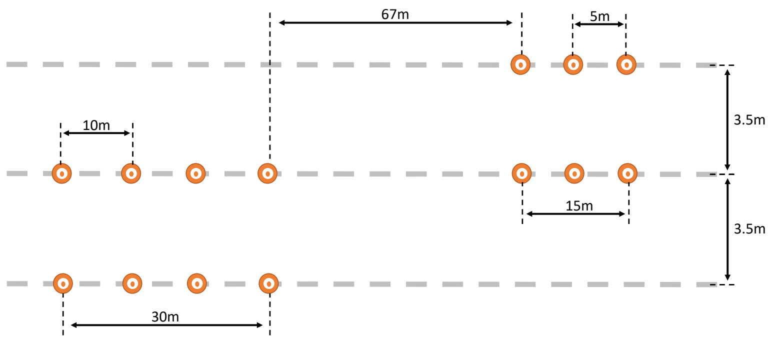
Vehicle Dynamics Testing in Driving Simulators

A Case Study for Heavy Vehicles



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Preface

The project *Vehicle Dynamics Testing in Simulators (VDTestS)* was a joint effort between the Swedish National Road and Transport Research Institute (VTI) and Volvo Group Trucks Technology (VGTT) within the ViP Driving Simulation Centre (www.vipsimulation.se). The project aimed to probe the potential of a driving simulator in the field of vehicle dynamics testing and should be regarded as a pre-study investigating the feasibility of using a driving simulator as a complement to traditional real-world vehicle dynamics testing. For this purpose, a simulator test case was prepared embodying the nature of a vehicle dynamics test set-up. The test was carried out in VTI's motion-based driving simulator Sim IV in Gothenburg, with assistance from engineers and mechanics from VGTT product development well familiar with truck mechanics and truck driving. This made it possible to gather feedback about the suitability and potential of the driving simulator for dynamics testing from the point of view of professionals in the field. This report describes the motivations and preparations behind the undertaken work, as well as its results and conclusions.

VDTestS was supported by the competence centre ViP, i.e. it was co-financed by the Swedish Governmental Agency for Innovation Systems (VINNOVA, grant number 2007-03083) and the ViP partners.

Given the small scale of the project, the dissemination focus will revolve around the ViP centre and its partners, and the bulk of the efforts will be concentrated in this final report which shall also be made available to the public. Additionally, an article titled "Vehicle dynamics testing in motion based driving simulators" has been published in Vehicle System Dynamics Journal.

The participants in the VDTestS project originate solely from VTI and VGTT. From VTI the participants were Bruno Augusto (project manager) and Sogol Kharrazi. From the VGTT side Niklas Fröjd was the sole participant.

Gothenburg, February 2017

Bruno Augusto

Quality review

Peer review was performed on 16 March 2017 by Jolle Ijkema, Scania and on 28 March 2017 by Bengt Jacobson, Chalmers. Bruno Augusto and Sogol Kharrazi have made alterations to the final manuscript of the report afterwards. The ViP Director Lena Nilsson examined and approved the report for publication on 29 January 2019.

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Abbreviations

DOF	Degree of Freedom
VGTT	Volvo Group Trucks Technology
VTI	Swedish National Road and Transport Research Institute

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Vehicle Dynamics Testing in Driving Simulators: A Case Study for Heavy Vehicles

by Bruno Augusto[1], Sogol Kharrazi[1], and Niklas Fröjd[2]

[1] Swedish National Road and Transport Research Institute (VTI)
[2] Volvo Group Trucks Technology (VGTT)

Executive summary

VDTestS set out to probe the potential of a driving simulator in the field of vehicle dynamics testing. For this purpose, a simulator test case was prepared embodying the nature of a vehicle dynamics test set-up. The goal was to figure out if the drivers in the simulator could identify the handling differences owed to changes in vehicle settings, while driving simulated trucks.

A truck model was validated against the performance of a real vehicle under a predefined set of manoeuvres. This was coupled with the tuning of the simulator motion to improve the perception of the vehicle dynamics. These efforts were followed by definition of a group of four test cases, each corresponding to a set of alternate vehicle properties. These sets were selected based on their potential impact on the vehicle handling and correlation with changes that could occur in a real vehicle. Finally, experiments were conducted in VTI's motion-based driving simulator, Sim IV in Gothenburg, with participation of ten engineers and mechanics from VGTT product development well familiar with truck mechanics and truck driving. The set-up made it possible to gather feedback, about the suitability of the driving simulator in these testing conditions, from professionals in the field. Data was collected subjectively via interviews and questionnaires as well as objectively from the logs comprising of driver inputs and vehicle motions generated during the simulator drives.

Results show that the drivers could clearly identify the differences in vehicle behaviour for most of the performed tests, which motivates further investigative work in this area and exposes the feasibility of vehicle dynamics testing in simulators.

1. Introduction

Driving simulators are a controllable and versatile environment which allows drivers to experience situations that would otherwise be impracticable in real-world conditions due to e.g. threats to physical integrity, logistical costs, and conceptual technology, to name a few. They come in different shapes and sizes corresponding to different fidelity levels and are usually developed having in mind a specific set of utilization conditions. As a tool, a driving simulator can be considered in a broad spectrum of applications such as analysis of driver behaviour, development of vehicles, and studies of new functionalities in vehicles, road infrastructure design, driver education, among many others.

With such potential, it is expected that a driving simulator could also be regarded as part of a tool chain for vehicle dynamics development, which is not the case today. Usage of driving simulators for vehicle design and engineering is uncommon [1, pp. 12-10]. When the aim of the driving simulation is focused solely on the vehicle performance, as is the case in these types of tests, the simulator implementation needs to be such that it is possible to reproduce vehicle cues with a higher fidelity threshold, when compared with the great majority of other simulator applications. In these circumstances, phase difference between cues plays an important role in the perception of the vehicle dynamics. Furthermore, it is important to really enforce driving under the validated working envelop of the simulator to avoid the problem of extrapolation [1, pp. 7-5]. In addition, motion feedback is an important component of evaluating or “feeling” the vehicle performance and, assuming the simulator under question can even present motion cues, the limited motion envelope of the simulator acts as a constraint on the type of viable manoeuvres around which it is possible to maintain fidelity.

The limitations above can possibly explain why the usage of driving simulators is not widely spread within vehicle dynamics testing. However, in the same way that simulators are validated for certain working regions for other applications, they could similarly be tuned for vehicle dynamics tests. In these circumstances one certainly faces a more restricted validated region which could even be non-existent in certain simulators.

If a driving simulator can be validated to reproduce the vehicle behaviour to a level of fidelity which satisfies the requirements of vehicle dynamics testing, a novel set of vehicle testing alternatives is made available. These could complement and possibly even replace some of the current methods that are conducted in test facilities today. When compared with the existing methods, a driving simulator’s versatility would create an environment capable of emulating different testing set-ups and vehicles, all while reducing the preparation overhead and keeping the driver and others away from risk.

The current work focuses on analysing the potential of using driving simulators for these types of tests. First, vehicle dynamics tests are addressed to highlight their importance, explain how they are commonly performed and, how a driving simulator could be integrated in the testing loop. Second, suggestions are given regarding the integration of vehicle dynamics testing and driving simulators, in terms of what conditions need to be fulfilled in a driving simulator to allow for this type of activities. This is followed by the description of a case study and its results. The case study focused on heavy vehicle dynamics testing and was performed in the VTI’s motion-based driving simulator Sim IV [2] in Gothenburg. Finally, the conclusions of this work are presented together with suggestions for future work in this area.

2. Vehicle dynamics testing and driving simulators

2.1. On vehicle dynamics testing

Vehicle dynamics testing involves subjecting the vehicle to a set of inputs and assessing the vehicle motion to characterize the vehicle performance. This can be done in different ways, by pure simulations with vehicle models, hardware-in-the-loop simulations or testing the actual vehicle on a test track or on a road. In case of simulations, with no drivers in the loop, the assessment is done objectively by calculating the vehicle motion outputs. However, the objective evaluation of a vehicle's performance is not enough, hence it is complemented with subjective evaluation by test drivers. This is commonly achieved by conducting tests with the actual vehicle, which enables both objective evaluation of the vehicle performance by measuring the vehicle outputs, and subjective evaluation of the vehicle motion by test drivers. Furthermore, having the driver in the loop is also important for objective evaluation, from the aspect of exposing the vehicle to more naturalistic inputs, or reactions in case of testing an active system.

2.2. Driving simulators as a resource for vehicle testing

As stated in the introduction, a driving simulator is a tool which enables evaluation of the vehicle performance with the driver in the loop. Thus, it can be regarded as part of the tool chain for vehicle dynamics development. However, this is rather uncommon. Therefore, the feasibility of using driving simulators as a resource for vehicle dynamics testing is investigated in this study.

2.2.1. When

The purpose of a driving simulator lies in having a driver in the loop. Putting aside for the moment considerations of simulator validity/fidelity, as well as availability of simulated cues, one could assume that if a certain vehicle testing activity requires having a driver in the loop, it could be performed in a driving simulator.

