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Vehicle dynamics testing in motion based driving simulators

Sogol Kharrazi[a], Bruno Augusto[a] and Niklas Fröjd[b]

[a]Swedish National Road Transport Research Institute (VTI), Linköping, Sweden; [b]Volvo Group Trucks Technology, Gothenburg, Sweden

ABSTRACT

This article investigates the potential of a motion-based driving simulator in the field of vehicle dynamics testing, specifically for heavy vehicles. For this purpose, a case study was prepared embodying the nature of a truck dynamics test setup. The goal was to investigate if the drivers in the simulator could identify the handling differences owed to changes in vehicle parameters, while driving the simulated trucks. 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 heavy vehicle dynamics testing in simulators.

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Perceived realism; relative fidelity; vehicle handling; motion cueing

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. Driving simulators come in different shapes and sizes corresponding to different fidelity levels and are usually developed having in mind a specific set of utilisation conditions. They are used in a broad spectrum of applications such as analysis of driver behaviour, development of vehicles, and study of new functionalities in vehicles, road infrastructure design and driver education. However, traditionally usage of driving simulators as a tool for vehicle dynamics testing has been uncommon due to limitations in the simulator fidelity or availability of simulated cues and feedback to the driver [1]. In recent years, a few car manufacturers have developed advanced motion-based driving simulators, which reportedly have been also used for vehicle dynamics testing. However, the publicly available information about the extent of these tests is limited.

Vehicle dynamics testing involves subjecting the vehicle to a set of inputs and assessing the vehicle motion to characterise the vehicle performance. This can be done in several 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 the case of simulations, with no drivers in the loop, the assessment is done objectively by calculating the vehicle motion outputs. The objective evaluation of a vehicle performance needs to be complemented with

CONTACT Sogol Kharrazi sogol.kharrazi@vti.se

subjective evaluation by test drivers. Having the driver in the loop is also important for an improved objective evaluation, since it exposes the vehicle to more naturalistic inputs.

A driving simulator is a tool which enables evaluation of the vehicle performance with the driver in the loop. Thus, it can be a valuable addition to the tool chain for vehicle dynamics development. A driving simulator presents a flexible testing environment which can easily be altered to simulate any kind of testing environment or changes in vehicle design and characteristic. Additionally, a driving simulator provides repeatability, as well as safety, enabling the possibility to test dangerous scenarios virtually. These properties broaden the scope of testing by creating possibilities which are unfeasible in a real vehicle.

Within the scope of vehicle dynamics testing, a driving simulator could be used in test iterations at early stages to gather a better subjective understanding of various vehicle designs. This would help to assess and refine the vehicle design before moving to real-world testing, thus sparing time and resources. Also, in a driving simulator, the vehicle setting changes can occur immediately, leaving the driver with a fresher recollection of previous experiences, which will result in an improved comparison judgement.

When assessing a vehicle dynamics performance, motion feedback is a key component. Thus, the herein discussion on the feasibility of using a driving simulator for vehicle dynamics testing is limited to motion-based driving simulators. Even for a motion-based driving simulator, the restricted motion envelope of the simulator acts as a constraint on the type of manoeuvres which can be performed with adequate fidelity. The fidelity of the simulator arises from the comparison of the simulated driving experience and the actual driving experience, as perceived by the driver. The closer one gets to the sensation of driving a real vehicle the higher the simulator fidelity [1]. However, it is often difficult to assign an objective value to simulator fidelity, given its subjective nature.

Vehicle dynamics tests might stimulate a broader range of dynamics than everyday driving. This implies that the fidelity requirements of a motion-based driving simulator need to be stretched, possibly with more integrated cues, to accommodate for vehicle dynamics testing. It is probably easier to motivate vehicle dynamics activities in a driving simulator if the focus is relative fidelity rather than absolute fidelity. These would be tests where the driver compares a given setting to a baseline experience, both in the simulator, and compare the experienced changes with the actual changes in reality; as opposed to comparing each setting with its real-world reference.

This article investigates the potential of using motion-based driving simulators for these types of vehicle dynamic testing. The focus is on heavy vehicle dynamics testing, since driving simulators have been rarely used for such a purpose. To do so, a case study on alternative parametrisations of a reference truck model and their effects on driver perceived handling, was performed in a moving base simulator.

2. Case study

The goal of the case study was to investigate if a moving base driving simulator can provide a realistic driving experience, with respect to parameter alterations of a truck model, in such a way that the drivers are able to correctly perceive the changes.

