yaw Rotation Centre on the Driver Behaviour,* in Driving Simulation Conference, Tubingen, 2015.

Paper C. A. Kusachov, F. Bruzelius and M. Hjort. *Perception of Tire Characteristics in a Motion Base Driving Simulator*, in Driving Simulation Conference, Paris, 2016.

Paper D. A. Kusachov, F. Bruzelius, M. Hjort and B. Jacobson. *A double interaction brush model for snow conditions*, submitted to Journal of Vehicle System Dynamics, 2016.

The author of these thesis has the main responsibility for implementation the model, data analysis, and writing. Bruzelius contributed greatly with reviewing, editing, and good ideas. Both Kusachov and Bruzelius designed the experiment in papers B and C. Xie was responsible for designing and conducting the experiment in Paper A. Augusto was a technical adviser and reviewer. Fischer was a technical adviser. Hjort conducted the field measurements (with help of Kusachov) and reviewed the model in paper D. Jacobson helped to evaluate the model in paper D.

Contents

1 Introduction and background

1.1 Background and motivation

Many traffic accidents are caused by situations related to winter conditions, such as snowy or icy roads, black ice, limited visibility, etc., see e.g. [1, 2]. Both road administration and vehicle original equipment manufacturers (OEM) spend significant resources to reduce the risk of such events [3, 4, 5]. Many issues related to driving in winter conditions stem from driver behavior, such as risk-taking, lack of driving skills and awareness [6, 7]. Thus, studying driver behavior in winter conditions in general and reaction to specific winter related phenomena is a step towards reducing the vehicle accident risk.

Driving simulators are convenient tools for studying the interaction between driver and vehicle in certain traffic situations. There is a large number of studies that involve driving in winter conditions, see e.g. [8, 9, 10, 11]. Today's level of hardware reduces the constraints on graphic, sound and motion cues. This allows for increased simulation realism[1]. However, to improve these cues, it is required to understand the differences between winter and summer driving and how to represent them in a driving simulator. This thesis focuses on motion cues in driving simulators, which are influenced mostly by two factors – the motion feedback and the tire model.

To improve the realism of driving simulators in terms of perception of winter conditions, it is important to know how different they are from summer conditions. A simplistic way to create a winter driving simulation environment is boiled down to lowering the friction coefficient and creating the winter-like graphical environment. However, the difference in real life is substantially more complex. Driving in winter conditions is characterized by more moderate accelerations, changes in motion and vibration due to different road surfaces, more pronounced yawing and usually lower driving speeds compared to the dry summer-like condition.

1.2 Research questions

To introduce a winter driving sensation into a driving simulator environment, we need to understand how drivers perceive winter roads and how different cues contribute to the winter-like drive feeling. While mostly considering vehicle motion, this thesis raises the following research questions:

1. How important is yaw motion in driving simulators and how does it affect the driving behavior and perception? (Addressed in the Paper A)
2. What is the impact of correct representation of the rotation center in driving simulators? (Addressed in the Paper B)
3. How are different characteristics of tire to road interaction perceived by the driver? (Addressed in the Paper C)
4. How to capture tire on snow behavior in a mathematical model? (Addressed in the Paper D)

1.3 Aims

The main aim of this research is to create a knowledge basis for a winter simulation environment in driving simulators for various human factor and vehicle systems studies. Such test environment

[1] In this text the term "realism" should be understood as a synonym of an "ecological validity" [8].

would be a strong complement to field vehicle testing. It would enable the possibility to further improve efficiency of simulators study in terms of time and cost by use of driving in this context. Generally, driving simulators provide a test environment:

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

As any other test environment, a driving simulator requires high validity to be treated as a complement to field testing. This performance is a result of many synergetic working systems, such as motion, graphic, sound, etc. The output of the motion system depends on the vehicle model and the motion cueing algorithm. Both of them were studied during the project as two different approaches to reach the objective.

1.4 Limitations

This research considers vehicle planar motion of the simulated vehicle on snow surfaces and representation 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 work.

The current research is 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 center. However, heavy trucks are not covered in this research.

Finally, all the driver in the loop experiments were conducted in the VTI SimIV driving simulator thus, the generality of the results might be affected by this specific simulator construction and setup. Thus, it would be beneficial to repeat some of the experiments on different simulator facilities.

1.5 Outline

Chapter 1 presents the background and the motivation of the thesis. Chapter 2 describes motion feedback systems and algorithmic approaches to motion cueing. Chapter 3 addresses the vehicle model, and more specifically characteristics and modeling approaches to the tire to road interaction. Chapter 4 summarizes the most important findings from the appended papers. Chapter 5 contains discussion of the research questions, discussion about the results and justification of the assumptions made in this thesis, as well as the conclusions and future work in this research direction.

2 Motion feedback

Ideally, a simulator should reproduce the vehicle motion in a full scope – all motions of a real car during a maneuver would be replicated by the simulator one-to-one. This would imply that the motion envelope of such simulator would not differ much from the real vehicle's environment. There are, however, always boundaries which limit the capabilities of the simulator. These boundaries originate from the actuators limitations, such as a limited stroke, latencies, available power, etc. To take these limitations into account and, at the same time, represent the sensation of vehicle motion, a motion cueing algorithm (MCA) is used.

The motion cueing algorithm 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 is studied from winter driving simulation perspective. Since perceived vehicle motion in winter conditions is different from summer driving, this balance may need to be shifted to increase the realism of 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 the study of yaw motion feedback of particular interest in a context of winter driving in the simulator.

In hexapod based motion systems, all 6 DOF are mechanically connected to each other, which implies that extensive using of one of them will limit all the other. On the other hand, slower dynamics of the vehicle, e.g. lateral and yaw acceleration, are common for winter driving. This allows using the simulator's motion system to a larger extent. This opens up for more possibilities for one or several of the DOF. However, to give more freedom to yaw motion, the effect it has on the driver should be studied.