2.2.2. Why

Essentially, the simulator would present a testing environment which is easily malleable, being able to simulate any kind of testing environment at any given moment, without the overhead introduced by its real-world counterparts. This could considerably speed up testing procedures, since conditions can be changed instantaneously with much less waiting time. Additionally, a driving simulator provides repeatability, as well as safety, enabling the possibility to test dangerous scenarios virtually.

Furthermore, the vehicle models in a driving simulator are usually mathematical formulations which can be easily changed and parameterized. This broadens the scope of testing by creating possibilities which are unfeasible in a real vehicle. Also, the vehicle setting changes can occur immediately in a driving simulator, leaving the driver with a fresher recollection of the previous experiences, and consequently in an improved position to perform comparison judgements.

2.2.3. How

Within the scope of vehicle dynamics testing, a driving simulator could be used in test iterations at early and mid-stages of development to gather a better subjective understanding of the vehicle and to evaluate the vehicle performance with a driver in the loop. This would help to refine future testing demands before moving the scrutiny to the real world, thus sparing time and resources.

2.2.4. Setbacks

A driving simulator will never deliver an exact sensation of driving. The dynamics of the driven vehicle are modelled from a real-world reference and such models carry assumptions and simplifications which, while acceptable, mean that it is not possible to thoroughly represent all vehicle motions. Furthermore, the environment and any driving cues are also reproduced based on similar models which fall short of a fully accurate portrayal of reality.

In a simulator, the closer one gets to the sensation of driving a real vehicle the higher the simulator fidelity [1, pp. 7-2]. However, it is often difficult to assign an objective value to a simulator fidelity, given its subjective nature. Furthermore, it is reasonable to assume that vehicle dynamics tests stimulate a broader range of dynamics than standard everyday driving. This implies that the fidelity requirements need to be stretched to accommodate new working regions. Often, this is translated in greater monetary and workload efforts related with purchasing, developing and integration of simulator components which *might* allow a driving simulator to meet the increasingly tougher thresholds for fidelity.

Essentially, a driving simulator could be regarded as a collection of cues aimed at replicating their real-world counterparts. The choice of integrating these cues in a driving simulator environment is usually dependent on the planned use for the simulator and the perceived weight of said cues in the planned driving tasks. Simulator variety and the lack of standards make it impossible to determine if, in general, a simulator is appropriate for vehicle dynamics, and even if so, for which driving tasks its performance can be validated. The evaluation procedure most likely needs to be performed for each simulator test case and set of dynamic manoeuvres for a given vehicle, greatly increasing the efforts of the experimental set-up.

Given the presented setbacks, it is probably easier to motivate vehicle dynamics activities in a simulator if the focus is relative validity rather than absolute validity. Relative validity tests would require the driver to compare a given vehicle set-up with a baseline set-up, both taken in the simulator, as opposed to using real-world experience as a reference. Even though both relative and absolute validity place a strain on simulator capabilities, the latter encapsulates a smaller niche of possibilities than the former, thus making it less attainable.

2.3. Merging vehicle dynamics testing with driving simulators

Presented in the previous section are setbacks that might hinder the utilization of driving simulators as tools for vehicle dynamics testing. As cumbersome as they might be, the possible advantages of using a driving simulator have been shown and these might be attractive enough to warrant the investigation of a simulator’s suitability for a given manoeuvre set, in relation to a given vehicle.

The concept of fidelity has been introduced in the previous chapter. To summarise, in this report the fidelity of the simulator in general, or relatively to a specific cue, refers to its perceived quality relative to its real-world counterpart. A fidelity threshold then means a level of perceived quality above which a simulation set-up is acceptable. When a certain simulation set-up is considered valid, it means that the experience of a simulation with all cues in place is above the required fidelity threshold. In the rest of section 2.3 vehicle models and the driving cues in a simulator, which have a major role in the perceived realism, are discussed.

2.3.1. Vehicle models

A vehicle model is a mathematical representation of the dynamics of a real-world vehicle. Said models can have different levels of fidelity depending on the level of detail of the vehicle dynamics they emulate and on the quality of the parametrization/validation efforts.

When a vehicle model is used for vehicle testing, it is important that its dynamics are validated for the manoeuvres of interest. In other words, the model should be able to replicate all vehicle motions of interest to an acceptable degree. This validation is usually performed by comparing the motion outputs of the vehicle model with measured data in an actual vehicle.

2.3.2. Driving cues in the simulator

Evidently all cues contribute to the driving experience in a driving simulator, however, for the purpose of vehicle dynamics testing, the authors consider the following cues to be of great importance in the perceived realism:

- *Visual cues* since they are arguably one of the most important cues used to orient a vehicle and track a defined path.
- *Motion cues* that map the modelled vehicle movements into something the driver's body (vestibular system and kinaesthetic sense) can use as information to complement the understanding of the vehicle motions.
- *Steering wheel torque feedback* because it provides the driver with information about the contact forces between the tire and the road and the vehicle handling.

What follows are considerations within each of the above three topics.

2.3.2.1. Visual cues

Given the dynamics of the manoeuvres under consideration visual cue latency will play a big role in the perception of the vehicle motion, presumably more so than for casual driving. Latency is here understood as the time between a driver's input to the vehicle and the visual display of the resulting motion. [3] performs an overview of literature on the effects of latency showing that maximum thresholds for delay acceptance range from 50 ms to 150 ms. It is reasonable to assume that for vehicle dynamics testing one needs to keep this value as low as possible to ensure high responsiveness of the visual cues.

Visual latency is mostly related with the frequency at which updated positioning information is available, the overhead introduced by rendering and displaying updated images. All these delays should be accounted for and minimized.

Even though the latency may be small, poor display refresh rates will lead to the perception of non-smooth motion. In [1, pp. 8-6], the authors suggest a minimum update rate of 30 Hz based on an overview of previous research efforts. With today's hardware and software, it is possible to aim for refresh rates comfortably higher than the recommended limit, ensuring smooth motion representation.

Extra efforts should be made to ensure that the position of the observer in the graphical representation has the right placement relative to the body of the represented vehicle. This is required to guarantee that the driver correctly perceives the displayed motions.

2.3.2.2. Motion cues

As previously stated, a driving simulator cannot represent the full array of driving sensations with full accuracy. However, with help of different motion cueing strategies the simulator motion can be tuned to improve the fidelity of the motions of interest. Still, this will be limited due to the physical constraints of a driving simulator.

Primarily, not all simulators have the possibility to present motion cues. These depend on the existence of a motion system which considerably increases the size of the facility hosting the simulator and is often the most expensive component of a driving simulator. Secondly, motion systems are limited in their motions in a way that vehicles are not. Whereas a vehicle can travel for long distances on the road simulators are constrained in a motion envelope which, being simulator specific, limits the available ranges of accelerations and rotations that can be presented to the driver. This means that motion cues are always a compromise between how the modelled vehicle behaves and the motion range of a simulator.

Motion cueing algorithms are responsible for mapping vehicle motions to simulator motions. There is an immense variety of said algorithms, the most common ones usually coupling the generation of the motion cues to preselected bandwidths of the vehicle dynamic states.

Motion cueing algorithms and tuning

Motion cueing algorithms are usually tuned subjectively, after some initial rounds of objective considerations about the characteristics of the desired motion range. They can be set on covering general driving characteristics with acceptable fidelity or aimed at the dynamics, representative of a set of manoeuvres, with a possible increase in fidelity. The former is probably the most appropriate when considering vehicle dynamics testing.

Further, in the author's opinion, consistency in the presentation of motions is of great importance. It is sometimes a necessity to augment the motion cueing algorithms with special motion considerations like, for instance, management of motion hardware boundaries. In other situations, such add-ons might be present to improve the simulator driving experience, for example dynamic scaling of reference signals from the vehicle model. These augmentations can lead to situations where similar inputs to the cueing algorithm yield different outputs. Such inconsistencies should be minimized as much as possible to ensure a dependable behaviour of the simulator from the driver's perspective.

In line with the previous topic, one should favour motion cueing algorithms whose design is comprehensible enough to facilitate understanding of how the reference vehicle motions become simulator motion cues. More intricate design of motion cueing strategies can lead to the problem mentioned in the previous paragraph by masking inconsistencies in motion representation.

Finally, motion cueing algorithms are validated for a given set of manoeuvres, for a specific vehicle model. It is important that the test drivers are aware of this information so that there are no expectations of valid vehicle feedback out of the validity region.

2.3.2.3. Steering wheel torque feedback

This is an important cue used by the driver to perceive the vehicle state since it is directly coupled to the contact forces between the front axle tires and the road. Together with the motion cues it allows the driver to improve vehicle control. Application of this torque needs to be performed with enough bandwidth to match that of the simulated vehicle under consideration, at least for the scrutinized manoeuvres. This place demands on the actuator used to generate the torque but also on modelling the steering system from the forces on the tires up to the torque applied by the steering servo to the steering wheel.