The applied parameter changes resembled hardware changes which affect the truck's handling characteristics and are realistic to implement. The study consisted of a comparison of a baseline truck with four modified versions of it, each with a different parameter

Figure 1. Driving simulator.

set aimed at altering its dynamic behaviour. By comparing the drivers' perceived changes in the vehicle handling with the applied parameter changes and their expected effects, it is possible to assess if the simulator can represent the relative differences between the baseline and modified vehicles.

The evaluation of the simulator absolute validity with respect to real-driving was also under consideration. Therefore, the study was designed so that drivers start with driving the baseline truck in the driving simulator on different simulated roads, exciting the lateral and vertical dynamics of the vehicle, and answering questions on their perception of the realism of the driving experience.

2.1. Driving simulator

The study was performed in a moving driving simulator, equipped with a hexapod with six degrees of freedom (roll, pitch, yaw, surge, sway and heave) which is mounted on a sled with two extra degrees of freedom permitting significant linear movement along both longitudinal and lateral directions. It has two LCD displays for rear-view mirrors and a visual system comprising nine projectors. The visual system gives the driver a 210-degree forward field of vision. Vehicle and environment sounds are provided by the vehicle speaker and a few complementing speakers for surround sound setup, see Figure 1 [2].

2.2. Driving scenario

Each driver started with a 5 min training session where they got accustomed with the driving simulator; after that they proceeded to perform the main study.

The first part of the study on the evaluation of the absolute validity of the driving simulator was focused on exciting lateral and vertical dynamics. Driving close to the handling limit was not included in the driving scenario, since the objective was to capture natural driver behaviour in everyday driving scenarios and avoid unrealistic driving behaviour due to increased safety of the driving simulator in dangerous situations. The driving simulator motion envelope was the constraint for manoeuvre selection. The driving scenario for this part consisted of the following activities:

- Free driving on a straight road where the drivers were encouraged to excite the vehicle model laterally.

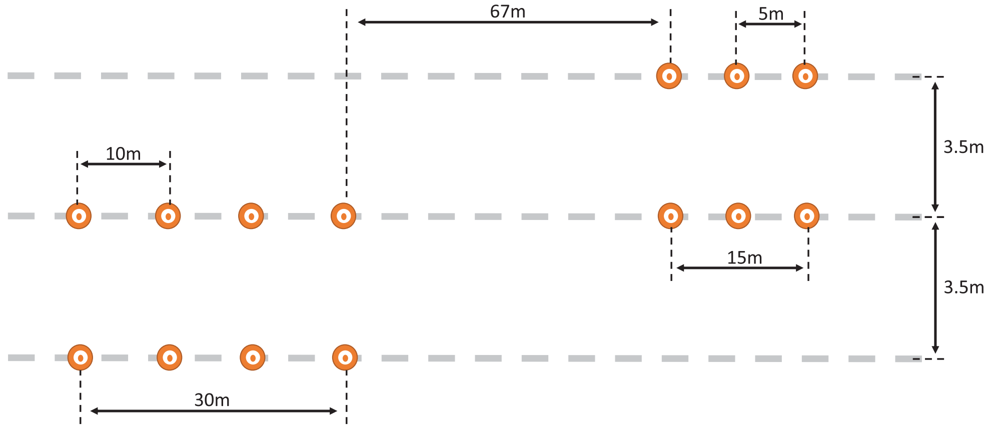

Figure 2. Lane change configuration in the driving scenario.

- Single lane change manoeuvres through cones, aimed at steering inputs between 0.3 and 0.5 Hz, resulting in lateral accelerations ranging from 1 to 2 m/s^2, see Figure 2.
- 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

To minimise the effects of possible speed variation, all driving sessions were conducted at a constant speed of 70 km/h using a cruise controller. After the first driving session, the drivers were asked to fill in a questionnaire, described in Section 2.4, with 5-grade scale answers on the realism of the driving experience.

In the second part of the study with a focus on vehicle handling tests, the drivers were asked to drive and compare a baseline truck and four modifications of it in the driving simulator. Since the focus was on lateral dynamics, only free driving on the straight section of the road and lane change manoeuvres were used in the second part. Before and after driving each modified vehicle, the drivers got to drive the baseline vehicle for better comparison. The time it takes to change the vehicle model in the simulator is less than 5 min. This procedure was repeated 4 times, one per modified vehicle. A questionnaire, described in Section 2.4, had to be answered after each drive, which included questions on differences between the modified truck and the baseline truck.