The yaw motion is a rotation around the vertical axis. The instantaneous center of rotation is a point where the entire vehicle's motion is described by rotation. In the lateral direction, this point can be found as a ratio between the longitudinal velocity and the yaw rate. Thus in the case of straight forward movement, this point is infinitely far sideways from the vehicle. Such magnitudes are impossible to implement in the simulator. For the longitudinal direction, this point can be found as a ratio between the lateral velocity and yaw rate. For low speed, it is located between the rear wheels and moves forward with a level of over-steering and rearwards with understeering. In the longitudinal direction, it is possible within the stroke of most motion platforms to actuate a correct rotation center for non-extreme maneuvering. However, in the case of the correct representation of the rotation center, its longitudinal position relative to the vehicle is singular for straight driving, which requires special techniques to represent it.

The following subchapters present a brief overview of existing motion cuing algorithms and motion platform setups. The solutions described below, approach the simulation of motion in a very different ways, providing a wide range of possibilities in terms of motion perception and handling the limitations.

2.1 Motion platforms

A *Gough-Stewart platform* or *hexapod* (a.k.a. *six-axis*, *6-DOF* or *synergetic motion platform*) is a very commonly used hardware platform for the motion-based driving simulator [12]. This parallel controlled motion system consists of six independently controlled prismatic actuators which move the load within 6 degrees of freedom - 3 linear and 3 rotational, along and around Cartesian axes:

- surge (forward and backward translation along its x-axis)
- sway (sideways translation along its y-axis)
- heave (vertical translation along its z-axis)
- roll (tilting rotation around the x-axis, ϕ)
- pitch (tilting rotation around the y-axis, θ)
- yaw (horizontal rotation around the z-axis, ψ)

One of the main motion stroke limitation of the hexapod is that all the DOF are mechanically connected. Saturating one DOF will limit the strokes of the other five.

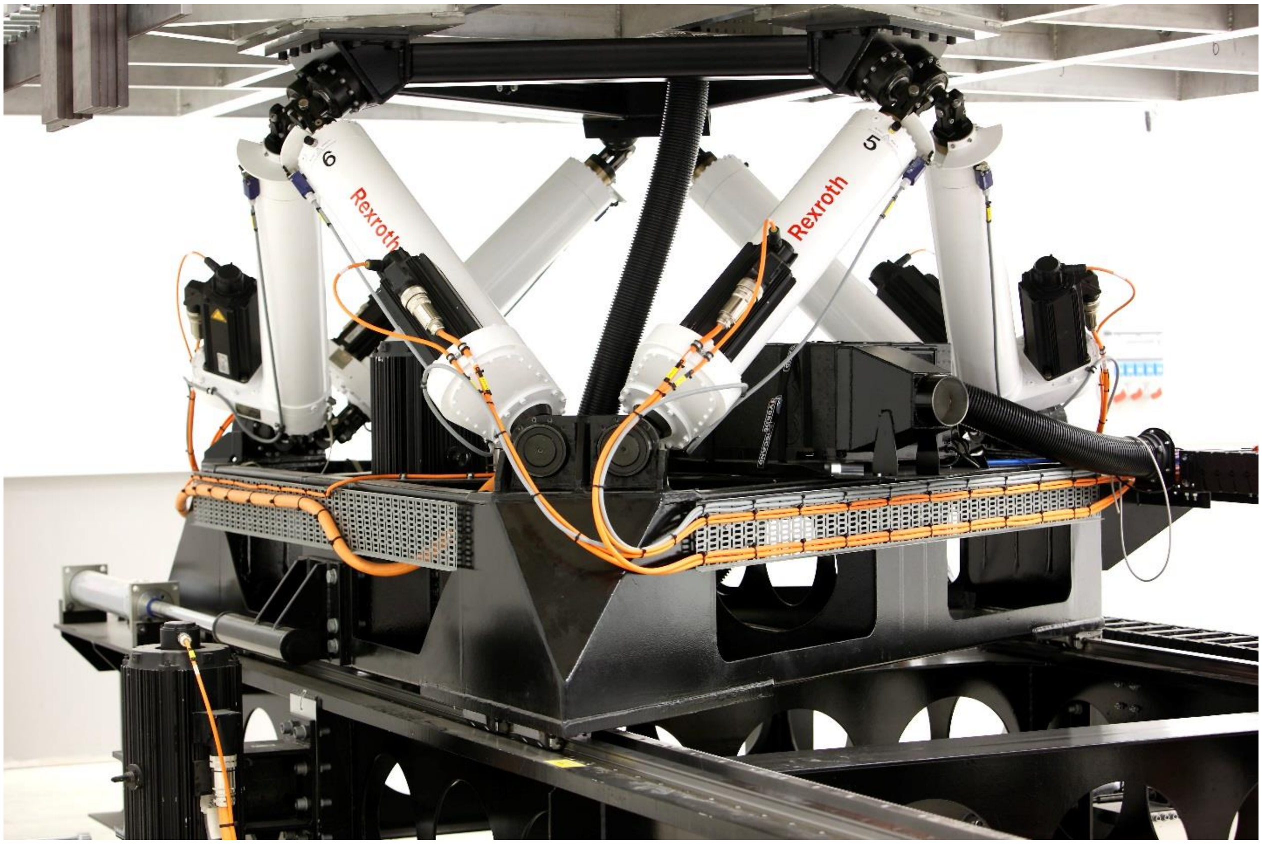

Figure 1. Hexapod. (Photo: Hejdlösa Bilder AB)

It is a possible to combine the hexapod with an XY-sled which results into two more DOF. Such motion system is used in VTI Sim IV [13], see Figure 2, Renault's Ultimate simulator [14], Toyota's driving simulator [15] and a driving simulator at the University of Leeds [16] to name some examples.

Figure 2. VTI SimIV. Hexapod with XY-sled motion platform. (Photo: Hejdlösa Bilder AB)

The hexapod construction also has variations, for example, the *inverted hexapod* which is used as a motion system in the DLR driving simulator [17, 18]. While the normal hexapod holds the load on above the top plate, on the inverted hexapod it is located under it [17].

Another mechanical platform for driving simulators are a *serial manipulator* or a *robot arm*. This mechanism offers 6 DOF motion capabilities with wide workspace, high dexterity, and relatively low cost. MPI CyberMotion Simulator [19] is based on the anthropomorphic robotic arm platform combined with a linear sled. Since the DOFs of the robot arm are not coupled, this motion platform has larger motion envelope compared with hexapod. A robotic arm based simulator can be used to move participants into positions that cannot be attained by a hexapod.