2.3.3. Test manoeuvres

So far, it has been discussed that both vehicle models and motion cueing algorithms need to be validated for the manoeuvres at hand. Ideally, this should be performed in an iterative process including:

1. Defining manoeuvres of interest based on what design changes to be evaluated.
2. Verifying if it is possible to model and validate a vehicle model for said manoeuvres and design changes. Some conditions to consider are that:
    a. The model needs to run with a certain sampling period to simulate the frequencies of interest.
    b. There is enough data to perform an accurate parameterization.
    c. The model emulates the dynamic phenomena of interest.
3. Verifying that the available motion cueing algorithms can be tuned to an acceptable level of fidelity for the given manoeuvres. Regardless of the test methods, test drivers should subjectively approve it.

If steps 2 and 3 above are not met, it is always possible to keep iterating and restart with step 1 again, narrowing the set of manoeuvres of interest until an acceptable solution is identified.

Given all the constraints on the modelling of vehicle dynamics and especially on the motion of the simulator, it is not possible to present all dynamic manoeuvres in a driving simulator with an acceptable fidelity level. However, for those that can be driven in the simulator, this test tool opens a whole new set of test possibilities.

3. Case study

3.1. Description

As a case study, this work focused on the effects of changing the parameterization of a vehicle dynamics model on the perceived handling of the vehicle by drivers in a motion-based simulator. The applied parameter changes resembled hardware changes which affect the vehicle's handling characteristics and are probable in real world testing. The goal was to understand if the simulator in question, Sim IV at VTI in Gothenburg, could provide a realistic driving experience regarding the modifications of the vehicle model. The idealized trial consisted of comparing a baseline vehicle with four modified versions of said vehicle, each with its unique parameter set aimed at altering dynamic behaviour. By comparing the drivers' described perceptions with the expected perceptions introduced by the modifications it was possible to draw some conclusions on how well the simulator can represent the relative differences between the baseline and modified vehicles.

The absolute evaluation of the simulator, relative to real driving, with respect to lateral and vertical dynamics was also under consideration. It was performed while driving the baseline vehicle along a road based on real-world road geometry recommendations, with and without surface roughness.

Different vehicle types bring out unique fidelity demands on simulators and this case study was performed with a truck. Heavy vehicle dynamics are not as fast as those of conventional passenger vehicles, thus relaxing the fidelity thresholds meaning that the fidelity of the driving simulations can be maintained for a wider range of manoeuvres.

Given the small size of this exploratory study and its consequently probing nature it was only possible to use 10 test participants. Such a limited number of participants weakens the statistical significance of the conclusions drawn from this work. Thus, the undertaken work should be regarded more as an (dis)encouragement for in depth future work.

3.2. Manoeuvres

The trials in this case study focused on exciting lateral and vertical dynamics, and the simulator motion envelope was the constraint for manoeuvre selection.

The driving scenario in the simulator was divided in two parts, the first of which focused on an absolute comparison between the virtual truck and a real truck. It consisted of the following activities:

- Free driving on a straight road where the drivers were encouraged to excite the truck model laterally.
- Single lane-change manoeuvres through cones, aimed at steering inputs between 0.3 Hz and 0.5 Hz, resulting in lateral accelerations ranging from 1 to 2 m/s^2. The layout is depicted in Figure 1.
- Driving on a road with constant curvature to expose the drivers to sustained lateral forces.
- Driving on a bumpy road to expose the drivers to vertical disturbances.

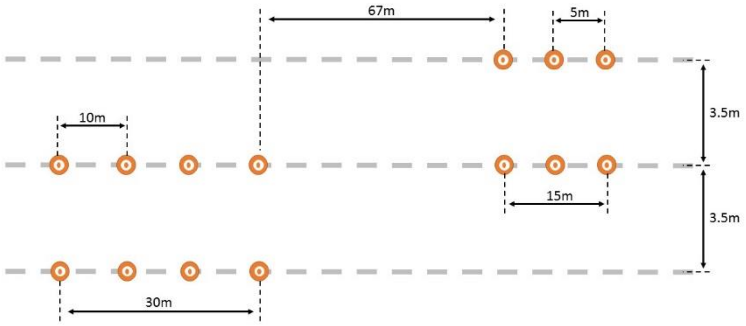

Figure 1. Lane-change configuration.

For the second part of the driving scenario, addressing vehicle handling tests, the focus turned to transient lateral dynamics only. Thus, only the free driving in a straight section and single lane-change sections of the scenario were used.

To minimize the effects of possible speed variation, and thus longitudinal dynamics, all driving sessions were conducted at a constant speed of 70 km/h. The asphalt was simulated as dry and the road geometry design was based on Swedish road design recommendations [4], see details in section 3.5.

3.3. Vehicle model

The truck model used in this study was represented with a vehicle model library called VTM (Volvo Transport Models), which is developed by Volvo and based on Matlab/Simulink. The truck model was a multibody model suitable for real-time simulations. The dynamics modelling covered a simplified torsional compliant frame, suspended axles and a suspended cabin. Further, the truck model included rotating wheels, PAC2002 Magic-Formula tire models and a compliant steering system. The steering system was modelled by VTI but parameterized to the characteristics of a Volvo truck. For this project, the truck model represented a fully loaded 6x2 rigid truck with a wheel base of 5.2 m and a steering wheel ratio of 18, Figure 2. The front axle ground pressure was 8 tonnes and the bogie pressure was 18 tonnes. The powertrain contained a representation of an automatic transmission (Volvo I-shift) and a typical 13L engine.

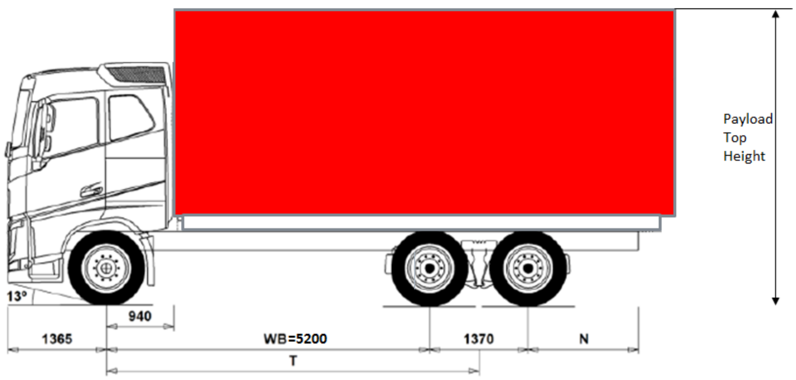

Figure 2. Simulated truck.

3.3.1. Validation

The truck model was validated against measurement data gathered using a 26-ton truck with a low centre of gravity, which corresponds to a pay load top height of 1.75 m in the model. The test data was gathered at the speed 90 km/h. To check the fidelity of the lateral and roll motion of the model, which are the motions of interest in the planned handling test scenario, simulated yaw rate and cabin roll gains with respect to the steering wheel angle were validated against the measured data, see Figure 3.

Furthermore, to assess the steering feel in the simulator, the simulated steering torque which is fed back to the driver, was compared with data from measurements, Figure 4. The agreement between the simulated and measured steering torque looks better for positive steer angles, compared with negative steer angles. Therefore, before the study, the steering feel in the simulator was subjectively validated and tuned with help of a test truck driver. This was done by tuning the parameters of the servo system as well as the friction and damping in the steering system actuators in the truck cabin.

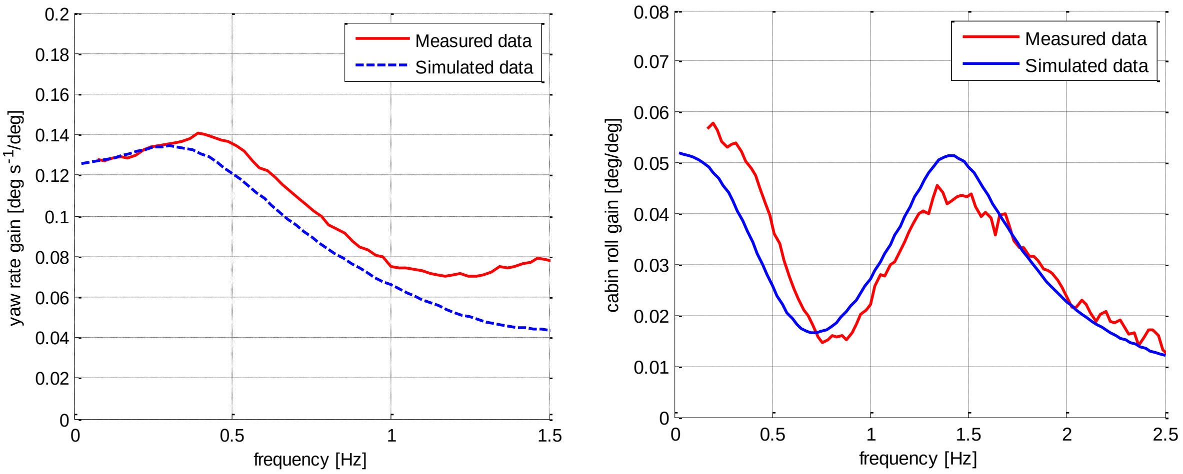

Figure 3. Yaw rate and cabin roll gains with respect to steering wheel angle at 90 km/h. Model outputs versus measurements.