When all the driving sessions were finished, and the questionnaires answered, an informal discussion was carried between the driver and experiment leaders to gather general feedback about the experiment.

2.3. Road design

The road geometry design was based on Swedish road design guidelines, published by the Swedish Transport Administration [3]. This was to ensure that the geometry, curvature, and banking of the modelled roads match the corresponding values on actual roads. Additionally, the modelled road surface irregularities were based on data measured on actual roads in Sweden in a project called Knownroads [4].

The road was split into three parts consisting of a straight part with a smooth surface, a curved part also with a smooth surface, and a straight part with a rough surface. All roads consisted of two lanes, one in each direction, with a lane width of 3.25 m with a roadside width of 0.75 m. The asphalt was simulated as dry.

The straight parts of the road had a banking of 2.5%. The curved part consisted of connected curves and straight sections, some curves were banked at 4%, and transition curves were used to bridge the banking difference between the curves and straight sections. Rest of the curves with banking of 2.5% were connected directly to a straight section without any transition curve.

2.4. Questionnaires

Two questionnaires were used in the simulator study; one for each part of the driving scenario. The first questionnaire was used after the first part of the study, focused on evaluating the absolute validity of the driving simulator, including the following questions:

- How realistic are the perceived motions (roll and lateral motions) while manoeuvring?
- How realistic is the steering feel while manoeuvring?
- How realistic is the perceived vehicle motion in and out of curves?
- How realistic is the steering feel while in and out of curves?
- How realistic is the general perception of the ride on the uneven country road?
- How good is the agreement between the visual perception of the road unevenness and the ride feel?
- How realistic is the general driving experience in the simulator?
- How useful is this kind of simulator for vehicle dynamics testing, in your opinion?

The questions had a 5-grade scale answer, 1 being vey unrealistic/poor, 5 being very realistic/good, and the middle grade, 3, being moderate. The drivers were also asked to describe how the simulator drive differed from reality and how it can be improved with their own words.

The second questionnaire was used to evaluate the relative validity of the driving simulator and compare the driving experience with the baseline truck in the simulator with four modifications of it. This questionnaire was filled four times, once after each comparison between the baseline truck and one of its modifications with a new parameter set. Here are the questions included in the second questionnaire:

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

This question had a 5-grade scale answer, 1 being none, 5 being very noticeable, and the middle grade, 3, being noticeable. This question was followed with:

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

This question was asked with respect to yaw, roll, and steering feel separately.

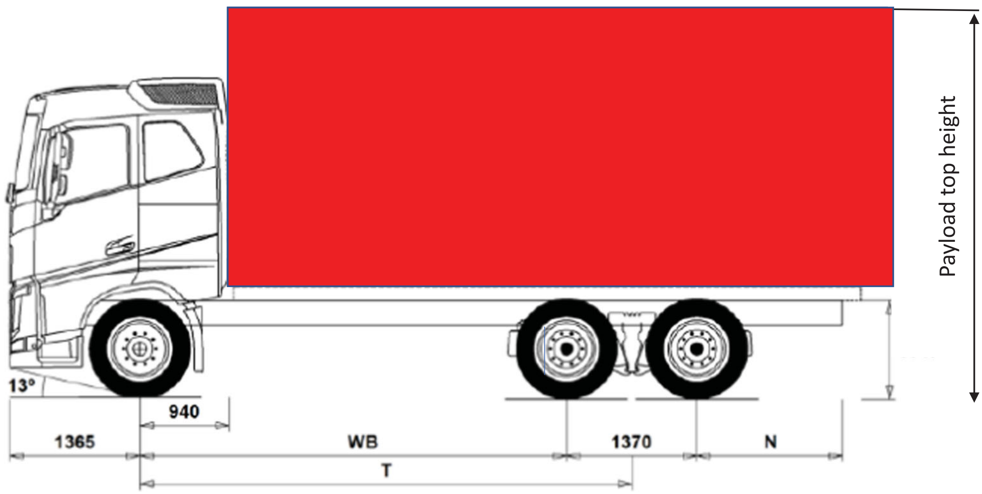

Figure 3. Simulated truck.

The questions had a 5-grade scale answer, 1 being very negative, 5 being very positive, and the middle grade, 3, being neutral. The drivers were also asked to describe the perceived differences for each of the modified trucks compared to the baseline, with their own words.