There is also a number of unique hardware setups used for the various driver-in-the-loop simulations. For example, Desdemona [20] - 6 DOF motion platform with serial kinematics. Compared to the parallel kinematic design of conventional hexapod platforms, Desdemona can combine limited linear motion in any arbitrary direction with centrifugal acceleration and unlimited rotations. Innovative motion platform design is a cable-driven parallel robot [21], co-developed by Max Planck Institute for Biological Cybernetics (MPI) and Fraunhofer IPA. In the cable-driven simulator, the motion of the simulator cabin is controlled by eight unsupported steel cables attached to winches. In contrast to conventional motion simulators, the use of cables makes it possible to reduce the moving mass and to scale the workspace to any required size. Another motion based driving simulator that has virtually unlimited working space is the Auto-Mobile.Driving Simulator

[22], developed at TU Dresden. This motion platform is based on wheels, which eliminates the travel restriction.

2.2 Motion cueing strategies

This subchapter gives the introduction of commonly used motion cuing strategies and techniques to show the variety of possible approaches to the motion cueing problem. The possibilities to improve realism of winter driving simulation that these strategies can provide is not studied in these thesis. However, the subchapter presents a general idea of what challenges these MCAs have and what sort of problems they are aimed to solve.

2.2.1 Classical algorithm

Classical MCA splits input signals in the frequency domain by mean of high- and low- pass filters. Then different frequency signals are delegated the certain parts of the mechanical system which can represent them with the required frequency. This approach is called frequency split [23]. The tuning of such MCA is performed by adjusting the filters' cut-off frequencies and scaling factors for all DOF.

Classical MCA was originally developed for 6-DOF motion systems, e.g. the hexapod. If an XY-sled is added, classical MCA can be modified by adding another filter that divides the vehicle linear accelerations between translational motion and tilt coordination (see Chapter 2.2.2). The scheme of the Classical MCA is shown in Figure 3. In this hardware configuration, the sled system will be responsible for representing the linear middle-frequency accelerations, the hexapod translation will represent the high-frequency linear accelerations and finally, the hexapod rotations will represent the tilt coordination and the rotational content.

Typical inputs to the classical MCA are two triplets of accelerations or/and velocities, obtained from the mathematical vehicle dynamics model [23]. These triplets are:

Three linear accelerations/velocities:

- longitudinal acceleration (braking/accelerating)
- lateral acceleration (cornering)
- vertical acceleration (road roughness and bumps)

Three angular accelerations/velocities:

- roll (suspension effects of handling)
- pitch (suspension effects of braking/accelerating)
- yaw (actual yawing of the vehicle in a turn)

The classical MCA is the most commonly utilized in VTI SimIV and was used for most of the studies done in this thesis.

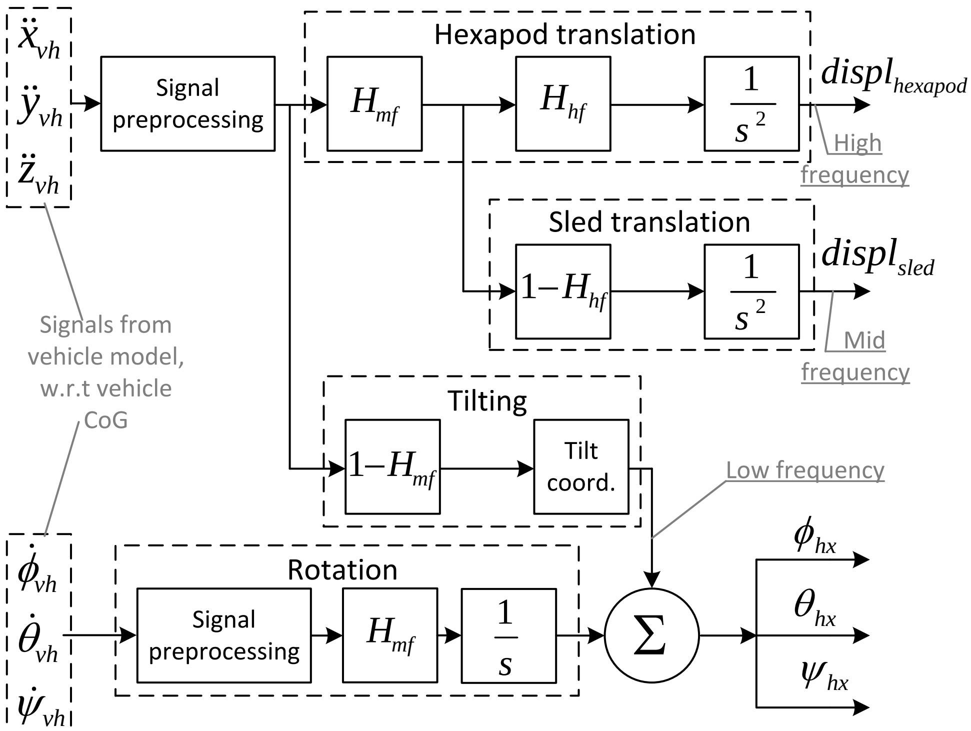

Figure 3. Classical motion cueing algorithm

2.2.2 Tilt coordination

Tilt coordination is a "perceptual trick" that allows representation of sustained translational acceleration by slow, below the perception threshold, tilting. The gravitational force pushes the driver in the tilting direction. If the translation is concurrently presented visually, the driver cannot distinguish between tilting and translation motion. In this way, the sensation of sustained linear acceleration is achieved [24]. A drawback of this method is that it introduces the lag in perceived acceleration [25].

2.2.3 Fast tilt coordination algorithm

It is challenging to achieve accurate acceleration perception with classical motion cueing algorithms due to the perceptional thresholds. One of the ways to deal with it is to minimize the tilting time, which allows much faster developing of a tilt angle. This allows to almost entirely handle the acceleration through the low-frequency tilt coordination filter. This *fast tilt coordination (FTC)* algorithm was evaluated in DLR [26] both longitudinally and laterally by comparing with the Classical MCA. There were no subjective preferences to any of them in the longitudinal task. For the lateral part, the FTC was noted considered significantly better in comparison with the classical algorithm.