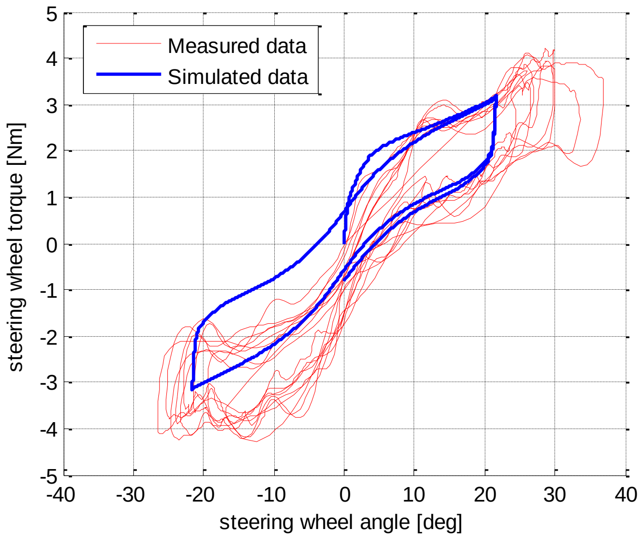

Figure 4. Steering torque of the truck model versus measurements, at 90 km/h.

3.3.2. Choice of parameter sets

As stated previously, this case study aimed at assessing the differences between driving a baseline and modified truck. Four different sets of test parameters were defined for the truck modifications in addition to a standard set which corresponded to the baseline truck. The parameter sets aimed at modifying the dynamics of the truck in reasonable ways that could be expected in similar real-world trials.

The validated truck model was used as the baseline model, with some modifications. The payload height was increased to 4 m to represent a fully loaded truck, so that the changes in the parameter sets would have a larger impact on the truck handling. This resulted in a centre of gravity of 1.88 m, which was used for all the parameter sets. Further, the cabin parameters were upgraded to represent the latest design of the Volvo FH truck, so that Volvo professional test drivers would be able to compare the driving experience in the simulator with the current Volvo FH truck.

The hereby introduced parameter sets are described in terms of the relative change of parameters with respect to the baseline truck, rather than absolute values, for the sake of simplicity.

Parameter set 1 – Increased roll stiffness

Characterized by a 100% and 50% increase of the roll stiffness of the rear and front axle of the truck, respectively, coupled with a 100% increase of the frame torsional stiffness. These modifications should lead to a stiffer ride with less roll, overall perceived as more stable.

Parameter set 2 – Decreased roll stiffness

Characterized by a 40% decrease of the rear axles' roll stiffness. This introduces increased roll angles which can be coupled to a feeling of decreased stability.

The effects of the changes in parameter sets 1 and 2 on the simulated cabin roll angle, which will also be felt by the driver in the simulator, are illustrated in Figure 5. A higher/lower roll stiffness will decrease/increase the cabin roll angle as expected. The changes of roll stiffness have a rather insignificant effect on the yaw rate gain and steering wheel torque, as can be seen in Figure 6. These plots are made for a truck speed of 70 km/h, which was the speed used in the simulator study, selected based on the common speed limit on rural roads and the road geometry used in the driving sessions.

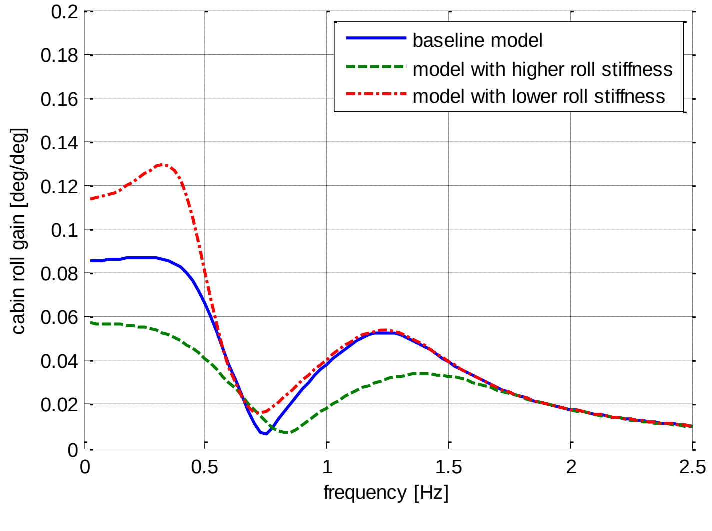

Figure 5. Cabin roll of the baseline model in comparison with a model with parameter sets 1 (higher roll stiffness) and 2 (lower roll stiffness), at 70 km/h.

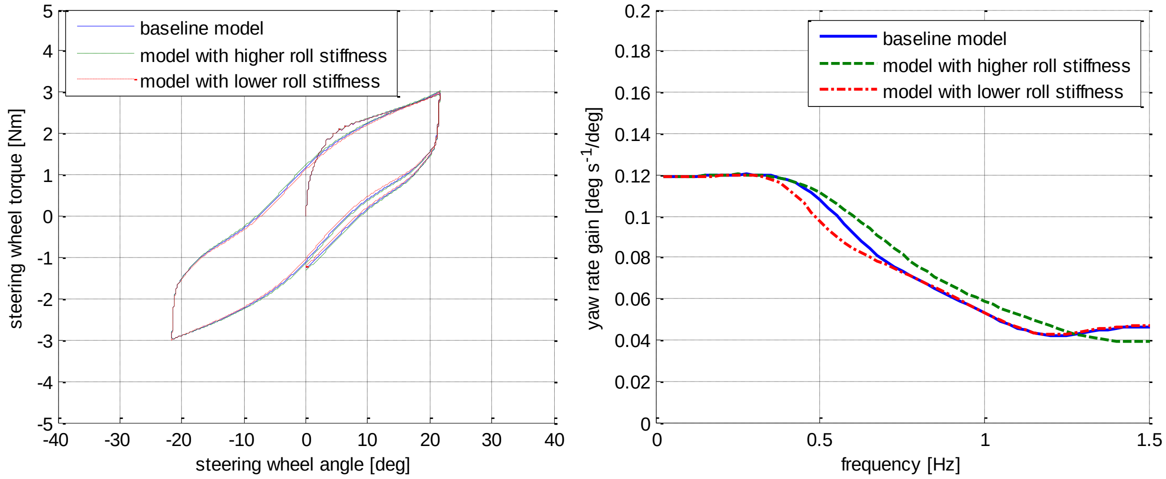

Figure 6. Effects of roll stiffness changes on steering wheel torque and yaw rate gain. Baseline model in comparison with a model with parameter sets 1 (higher roll stiffness) and 2 (lower roll stiffness), at 70 km/h.

Parameter set 3 – Softer rear tires

Characterized by a 25% decrease of the cornering stiffness in the rear axle tires. These modifications lead to an oversteered truck which could be translated into a feeling of increased yaw motion.

Parameter set 4 – Increased roll understeer front axle

The baseline truck had no direct influence of the axles' roll on the steering. In other words, its roll steer coefficient was zero. In this parameter set, a roll steer coefficient of -0.45 was considered to model roll understeering. It means that 45% of the axles' roll angle was added to the front axle steering angle, which created understeering. These changes were mapped linearly to a feeling of an understeered truck.

The effects of the changes in parameter sets 3 and 4 on the simulated yaw rate are illustrated in Figure 7. It should be highlighted again that these plots are made for a truck speed of 70 km/h, which was the speed used in the simulator study. As expected, having softer rear tires will make the truck oversteer more, which resulted in a higher yaw rate gain. Increasing the roll understeering had almost an opposite effect. The primary effect of parameter sets 3 and 4 was on the yaw behaviour of the truck. However, as shown in Figure 8, these parameter changes will also affect the steering wheel torque and the cabin roll gain. The truck with softer rear tires appears lighter to steer on centre, due to the delayed build-up of aligning torque, which resulted in less steering torque feedback on centre; while the truck with higher roll understeer provided more steering torque feedback and appears heavier to steer on centre. With respect to the cabin roll gain, the truck with softer rear tires rolls a bit more compared with the baseline truck while increasing the roll understeering decreases the cabin roll gain in the low frequency range. This is a clear example of the fact that it is not an easy task to identify the main reason for changes in truck handling, even for professional test drivers. This is a consideration which should be considered when analysing the results of the conducted driving simulator study.