2.2.4 Washout algorithm

During driving, the simulator eventually will reach its physical bounds – sled system will end up in its limit or the hexapod will saturate one of its degree of freedom. To prevent this, the motion platform needs to be returned to its initial position. This is often called *washout* and is implemented through a *washout algorithm*. The washout needs to be performed such that the driver does not notice the displacement. Failing to perform this under the perception thresholds will lead to false cues, i.e. perception of incorrect motions. Some studies found that the perception threshold for the linear displacement is 0.01g [27], and for the rotation 3°/s and 0.3°/s^2 [28]. However, these numbers can vary and if other cues also take place or with the experiment context, driver's sensitivity etc.

2.2.5 Adaptive algorithm

Adaptive algorithm, first introduced by Russell V. Parrish in 1975 in [29], aims to minimize the cost function by real-time adjusting the parameters of the motion cueing algorithm based on the current simulator and vehicle state. This is done by introducing penalties on certain states, which means that some states of the motion are considered as "more important" than the others. For example, it means that rough maneuvers can be represented in a very close to the reality manner, while gentle maneuvers will be almost unnoticeable or vice versa. Because of the real-time adaptation of the parameters, the same maneuver may be represented differently on different occasions. This inconsistency is most often undesirable as it violates the expectations and anticipations of the driver.

2.2.6 Optimal control algorithm

Optimal control algorithm is searching for a control law that satisfies certain criterion of optimality. In the same way as the adaptive algorithm described in the chapter 2.2.5, it changes the motion cueing parameters in real-time, which leads to the same drawbacks. However, the optimal control algorithm can take into account not only the simulator and vehicle states but also a motion perception model [30]. This approach rarely used in driving simulators so far due to the imperfection of the motion perception model. The development of such model is a rather complex task [31], and likely will not give significant benefit compared to adaptive algorithm, as it was proven for the flight simulator [32].

2.2.7 Model Predictive Control

In *Model Predictive Control (MPC)* approach, the control actions are optimized to the current system and to the number of constraints on the inputs, states and outputs change rates. The control action for certain prediction horizon is solved on every time sample, respecting the predefined constraints. Each calculation time step the current state of the system is taken as an initial and the optimization algorithm generates the optimal control sequence [33].

The biggest advantage is that this algorithm respects input and output constraints by direct embedding them into the optimization problem. The control objectives are defined in a very convenient form of the cost function, where different parameters are weighted parameters can be chosen based on the preferences, [33].

However, stability and performance features of the MPC are its weak points. It is difficult to explore the stability since introducing the optimization process with constrains makes the closed-loop system non-linear even if the controlled system is initially linear [34]. In addition, the computation effort required to solve the optimization problem in real-time is large, and in some situations infeasible.

2.2.8 Road related

While the classical motion cueing algorithm separates both longitudinal and lateral accelerations in the frequency domain, using high-pass and low-pass filters, *road* or *lane dependent* algorithm split the accelerations with respect to the position of the car on the road [23].

This approach is mostly suitable for simulators with significant displacement capabilities. For example, where the lane position can be presented with a scaled position in the motion system's lateral DOF. There are some assumptions and limitations, for instance, the road width is known in advance and the driver supposed to stay within the road boundaries.

One of the drawbacks of this method is that the lateral forces caused by the road curvatures are still need to be represented by tilting. Hence, there is a need to balance these two ways to present lateral acceleration while simulating curve negotiation. This balance is non-trivial and the risk of false cues is imminent. The road related strategy cannot be extended to the longitudinal case, implying the need to treat longitudinal forces differently.

2.2.9 Prepositioning

As previously stated, driving motion simulators suffer from the physical limitations of the motion envelope. It is recommended to minimize or, if possible, avoid representing acceleration with help of the tilt coordination [35, 36, 37, 25], since high tilting rate will be noticed by the driver and low tilting rate will rise a lag in perceived acceleration [25]. It is possible if one can transfer energy from low-frequency part (accelerations presented by tilting the hexapod) to middle frequency (sled).

The washout algorithm tries to return the motion platform to some default position. This position is usually the center of the sled. This is the most advantageous position in terms of available displacement possibility, given no a priori information on future motions. However, the central position is not most advantageous with respect to future maneuvers. Positioning the sled based on future maneuvers is called the *prepositioning* [38]. The prepositioning need to be performed bellow the perceptional threshold rate to avoid false cues. An algorithm was implemented and studied in VTI Sim IV within the current project, [39].

3 Tire models and characteristics

In a context of winter driving simulation, it is reasonable to assume that the largest difference between summer and winter conditions originates from the tire and its interaction with the road. In vehicle dynamics simulations, this interaction is described by a mathematical model of the tire.

Driving in winter conditions, i.e. on slippery surfaces, compared to summer condition driving is closer to the limit of what the tire surface interaction can generate in terms of forces. Hence, the existing vehicle dynamic models need to be reviewed and revised to cope with the winter conditions. It is required to have a tire model that can accurately calculate the tire force on all slip levels.

It was observed in multiple measurements that the slip/force and the self-aligning torque curves for the tires driven on snow and asphalt have substantially different shape. Commonly used tire models assume the road to be a solid surface, which is not true in the case of driving on snow. Thus, these models usually have low accuracy in the tire on snow simulations. Moreover, it is desirable to understand whether the tire model significantly influences the driver's perception in a driving simulator and, if so, how a tire on snow then should be modeled in the best way.

The forces generated by the tire depend on many factors, such as the road surface properties, tire tread pattern, stiffness, and tire type, etc. Most of these factors are perceived by the driver in a real vehicle. In a driving simulator, the tire model describes the tire to road interaction, incorporating the tire and road surface characteristics. However, it is not clear how each of these characteristics is perceived by the driver separately.

The following subchapters give a brief overview of some of the tire characteristics and commonly used tire modeling approaches. These approaches describe the tire to road interaction and how the properties of tire and surface influence this interaction.

3.1 Tire characteristics

The interaction between the tire and the road surface is a very complex phenomenon, which can be seen from very different perspectives, like vehicle dynamics, aerodynamics, safety, economics, and environment, among others. This chapter describes some of the most fundamental characteristics that are commonly used to describe the tire from a vehicle dynamics perspective.

3.1.1 Friction

Friction force is a force that resists the relative motion of two surfaces. Maximum available tire force is directly proportional to the applied load. The ratio between the friction force that tire can extract and the applied normal load is limited with friction coefficient μ. The friction coefficient depends on the tire, the road surface and the applied load. The value of the friction coefficient can range from 0 to greater than 1. Typical values for different road surface are around 0.05-0.2 for ice, 0.6-0.8 for wet asphalt, 0.9-1.1 for dry clean asphalt. On a force/slip curve, the friction coefficient determines the level where the curve is saturated. Different coefficients of frictions are illustrated in test track measurements in Figure 4, where tire 1, for example, reaches a friction level of 0,57 while tire 2 reaches a friction level of 0,81.

3.1.2 Tread stiffness

The tread is the rubber on the tire's circumference surface. When the force is applied to the tire, this rubber elastically deflects. The stiffness of this deflection depends on factors like the rubber material itself, the tread pattern and height, tire wornness, size, speed of rotation and temperature, etc. In a force/slip curve, this stiffness is represented by the initial slope. It can be seen in Figure 4, where all tires have different tread stiffnesses.

3.1.3 Soft transition

Soft transition is a characteristic observed for loose soil surfaces like snow, see paper D or [40]. In force/slip curves for tires on this kind of surfaces, the transition between the linear region (for small slip) and saturated tire (for high slip) is softer comparatively with tires on solid surfaces. It can be seen in Figure 4, where Tire 1* has a softer transition from linear to the saturated region than Tire 2. Tire 1* is an up-scaled version of Tire 1 to make the comparison easier between Tire 1 and 2.

3.1.4 Friction pronounced peak

Pronounced peak tire characteristic can be observed when the stiction friction is higher than the sliding friction. In this case, when the tire contact patch starts sliding, the loss of adhesion friction causes a decrease in the tire force. This is common for slippery surfaces, like wet asphalt [41] and ice [42]. This phenomenon can also be observed in Figure 4, where the tire reaches μ=1, and then gradually decaying with increased slip.

3.1.5 Carcass stiffness

The carcass is the framework of the tire. The carcass refers to all layers made up of tire cord. It absorbs the tire’s internal air pressure, weight, and shock. Carcass design defines the tire load capacity and balances its handling, damping, and comfort. The carcass stiffness can be decreased by lowering the tire inflation pressure. Carcass stiffness is the part of the tire where the most of the dynamics that affects the vehicle handling happen. Usually, the carcass stiffness is modeled as tire relaxation, see subchapter 3.2.3.

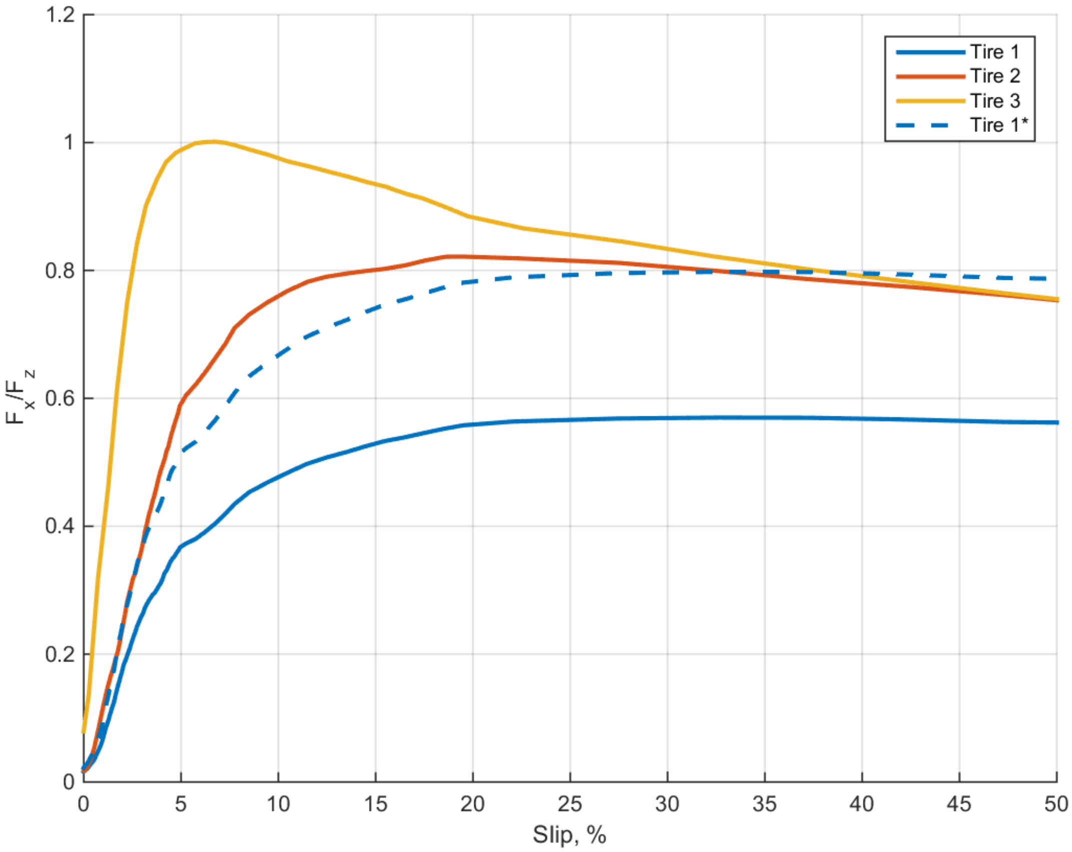

Figure 4. Tire characteristics from tire measurements. Tire 1 is a Nordic winter tire on a snow surface; Tire 2 is a studded winter tire on wet asphalt; Tire 3 is a summer tire on wet asphalt; Tire 1* is an up-scaled version of Tire 1, to illustrate the difference in shape between tire 1 and 2.

3.2 Tire modeling

Tire models describe the tire behavior or some properties by means of mathematical equations. The purpose and area of application of the tire model determine its complexity and the processes that a model describes. The complexity can range from a couple of simple algebraic equations for real-time vehicle dynamics simulation purposes, to complex system of differential equations for detailed studies of for example tread pattern influence on force generation or aerodynamic processes.

This section briefly describes some approaches to modeling of tire dynamics for real-time and offline vehicle handling simulations. This list of models is not exhaustive but represents some commonly used approaches. A vast majority of these models describe the steady state relationship between the contact patch force and the tire motion (slip).