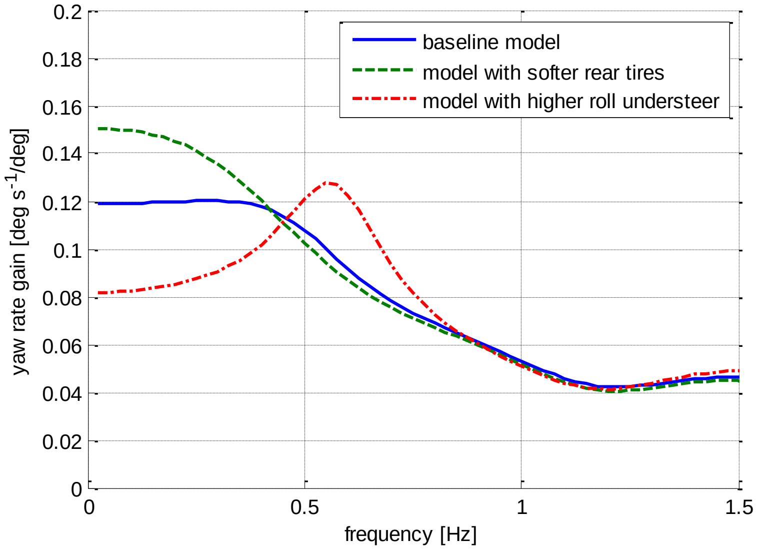

Figure 7. Yaw rate gain of the baseline model in comparison with a model with parameter sets 3 (softer rear tires) and 4 (higher roll understeer), at 70 km/h.

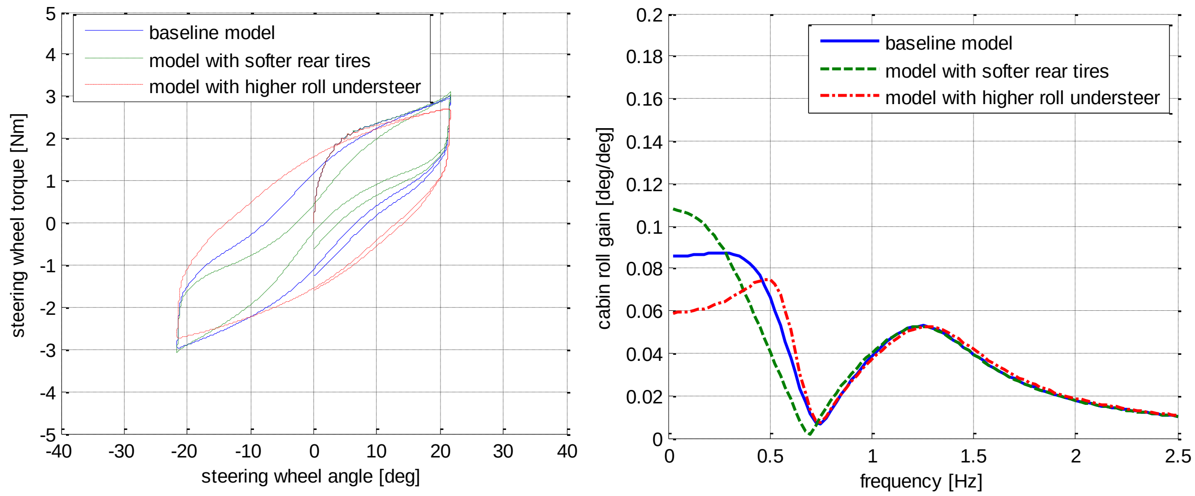

Figure 8. Effects of soft rear tires (parameter set 3) and roll understeer (parameter set 4) on steering wheel torque and cabin roll gain, at 70 km/h.

3.4. Motion cueing

Sim IV consists of a hexapod mounted on top of a sledge with the capability to displace longitudinally and laterally in the room, for a total of 8 DOF [2]. The motion cueing in use is a classical washout algorithm for 8 DOF, as presented by [5], but without the road related component. This algorithm was used due to the simplicity with which the vehicle states are handled which gives more control over what is displayed to the driver. Tuning such an algorithm comes down to some gain and frequency choices which can be related with the vehicle range of motions.

Given the nature of the selected manoeuvres, lateral and vertical dynamics were in focus. Table 1 illustrates how the simulator's degrees of freedom were handled in terms of gains and frequency ranges represented by the motion cueing algorithm. The algorithm does not take into consideration washout effects and the platform dynamics, whose performance varies for each DOF.

Table 1. Motion cueing tuning parameters.

Vehicle state	Gain	Presented frequencies (Hz)
Longitudinal acceleration	0.3	0.12 - 4
Lateral acceleration	0.5	0.2 – 5
Lateral acceleration (tilt coordination)	0.375	0 – 0.2
Vertical acceleration	1.0	0.2 - 4
Pitch rate	1.0	0.04 - 4
Roll rate	0.5	0.2 - 5
Yaw rate	0	NA

Tuning of the motion cueing algorithm was done together with a small group of professional test truck drivers (in an informal setting) whose feedback was invaluable to achieve the final gain and frequencies set.

Longitudinal accelerations were low priority from the beginning. Thus, tilt coordination was removed and the gain for longitudinal accelerations was set to a lower value than what was used for lateral accelerations. This would increase the hexapod's capacity to generate lateral and vertical motions, by toning down the longitudinal motions. Additionally, possible false cues introduced by tilt coordination in the longitudinal direction were removed.

For the lateral accelerations, it was decided that the tilt coordination should remain due to the need to simulate sustained accelerations in the curves. The tilt coordination acceleration was scaled differently from the remaining lateral acceleration since the drivers pointed out that the rotation was noticeable, thus generating a false cue. The issue could have been addressed by decreasing the threshold for rotation rate, but this was ruled out since it incurred in delays for the perception of lateral motion. The initial trials revealed that it was acceptable to use gains of up to 0.8 for the lateral acceleration and roll. However, the proximity to the limits of the motion envelope meant that every now and then the simulator would be limited by its displacement constraints, which introduced motion artefacts. To avoid this, it was decided to lower the gain to a conservatively safe (given the manoeuvres at hand) value of 0.5.

Pitch rate was presented almost in an unbounded state only missing a small part of the frequency range. It was important since it gives the driver an impression of the truck cabin movements during longitudinal acceleration changes and rough roads.

Yaw was not represented. No combination of gains or frequencies produced results which were depicted by the drivers to be better than not representing yaw. One possible reason for this can be an incorrect rotation point for representation of motions by the platform; but the value was double checked and did not seem to be the source of the problem. Another possible cause could be a wrong rotation point in the visual representation of the motion, which could not be verified in this trial.

Tuning of the roll motions was coupled to the lateral accelerations as these signals are linked given the nature of the lateral manoeuvres. Early efforts showed that more than having similar gains, it was important to guarantee that the border for low frequencies in lateral acceleration should be matched with the cut-off frequency of high pass filter of the roll rate. So, both frequencies were set to 0.2 Hz. As stated by the drivers, this yielded an improvement in the responsiveness of the vehicle.

3.5. Road

Designing the road was tightly linked to the requirements set up in the manoeuvres and was underlined by road design guidelines [4] published by the Swedish Transport Administration (Trafikverket). This was done to ensure that the geometry, curvature, and banking of the modelled roads matched the corresponding properties of existing Swedish roads. The geometry considerations were met to guarantee that the drivers would experience an environment as close as possible to what can be found in real-world driving, as well as to simulate realistic dynamic situations in the case of the curvature (lateral acceleration) and rough surfaces (vertical acceleration, rotations, steering wheel torque). The modelled road surface irregularities were based on data measured, [6], on actual roads in Sweden.

The aim was to reproduce the geometries of 70 to 80 km/h roads, based on the recommendations in [4]. Sometimes a range of values is given as an option for a certain road property. In these situations, the values chosen in this project correspond to the most demanding driving conditions, in respect to vehicle control.

The experiment road was split into three distinct driving sections. The first road section consisted of a straight line, i.e. zero curvature, with a smooth surface. The second road section was comprised of a collection of curves, also with a smooth surface. The third and final road section was designed as a straight line, i.e. zero curvature, with a rough surface. All three road sections had two lanes, one in each direction, each lane with a width of 3.25 m and a shoulder width of 0.75 m.

When referring to banking and slope, this report uses the definition presented in [7].

Straight section with smooth surface

This section had no slope and the banking values were set to 2.5%, according to the road geometry recommendations specified in [4]. Represented in the road surface were only wave lengths above three meters. This section was designed with a length of 30 km.

Curved section

This road section was made up of a collage of a geometry patterns which contained a straight part with zero curvature, a transition clothoid, an arc (80 m long or roughly four seconds driving at 70 km/h), another clothoid, and finally a straight section, Figure 9.

Figure 9. Curved geometry pattern. In black are the straight sections, in red the transition curves (clothoids) and in green the arc.

The geometry pattern was configured according to the desired banking values in the arc section, and one configuration was selected for the experiment. An inwards banking of 4% was selected for the arc, and transition curves were used to bridge the banking difference between the straight and arc sub-sections. The minimum allowed curvature for such banked curves is 500 m, according to the recommendations in [4].

Finally, the curved section of the experiment road was made of four consecutive geometry patterns with 4% inwards banked, with a total length of 3 km.

Straight section with rough surface

This section had no slope and the banking values were set to 2.5%, according to the road geometry recommendations specified in [4]. The rough surface consisted of an extra layer of height, slope, and banking data for small wave lengths, up to three meters. This extra layer was superimposed on the existing road profile and consisted of a sample of the road measured in the Known Roads project, [6]. The total section length was 10 km.