Currently, a large number of approaches to tire modeling exist, ranging from the purely mathematical curve-fitting, such as Magic Formula to physically motivated approaches, like brush model. Although the empirical tire models are very flexible in terms of matching measured data, they do not contribute to the understanding of the nature of tire to road interaction. Physically motivated models, on the other hand, can give the inside of this interaction, thus they are more practical to use in the research related to simulation different road conditions.

3.2.1 Physical tire models

This subchapter presents some tire models that have been derived based on physical assumptions. Usually, the parameters of these kinds of models have a physical interpretation and even something that may be measurable separately.

3.2.1.1 Brush model theory

The brush model is a well-known physically motivated approach to tire modeling [43]. The brush model theory assumes that the rubber volume in the contact patch is divided into small brush elements – linearly elastic and independently deforming plate-like bristles. Then the tire is propelled, due to the bristles elasticity and friction properties, they adhere to the surface in the front part of the contact patch and start sliding in the rear. These two areas are separated by the break-away point x_s.

In the adhesion region, the force is supported by the static friction and caused by the elastic bristle deformation. In the sliding region, the bristles slide supported by the sliding friction, thus, the generated force does not depend on the bristle deformation.

The size of the adhesive region is determined by the available static friction which is, given the normal force $dF_z(x)$, described by elliptic constraint:

$$\left(\frac{dF_{a,x}(x)}{dF_z(x)\cdot\mu_x}\right)^2+\left(\frac{dF_{a,y}(x)}{dF_z(x)\cdot\mu_y}\right)^2\leq 1$$

where the μ is the velocity independent coefficient of friction; $F_{a,x}$ and $F_{a,y}$ are adhesive forces; F_z is a normal load.

Introducing the pressure distribution $q_z(x)dx = dF_z(x)$, the size of the adhesive region can be calculated. Then, the adhesive force is calculated by integrating the bristle deformation force over the adhesive region. The sliding force is obtained by integrating $q_z(x)$ over the sliding region. The usual assumptions are to describe the pressure distribution in the contact patch as a symmetric parabolic or uniform function. More complicated functions give a relatively small gain in accuracy, while the resulting expressions complexity rising dramatically [43].

The resulting force is equal to the sum of adhesive and sliding forces for parabolic pressure distribution is given by,

$$F = C\cdot\sigma - \operatorname{sign}(\sigma)\cdot\frac{C^2\cdot\sigma^2}{3\cdot\mu F_z}+\frac{C^3\cdot\sigma^3}{27\cdot(\mu F_z)^2}$$

where C is a tire lumped bristle stiffness coefficients and σ is the tire slip.

3.2.1.2 String model

The main difference with the brush model approach is that the bristles deflection is assumed to be dependent on each other. This implies certain deformation of the tire sidewalls. The shape of the string is dependent on the side force and the sidewall properties, like material elasticity, tire profile height and so on. This model is implicit since the side force and the string shape affects each other, [44].

3.2.1.3 Beam model

The beam model describes the tire as a set of massless beams that have certain string stiffness/ longitudinal and lateral. The radial beams are connected to the tire rim from one side and linked together with shorter beams on the other side, forming a net. This net represents a tire tread. The forces generated by the tire is calculated as beams' deflection forces that are the result of the relative displacement of the beam elements with respect to each other and wheel rim, [45].

3.2.2 Empirical tire models

Tire models presented in this subchapter do not have a particular basis in physics. Instead, they are designed to fit real-life tire measurements well.

3.2.2.1 Magic formula

Magic Formula [46] tire model is probably the most known and widely used tire model. It is also commonly used in driving simulators. This model uses trigonometric functions to curve-fit the experimental data. In its most basic form, the curve expression has such form:

$$Force = D \cdot sin\left(C \cdot arctan\left(B \cdot slip - E \cdot \left(B \cdot slip - arctan(B \cdot slip)\right)\right)\right)$$

Although the model parameters do not have any physical meaning, they determine the curve shape as follows: B - stiffness parameter, C - shape parameter, D - peak value parameter, E - curvature parameter. These parameters can be made dependent on the vertical force. The expression above can be used to fit both tire force and the self-aligning torque, depending on the parameter combination.

3.2.2.2 TMsimple and TMeasy

TMsimple and TMeasy are also curve-fitting models. TMsimple is a simplified version of the TMeasy. TMeasy is further described in [47]. TMsimple is presented below.

$$Force = F_{max} \cdot sin\left(B \cdot \left(1 - e^{-\frac{|s|}{A}}\right) \cdot sign(slip)\right)$$

Where:

$$B = \pi - arcsin\left(\frac{F_\infty}{F_{max}}\right)$$

$$A = F_{max} \cdot B/\arctan(C)$$

With C is a curve initial slope, F_{max} and F_∞ are maximum and saturated tire forces.

3.2.2.3 Burckhardt

Burckhardt is a curve-fit tire model that exists in two variants – speed dependent [48] and independent [49]. The speed dependent version looks like:

$$Force = \left(c_1 \cdot \left(1 - e^{-c_2 \cdot slip}\right) - c_3 \cdot slip\right) \cdot e^{-c_4 \cdot speed}$$

For the speed independent model, c_4 is equal to 0.

3.2.3 Relaxation model

The relaxation model is aimed to describe the physical dynamic phenomenon of the gradual tire force development [50]. In other words, the first order dynamics between the moment when the slip is introduced and the force reached its steady state value. Usually, it is described as a distance (relaxation length) that tire need to roll before the tire builds up 63% of its steady state value [51]. Typically, the relaxation length can be approximated as "at nominal vertical load the relaxation length is of the order of magnitude of the wheel radius" or "approximately equal to half the contact length of the tire" [50]. This value can vary between the 0.1 and 0.5 meters, depending on the tire stiffness, inflation pressure and so on. The tire relaxation is typically modeled with a first order speed dependent system acting on the force.

3.2.4 Friction models

The aim of the tire to road interaction model is to describe the force development of the tire. Most of these forces are friction based. The friction force resists the relative motion of the surfaces that are in contact with each other. In the case of dry friction, it can be divided to static and kinetic frictions, depending on if the surfaces are stationary or moving with respect to each other. This phenomenon can be described in different ways, based on the made assumptions and simplifications.