3.6. Experimental layout

Once at the simulator facilities, the drivers were introduced to the purpose of the study at hand, in short, specified to them as “the evaluation of the simulator performance in terms of vehicle dynamics reproduction”, Appendix C. After this introduction and once the consent form was signed, the experiment started. Driving in the simulator was divided in three sessions, training, simulator fidelity evaluation, and vehicle dynamics tests. All sessions were conducted at a speed of 70 km/h, regulated by a cruise control which the drivers were instructed to use when not focusing on longitudinal dynamics.

Session 1 - Training

The training session consisted of a 5 minutes’ simulator familiarisation drive on a straight road section with smooth surface, and the baseline truck. During training the drivers were encouraged to excite the truck laterally and longitudinally.

Session 2 - Simulator fidelity evaluation

This session aimed at allowing an absolute comparison between driving in the simulator and driving a real truck. The drivers started driving on the straight road section with smooth surface (section 3.5), for 4 km. There they were instructed to excite the truck laterally either freely, or through the lane-change manoeuvres performed with the layout depicted in Figure 1.

Afterwards, without stopping the truck, the drivers entered the curved road section described in section 3.5. Once the curved road section ended, the drivers entered the straight road section with rough surface (section 3.5). After driving for three minutes in this section, the simulation was stopped and the drivers had to answer a questionnaire, see Appendix A. This evaluation was performed with the baseline truck.

Session 3 - Vehicle dynamics tests

The vehicle dynamics test drive aimed at comparing the perceived relative differences between a baseline truck and a parameterized version of that truck. Driven on a straight road with smooth surface, section 3.5, this drive consisted of a combination of single lane-change manoeuvres and free driving for each of the test parameter sets described in section 3.3.2.

First, the drivers drove the baseline truck for 25 seconds, which consisted of free driving plus a single lane change with cones, Figure 1. This was followed by driving a modified truck for 40 seconds in free driving plus a single lane change with cones. Finally, the drivers returned to the baseline truck for 25 seconds, which consisted of free driving and a single lane change with cones, at the end. This drive was performed continuously and with no interruptions between. Upon completion, the drivers stopped the truck and answered a questionnaire, see Appendix B. This procedure was repeated four times, once per parameter set. The single lane changes with cones were set up at the end to ensure that the drivers were exposed to the exact same manoeuvre, for all parameter sets, at least once.

To avoid order effects, the parameter sets were sorted with Latin square resulting in four orders of presentation of the parameter sets: (S1, S2, S3, S4), (S2, S4, S1, S3), (S3, S1, S4, S2) and (S4, S3, S2, S1).

Once the driving task was completed a discussion ensued between the driver and experiment leaders to gather extra feedback about the experiment.

3.7. Collected data

Subjective and objective data were gathered during the study. The former was represented by the impressions of the drivers, as collected in questionnaires and through discussions, whereas the latter consisted of the recordings of simulation states.

Subjective data

Two questionnaires were used for collection of subjective data. The first concerned the fidelity of the simulator as compared with real-world driving. The test drivers were asked to rank the realism of the perceived motions and steering feel during driving the different road sections depicted in section 3.5. Further questions focused on ranking the overall realism of the driving simulator as well as on the usefulness of such driving simulator studies for vehicle dynamics testing. A 5-grade ranking scale, from 1 very unrealistic to 5 very realistic, was used. The questionnaire was handed to the drivers after the simulator fidelity evaluation session and can be found in Appendix A

The second questionnaire focused on the perception of differences in the truck behaviour given changes in the truck model parameters. This questionnaire was answered four times, once for each parameter set included in the vehicle dynamics test session, and can be found in Appendix B.

Objective data

This data comprised all data logged by the simulation software. Along with the truck vehicle states, such as acceleration, rotation rates and position on the road, the driver inputs were also recorded. This data was collected with the purpose of investigating how the changes in truck parameters were related to differences in how the drivers controlled the truck, and differences in the truck motions.

3.8. Results and discussion

The study counted the participation of 10 professional test drivers from the Volvo group, of which 2 could not finish the study due to motion sickness. The achieved results are presented in this section.

3.8.1. Session 2 - Simulator fidelity evaluation

The simulator fidelity evaluation was primarily judged in terms of the subjective feedback given by the drivers. This was assessed via the questionnaire in Appendix A, and the results are shown in Table 2. Note that two of the test persons missed to fill in all the questions (FP6, FP7), and one test person (FP2) did not complete session 2 due to motion sickness.

The average ranking of both motion and steering feel perception was between 3 and 4 (between moderate and realistic) for all road sections, except the steering feel during lane changes which had an average ranking of 2.8. The overall realism ranking was quite high as well, with an average of 3.6 which means that the test drivers thought the simulator realism was better than moderate. More importantly the average ranking of the usefulness of the driving simulator, for vehicle dynamics testing, was 4.3 on the 5-grade scale from 1 not useful at all to 5 very useful. This means that the test drivers think that a motion-based driving simulator is a useful tool for vehicle dynamics testing.

Table 2. Drivers' ranking of the realism of the perceived motions and steering feel in the driving simulator at different parts of the scenario, and overall, as well as their ranking of the simulator's usefulness for vehicle dynamics testing. Scale from 1 very unrealistic/not useful at all to 5 very realistic/very useful.

	FP1	FP2	FP3	FP4	FP5	FP6	FP7	FP8	FP9	FP10	**Ave**
Lane change - motions	2	3	3	4	4	4	4	4	4	3	**3.5**
Lane change – steering feel	2	4	2	4	3	3	3	2	2	3	**2.8**
Curves - motions	2	4	3	3	4	4	-	4	3	3	**3.3**
Curves – steering feel	2	4	4	4	3	3	-	3	3	3	**3.2**
Uneven road - motions	3	-	4	5	4	-	5	3	3	4	**3.9**
Uneven road – steering feel	3	-	2	5	4	-	3	3	3	3.25	**3.3**
Uneven - visual vs. ride	3	-	3	4	3	-	5	3	3	3.25	**3.4**
Overall realism	2	4	4	4	4	-	4	4	3	3.75	**3.6**
Usefulness	3	5	5	4	5	4	4	5	-	3.75	**4.3**

The evaluation of simulator fidelity was organized so that each manoeuvre and road combination would excite dynamics of interest: curves for sustained lateral dynamics, uneven road for vertical dynamics and rotation, lane changes for transient lateral dynamics, and free drive for a combination of longitudinal and lateral dynamics. From the authors' perspectives, this set-up worked quite well in exposing the drivers to the simulator's equivalent range of motions to the ones perceived in the real world.

The drivers answered the questionnaire after the run was complete. This means that they did not have time to reflect after each dynamics section, but had instead to recall them one by one, after having experienced them in a sequence. This can dilute the driver's evaluation, as a bias towards any of them might have a bigger chance of influencing all other impressions. In hindsight, the test should have been divided into distinct driving sessions, each warranting its own separate questionnaire and focusing on only one set of dynamics. The order in which the sessions are driven should then be scrambled to mitigate the impact of order effects.

3.8.2. Session 3 – Vehicle dynamics tests

In the vehicle dynamics tests session, the drivers drove modified trucks which were compared with a baseline truck, see section 3.3.2. Here, subjective and objective data was analysed.

Subjective data

Following the drive with each modified truck, the questionnaire in Appendix B was answered. Its purpose was to investigate if the drivers could correctly deduce the changes in the truck parameters, associated with each parameter set. Evaluation of the answers was done based on the drivers' descriptions of the perceived differences in relation to the baseline truck (answers to question 3 in Appendix B). The drivers' descriptions were scrutinized for words or expressions belonging to various acceptance categories, see Table 3. The categories were defined considering the actual parameter changes and were based on the expected perception of the truck's dynamic behaviour. Acceptance of the drivers' descriptions, or lack thereof, was partitioned in three classes: correct (1), quite correct (0.5), or incorrect (0). It should be noted that the drivers' answers regarding the effect of the parameter changes on the vehicle handling, i.e. answers to question 2 in Appendix B, were also used to aid the grading in cases of ambiguous descriptions of the perceived changes.

Table 3. Acceptance categories for the drivers' descriptions based on the utilized words.

Parameter set 1 Increased roll stiffness	1 (correct)	stiffer, roll less, stable
	0.5 (quite correct)	better truck, better control
	0 (incorrect)	no difference, worse truck, other
Parameter set 2 Decreased roll stiffness	1 (correct)	roll more, softer (opposite to stiffer), loose
	0.5 (quite correct)	worse/oversteer/inconsistent
	0 (incorrect)	other
Parameter set 3 Softer rear tires	1 (correct)	oversteer, more yaw, need to steer back
	0.5 (quite correct)	jazzy, worse
	0 (incorrect)	other
Parameter set 4 Increased roll understeer	1 (correct)	understeer
	0.5 (quite correct)	strange yaw/steering/swims
	0 (incorrect)	other

The results are summarized in Table 4. In general, it seems that the test drivers could perceive the implemented parameter changes rather well. For parameter set 3 (softer rear tires), 75% of the drivers (6 out of 8) correctly identified the parameter change while the two remaining drivers also had a quite correct deduction. The results for the other three parameter changes (sets) were also very promising. There are only 2 incorrect answers out of a total of 32.