3.2.4.1 Static models

Static models are mostly simple mathematical representations of certain frictional behaviors. These models do not describe the process in complex, but only some phenomena, such as static friction, friction as a function of steady state velocity, etc. Probably the most used and the simplest example can be a Coulomb friction model [52], which does not consider any dynamic effects. It describes the friction force as a force that acts opposite to motion, with a magnitude proportional to the normal force. The main problem of this model is an inaccurate representation of the friction on close to zero velocity since it does not consider pre-sliding displacement. The viscous friction element models the friction force as a force proportional to the sliding velocity. The Stribeck effect describes the initial force decrease with increasing sliding velocity.

3.2.4.2 Dynamic models

Friction has memory-dependent behavior, like pre-displacement, rate-dependence, hysteresis, etc. To model these phenomena, dynamic models are required. One of the earliest dynamic friction models is a Dahl model [53], designed to simulate the symmetrical hysteresis. However, this model does not capture the Stribeck effect, thus cannot predict the stick-slip motion. The LuGre friction model [54] is an extension of Dahl model that capture this phenomenon.

4 Summary of papers

This chapter provides a brief description of the appended papers and present key findings.

4.1 Paper A. The Importance of Yaw Motion Feedback in Driving Simulators

In hexapod-based motion systems, all DOF are mechanically connected. This implies that all DOFs cannot be fully actuated and some balance between them need to be chosen. Thus, it is important to understand the effects of each cue for MCA development and tuning. Winter driving is characterized by more pronounced yaw motion as on low friction surfaces, the rear wheels can lose traction, causing oversteering. Paper A presents a study on the influence of yaw motion feedback in driving simulators on the driver's behavior.

The conducted experiment aimed to analyze the influence of yaw motion in simulator feedback in three driving situations – regular driving, at light impact and extreme maneuvering. The experiment was designed as a between subject study, where one group of test subjects had the yaw component in the motion feedback, and the other group did not have it. It was found that during normal driving conditions, subjects without yaw motion feedback positioned themselves in the lane in average 24 cm close to the center line than subjects with yaw feedback. Previous studies suggest that this behavior is more common in real life driving than to driving in a simulator. The lane position result can be seen as an indication that yaw motion feedback contributes a more realistic driving behavior. During the impact condition, a significantly larger lateral displacement was observed in the case of "without yaw" motion feedback. This happened due to different steering behavior, which could be caused by the lack of the motion feedback and worse awareness of the current vehicle state. In the extreme post impact maneuvering, a significant difference was found regarding the time required to return to the initial lane after the impact. This time was significantly shorter for the group with yaw motion in the feedback.

4.2 Paper B. The Importance of Yaw Rotation Centre on the Driver Behaviour

This paper investigates the importance of correctly representing the momentary rotation center of the simulated vehicle in the motion platform of a driving simulator. The comparison was done between steady state and dynamic representations of the vehicle's momentary rotation center.

The influence of the rotation center was studied through an experiment, where test subjects were conducting a series of cone-guided double lane change maneuvers. Two different strategies of the rotation center representation were used for the motion feedback: steady state and dynamic. The maneuver was conducted on two different friction levels, to study the effect of road grip. The experiment was designed as a within-subject study which contained both subjective and objective measures. The subjective assessment was performed through questionnaires, while for objective assessment the steering wheel angle input was used to compare the steering response in two motion feedback settings. The performance was self-rated slightly higher for the steady state rotation point setting, while the level of assistance was voted in favor for the dynamic rotation point. The analysis of the trajectory and steering wheel input showed that the drivers' responses were very similar for low speeds. However, with increasing speed the tendency of decreasing the reaction time was observed for the drivers with steady state rotation points. The cone hit analysis indicated that the drivers experienced problems positioning the vehicle on the road or with perceiving the vehicle dimensions. The higher speed driving maneuvers were conducted in conditions that are not close to the steady state, and the difference between the motion feedback settings was substantial. However, only a subtle difference was noticed in the driver's behavior.

4.3 Paper C. Perception of Tire Characteristics in a Motion Base Driving Simulator

Paper C presents a study of different tire characteristics perception in a motion base driving simulator. Perception of the tire to road interaction is complex and depends on many tire characteristics. However, it is not clear how any of these characteristics separately contribute to the perception of the vehicle motion.

An experiment was conducted in a motion base driving simulator. In the driving simulator, the tire to road interaction is described by a mathematical tire model. This enables to change any chosen tire characteristic without affecting any other one, and study them subjectively in isolation. The experiment was designed as a comparison between 4 different test tires and a reference tire. Each of the test tires had one parameter changed compared to the reference tire. The test subjects were not aware of the differences, only that different tires should be tested. They were asked to describe the difference in the vehicle behavior and name what tire characteristic was changed. The characteristics changed in the test tires were:

- lower tire tread stiffness – as if the tire has softer compound (like winter tire compared with summer tire)
- soft transition to a force saturation – phenomenon that can be observed when driving on loose soils like snow
- pronounced force peak – common on surfaces like wet asphalt
- weaker carcass stiffness – represents, for example, lower inflation pressure

The tire characteristics were perceived with different intensity. Among the studied characteristics, the most noticeable difference to the reference tire was the tire with lower tread stiffness. Many test subjects directly identified this characteristic. The tire with a soft transition was also identified, but slightly less precise than the tread stiffness. Driving with this tire was described as one could expect driving on snow would be described. This could be an indication that using this tire in the driving simulator may contribute to the perception of the driving on snow. The pronounced peak tire characteristic was not perceived strongly due to lack of force extraction in the experimental setup. The tire with the weaker carcass stiffness was in general described as having a slower response. At the same time, some test subjects commented that the vehicle was easier to control, which could be explained by personal preferences of finding it easier to control a vehicle with slower response in combination with the latencies that exist in the driving simulator.

4.4 Paper D. A double interaction brush model for snow conditions

Commonly used tire models assume the road to be a flat solid surface. Thus, when these models are used to simulate tires on snow, the simulation results are not accurate. Paper D presents a physically motivated tire model that takes snow shearing properties into account. The introduced set of parameters and low calculation complexity makes it suitable for the real-time simulations.