A change in the parameterization can yield alterations in the truck behaviour that span over a wide range of handling categories. This can further complicate identification of the changes in the vehicle since they might be diluted under other secondary cues. Despite this hindrance, the drivers had a surprising success rate which bestows the achieved results with extra significance.

Table 4. The correctness of the drivers' deduction of the applied changes of the truck model, or lack thereof, classified according to Table 3Table 3. (FP2 and FP9 did not complete session 3 due to motion sickness)

	FP1	FP2	FP3	FP4	FP5	FP6	FP7	FP8	FP9	FP10
Parameter set 1 - Increased roll stiffness	0	-	1	0.5	1	0.5	1	1	-	1
Parameter set 2 - Decreased roll stiffness	1	-	1	0.5	0.5	1	1	1	-	0
Parameter set 3 - Softer rear tires	1	-	0.5	1	1	1	1	1	-	0.5
Parameter set 4 - Increased roll understeer	1	-	0.5	1	0.5	0.5	0.5	1	-	1

Objective data

Some vehicle states and inputs such as driver steering input, yaw rate and cabin roll angle, were studied to verify the correlation between the drivers' perception of the truck performance and objective performance data. What follows is a presentation of the objective results, an example from each parameter set, from drivers who identified the changes correctly.

In Figure 10, the cabin roll angle is plotted for the baseline truck and for the modified trucks, parameter set 1 (increased roll stiffness) and parameter set 2 (decreased roll stiffness). The lines depicted in Figure 10 represent the lane changes performed by test driver 3 who had correctly deduced the parameter set changes applied to the truck. As expected, the cabin roll is reduced/increased for the truck with higher/lower roll stiffness in comparison with the baseline truck. Figure 11 shows that the driver performed rather similar lane changes with each truck parameter set, so the differences in cabin roll angle are mostly due to the different truck set-ups rather than the driver input.

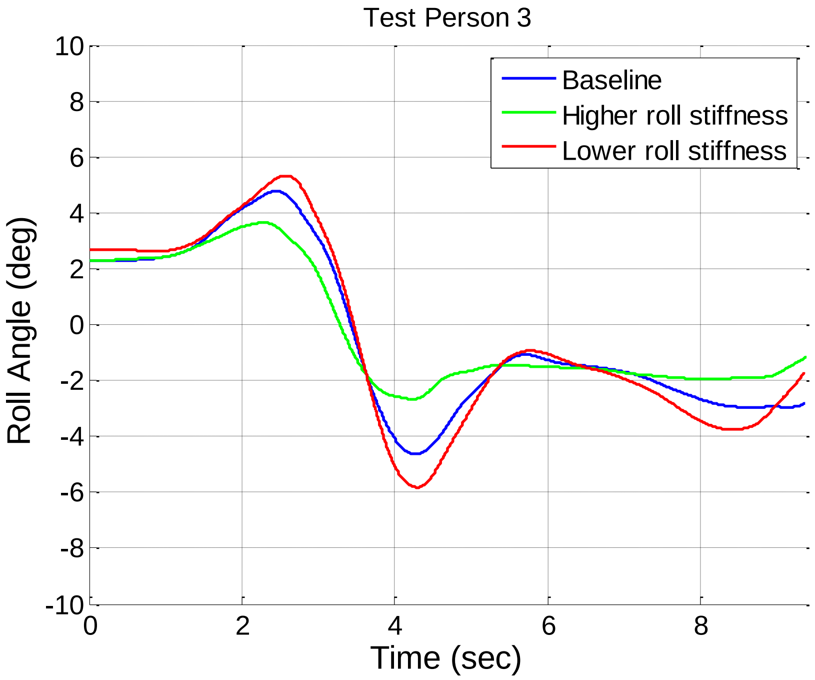

Figure 10. Cabin roll angle during lane changes with trucks with different roll stiffness.

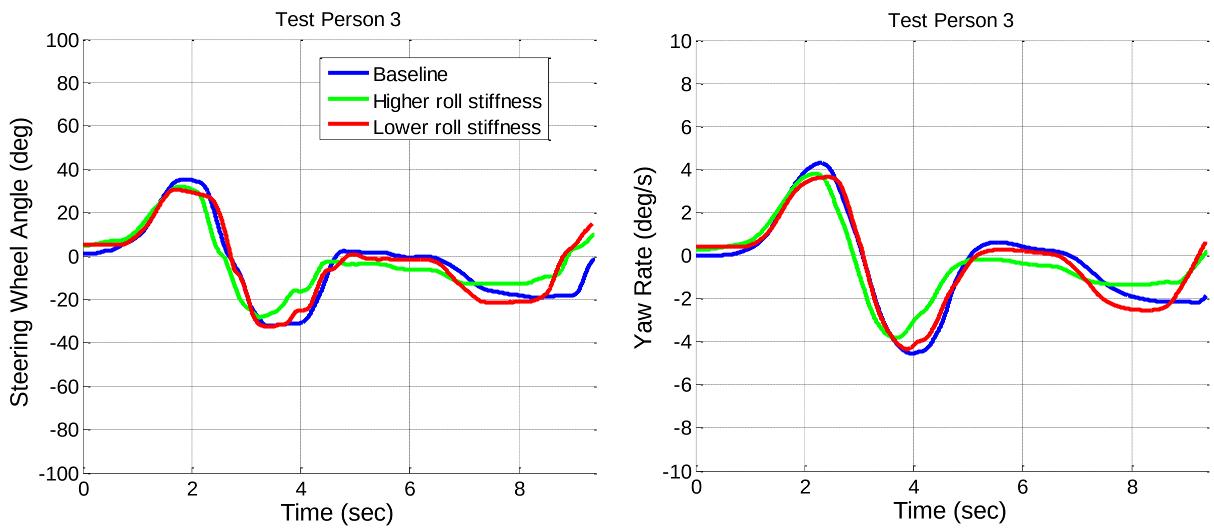

Figure 11. Driver input (steering wheel angle) and truck yaw rate during lane changes with trucks with different roll stiffness.

Figure 12 shows a comparison between the baseline truck and the truck modified with higher roll understeer (parameter set 4), for lane changes performed by test driver 4. There, it is possible to see that the driver had to steer considerably more in the modified truck, in order to achieve yaw motions with comparable amplitude to the ones experienced in the baseline truck. Also, in this case, the driver's interpretation of the differences between the baseline and modified truck was correct and in line with the observed objective behaviour.

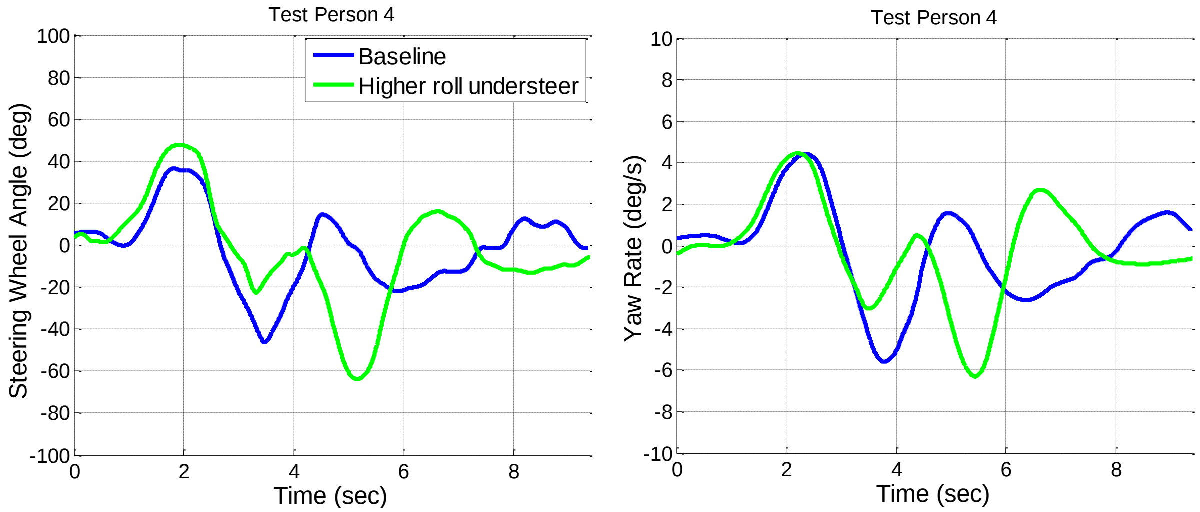

Figure 12. Driver input (steering wheel angle) and truck yaw rate during lane change with baseline truck vs. truck with higher roll understeer.

In the last example, shown in Figure 13, the truck with softer rear tires (parameter set 3) has larger yaw rate values compared with the baseline truck, although the driver (in this case test driver 5) was providing similar steering input. The driver detected this oversteering behaviour correctly.