Snow test track measurements were compared with the Magic Formula tire model and the brush model with different pressure distributions. The Magic Formula tire model offers a good fit for the measurement data due to its curve-fit nature. However, the parameters of this models do not have any physical interpretation. Moreover, the number of parameters is higher compared with, for example, the studied brush models. The magic tire formula requires 12 parameters to generate the longitudinal and lateral force along with the self-aligning torque, while the brush models require only 4 each. Lastly, as any empirical tire model, the Magic Formula is problematic to tune without access to real-life measurements. Hence, conducting a simulation with a new type of tire can become an expensive process. All this makes the physically motivated tire models preferable in the driving simulator applications. The physically motivated approach used in these models makes them easier to parametrize, modify, extend and predict the behavior, in case certain measurements are not available.

The model presented in Paper D assumes that the main difference between the behavior of the tire on asphalt and snow is caused by the snow that gets stuck in the tire voids and sipes. This snow also interacts with the snow on the road surface, contributing to the force generation. Both rubber to surface and snow to surface interactions were modeled with the brush model theory. This assumption implies that each of the interactions requires its own set of parameters – longitudinal and lateral stiffness coefficients and the friction coefficients. The performance of this model was compared with the Magic Formula and conventional brush model with different pressure distributions towards the snow test track measurements. The double interaction model captures the phenomena called “soft transition” in Paper C. It has 8 parameters and shows smaller fit error compared with the conventional brush model and similar error compared with the Magic Formula tire model. Moreover, this model manages to correctly predict the self-aligning torque using the parameters obtained from the force measurements.

5 Discussion and conclusion

Driving in winter conditions is in many ways different from summer driving. However, it is not always clear how to quantify it or even describe it in details. Moreover, we need to know the main contributors to the winter-like driving impression. Understanding this is required to increase the realism of winter driving simulations in motion base driving simulator. This thesis describes a study aimed to approach this problem.

Current research focuses only on some aspects of vehicle motion and its perception in driving simulators. Other cues, such as sound, graphics and vibrations have not been considered in this thesis. It was suggested that the main differences in terms of vehicle motion pertain to the more extensive yawing and difference imposed by the winter road surface. To study these assumptions the questions stated before will be discussed in the light of the obtained results.

1. *How important is yaw motion in driving simulators and how does it affect the driving behavior and perception? (Addressed in the Paper A)*

Drivers that had yaw motion feedback tend to position the car on the road more similar to the real-life driving. This can be an indication of a more realistic driving impression during the experiment. Also, they have better extreme maneuvering performance and regain the control over the car faster. This can be seen as an indication that yaw motion feedback in the motion driving simulator contains information which makes the motion feedback more complete, contributing to easier maneuvering. Its absence, on the other hand, limits the perception of motion, which affects driver's behavior.

2. *What is the impact of correct representation of the rotation center in driving simulators? (Addressed in the Paper B)*

It was found that correct representation of the rotation center is more conducive to performing the maneuver, although the self-assessed driving performance was rated higher for the steady-state rotation center representation. However, neither of these differences were found to be statistically significant. Concerning the driver behavior, only a subtle difference in the steering reaction time was found between studied feedback strategies. Although the observed differences are small, the rotation center contains information that can be valuable to the driver in terms of perceiving the vehicle motion state. Thus, the correct representation of the rotation center is preferable to a steady state one with respect to driver behavior and motion perception.

3. *How are different characteristics of tire to road interaction perceived by the driver? (Addressed in the Paper C)*

Different characteristics of tire to road interaction are perceived with different intensity. The differences caused by the change in tread stiffness are perceived strongly and in many cases the changed characteristic was named. This points to the importance of this characteristic in the driving simulation. For the soft force transition, the difference was perceived, but not identified. Since this characteristic is common for driving on snow surface, we conclude that presenting this characteristic during simulation can be beneficial for increasing the perception of winter driving in the driving simulator. The presence of the pronounced peak was not noticed in the given experiment setup. Weaker carcass was noticed, but the difference was described somewhat contradictorily. The amplitudes of characteristics changes were kept within a realistic range but yet chosen freely. Thus, the intensity of perception of these characteristics should not be compared between themselves.

4. *How to capture tire on snow behavior in a mathematical model? (Addressed in the Paper D)*

It was noticed that the force/slip characteristic for the tire on snow has a softer transition from the linear to saturated tire region, compared with the tire on asphalt. It was suggested that this difference in tire behavior can possibly be explained by the interaction between the snow that stuck into the tire pattern voids and the snow on the road surface. This interaction was modeled using a brush model theory. The comparison with the real life measurements shows that this model allows capturing the soft transition from the linear to saturated tire region. The developed model has a good match with the real life measurements. Also, this model allows to correctly predict the self-aligning torque using only the parameters obtained from fitting force measurements.

The research done in this thesis concerns only vehicle yaw rotation and the tire to road interaction. Both of these aspects affect the vehicle planar motion. However, there are other phenomena, both vehicle, and environment related, that affect the longitudinal, lateral and yaw motion of the vehicle. The choice of the research questions was based purely on researchers' intuition. Thus, it is required to conduct more sophisticated studies that can tackle the question of what other vehicle motion related factors are important for increasing the simulator's fidelity in winter condition simulation and how they weigh in the perception of fidelity. Other road surfaces, like ice or ice-snow-asphalt combinations with split and step friction, also should be studied and modeled. Moreover, although a large part of the findings is in line with the results obtained by other researchers, all the simulator studies in current research were conducted in the same simulator facility, which could affect the results.

Apart from the planar motion, there are other simulated cues that affect the realism of driving simulation. Undoubtedly, visual, acoustic and vibration cues would also play an important role in creating a winter-like driving experience. Proper winter graphical effects would definitely increase the realism of the simulation. Specific acoustic background and vibration with appropriate frequencies and amplitudes would increase the immersion and in some cases even provide the information about the surrounding environment, such as road condition. Probably, the best result with respect to the simulation realism would be achieved with the synergetic work of all these cues.

Answers to the questions stated above point that, indeed, both yaw motion and tire to road interaction modeling play important role in the perception of motion in the driving simulator. We can conclude, that tweaking these aspects in the motion driving simulator can contribute to increasing the realism of the experiments that involve driving in winter conditions. In order to achieve improved realism, the correct representation of yaw component in the motion feedback with the dynamic rotation point should not be omitted. Also, to present a more realistic vehicle-on-snow motion, using a tire model that captures the behavior of tire on snow is advisable.

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