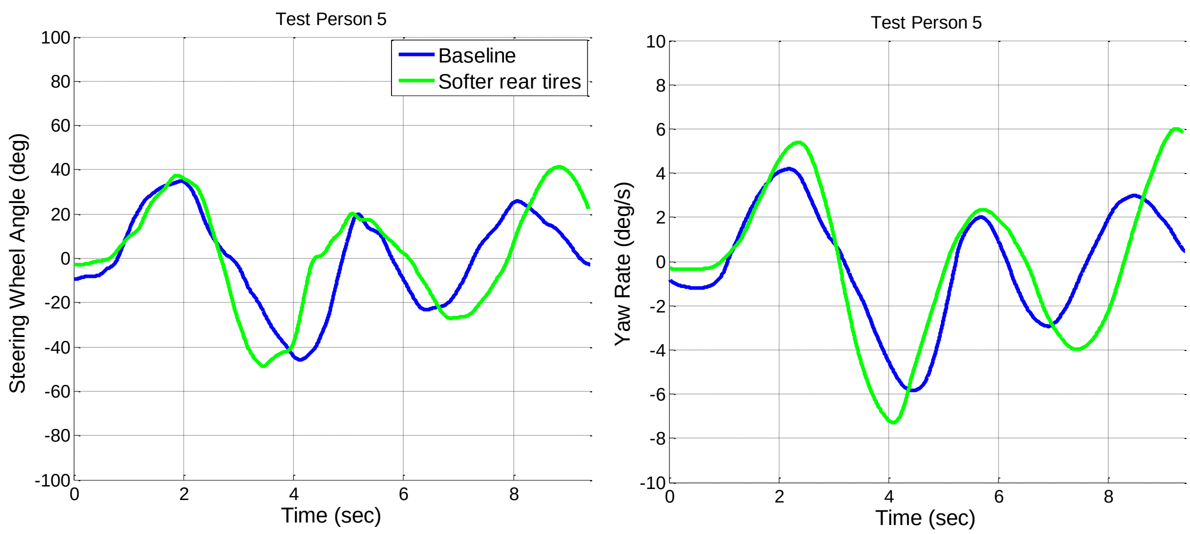

Figure 13. Driver input (steering wheel angle) and truck yaw rate during lane change with baseline truck vs. truck with softer rear tires.

General remarks

It is important to emphasize that the results from this study are only valid for the current test set-up and cannot be extrapolated to other types of vehicle dynamics models (passenger cars, bikes, etc.), manoeuvre types, and driving simulators. As stressed in section 2.3, validity of a given test case needs to be judged individually as a function of the dynamics, simulator and manoeuvres.

4. Conclusions

In general, this work discusses considerations which should be made with respect to performing vehicle dynamics tests in driving simulators. In particular, the case study under scrutiny investigated the suitability of a driving simulator for dynamics tests which are focused on evaluation of the vehicle handling. An experiment was set up where professional test drivers were asked to drive a simulator with design variations of a baseline truck model with the purpose of identifying the differences in the vehicle performance. Interpretation of the results leads to the conclusion that the driving simulator has the capability to provide the drivers with satisfactory feedback; enough to enable correct evaluations of the given manoeuvres and parameter variations. The attained results, even though not statistically significant, can encourage further research in the area of vehicle dynamics testing in motion-based driving simulators. In particular, the results motivate future efforts involving VTI's Sim IV with vehicle dynamics testing.

Driving simulators' shortfalls become conspicuous when the focus turns to representation of the vehicle dynamics. Activities within this scope place a demand for high fidelity in the whole range of existing simulated cues; recall that the results reported here are only valid for the considered dynamics, given the tested manoeuvres, if conducted in Sim IV at VTI in Gothenburg. Such are the limitations of vehicle dynamics testing in driving simulators. However, the flexibility, repeatability, controllability, and safety of a driving simulator environment make it an attractive testing environment. If used correctly it could benefit the field of vehicle dynamics testing, not as a replacement but rather as a complementing tool in the test chain.

4.1. Future work

The reported work focused mostly on motion cues, visual cues, and steering feedback and their significance for the simulation of vehicle dynamics in a driving simulator. Future work should go into more depth in these considerations and even study the impact of disregarded cues, such as sound, within the frame of vehicle dynamics testing. Perception of the road surface and longitudinal travel speed of the vehicle are also to be considered.

Simulator fidelity is regarded as the level of similarity between the simulated driving experience and real-world driving. Ultimately this will be subjectively evaluated by drivers after an initial period of objective simulator tuning. Differences in drivers' perception and inconsistencies in their ability to express the perceived driving sensations are the downside of subjective assessment, implying that actual validity can only be statistically ensured after evaluation by large groups of test participants. This is a heavy burden which can seldom be achieved. Future work should focus on bridging subjective approval with objective metrics thus expediting simulator validation procedures, as exemplified in [8] for the case of vehicle dynamics development.

Finally, it is imperative to understand that the simulator limitations will never allow it to represent the complete range of driving cues, meaning that not all vehicle dynamics tests can be performed satisfactorily in a driving simulator. It is necessary to grasp the nature of the simulator and desired tests to determine if such matching is feasible. The matching could benefit from a framework that translates a given matrix of tests into a set of demands in terms of simulator cues and fidelity levels, or vice-versa. If this is feasible at all is a question left open, however, its benefits are clear in terms of quick match-ups between simulators and vehicle dynamics tests.

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Appendix A – Questionnaire after first drive

Q1 -Questions regarding the free drive and lane changes

A – How realistic are the perceived motions (roll and lateral motions) and steering feel while manoeuvring?

	Very unrealistic		Moderate		Very realistic
Motions	☐	☐	☐	☐	☐
Steering feel	☐	☐	☐	☐	☐

B – Can you describe how the simulator drive differed from reality, in terms of the perceived motions and steering feel?

Q2 – Questions regarding driving through the curvy road

A – How realistic are the perceived vehicle motion and steering feel while in and out of curves?

	Very unrealistic		Moderate		Very realistic
Motion	☐	☐	☐	☐	☐
Steering feel	☐	☐	☐	☐	☐

B – Can you describe how the simulator drive differed from reality, in terms of the perceived motions and steering response?

Q3 - Questions regarding driving on the uneven road

A – How realistic is the general perception of the ride on the uneven country road?

	Very unrealistic		Moderate		Very realistic
Motions	☐	☐	☐	☐	☐
Steering Feel	☐	☐	☐	☐	☐

B – How good is the agreement between the visual perception of the road unevenness and the ride feel?

	Very poor		Moderate		Very good
Visual vs. ride	☐	☐	☐	☐	☐

C – Can you describe how the simulator drive differed from reality, in terms of the perceived ride?

Q4 - Overall questions

A – How realistic is the general driving experience in the simulator?

	Very unrealistic		Moderate		Very realistic
Driving experience	☐	☐	☐	☐	☐

B – How useful is this kind of simulator for vehicle dynamics testing, in your opinion?

	Not useful at all		Moderate		Very useful
Simulator for dynamic tests	☐	☐	☐	☐	☐

C – Any further comments on your driving experience in the driving simulator and how it can be improved?

Appendix B – Questionnaire after second drive

Q1 - When compared to the baseline truck, what kind of impact did the modifications have on vehicle handling?

	None		Noticeable		Very Noticeable
Impact	☐	☐	☐	☐	☐

Q2 - When compared to the baseline truck, how did the modifications affect the vehicle handling?

	Very Negative		Neutral		Very Positive
Yaw	☐	☐	☐	☐	☐
Roll	☐	☐	☐	☐	☐
Steering Feel	☐	☐	☐	☐	☐
________________	☐	☐	☐	☐	☐

Q3 – In case you have noticed a change in the vehicle handling with the modifications, please describe shortly the perceived differences when compared to the baseline truck.

Appendix C – Consent form and study information

Thank you for your participation today. This study is conducted and/or monitored by Bruno Augusto, Sogol Kharrazi (VTI, Swedish National Road and Transport Research Institute) and Niklas Fröjd (VGTT, Volvo Group Trucks Technology).

The study concerns the evaluation of the simulator performance in terms of vehicle dynamics reproduction. There will be two simulator driving sessions separated by a short brake for a questionnaire. After the last session an interview will ensue. The estimated duration of the experiment is around 1 hour.

Participation in this study is voluntary and you can decide to stop the experiment *at any moment* without having to provide any motivation.

All the information collected during the study, from the simulator (log files) as well as questionnaires, will be handled confidentially. This implies that your name will not be connected to the collected data. The logged data will be kept for 30 years. All questionnaires will be kept for 10 years. This backup is necessary in case the data needs to be re-evaluated.

Risks: Motion sickness can sometimes be associated to driving sessions in driving simulators.

Please refer to any of the experiment leaders to further clarify the information on this document or any other questions you might have about the experiment.

If you have read and understood the above description of the study and the implications of your participation, we would like to register your consent to participate in this experiment.

☐ I have read and understood the information above describing the implications of my participation in this study and I agree to participate.

Participant

Name: Date:

Signature:

ViP

Driving Simulation Centre

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.

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Centre of Excellence at VTI funded by Vinnova and ViP partners

VTI, Scania, Volvo Trucks, Volvo Cars, Swedish Transport Administration, Dynagraph, Empir, HiQ, SmartEye, Swedish Road Marking Association

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