3. Truck model

The truck model used in this study is based on an OEM owned Matlab/Simulink based heavy vehicles model library. It is modelled as multibody mechanical systems, using SimMechanics toolbox. It includes a simplified torsional compliant frame and suspended axles and a suspended cabin. Magic-Formula is used to model the tyres.

A steering gear model and steering wheel torque feedback system was added to the OEM model and parameterised to the characteristics of the OEM truck. The truck model represents a fully loaded 6×2 rigid truck with a wheel base of 5.2 m, bogie spacing of 1.37 m, and a steering gear ratio of 18, see Figure 3. The front axle load is 8 t and the bogie load is 18 t. The powertrain contains a representation of an automatic transmission and a typical 13L engine.

The truck model was validated against measurement data gathered using a 26 t 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 a speed of 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. The validation is illustrated in Figure 4, which shows a good match between the measured and simulated data. The difference between the two is not significant; this order of difference can, for instance, exist between two similar trucks with different tyres. Thus, considering that in the model a sample standard tyre is used, the existence of such a difference between the simulation and measured data is acceptable.

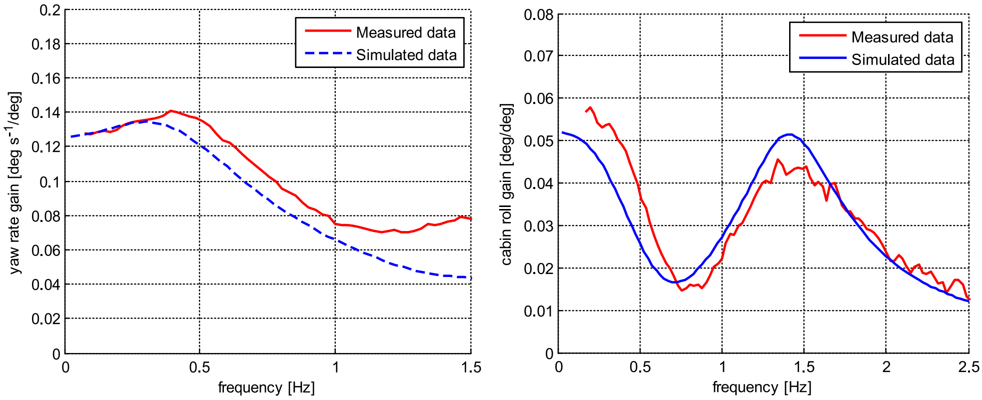

Figure 4. Yaw rate and cabin roll gains with respect to steering wheel angle, model outputs versus measurements.

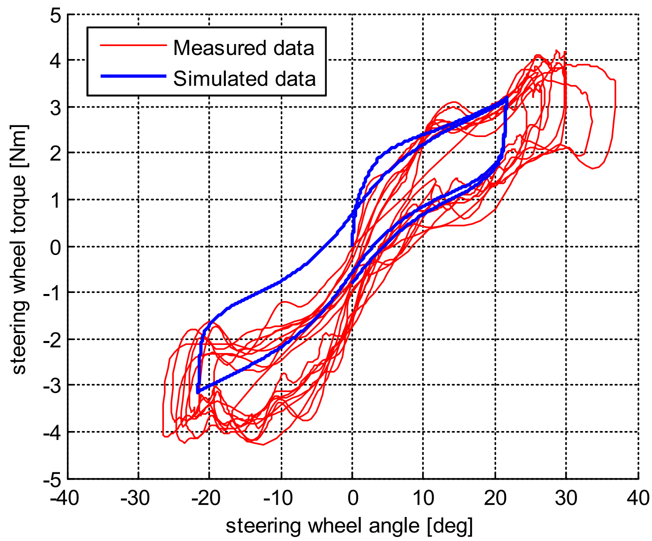

Figure 5. Steering torque of the truck model versus measurements.

Furthermore, for assessing the steering feel in the simulator, the simulated steering torque, which will be fed back to the drivers, was compared with the measured data, see Figure 5. The agreement between the simulated and measured steering torque looks better for positive steer angles, compared with negative steer angles. Considering the fact that the implemented steering system model is a simplification of a quite complex physical system with nonlinear properties, the final tuning of the steering feel was conducted subjectively in the simulator with the 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.

3.1. Truck parameter sets

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 vehicle 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 skilled test drivers would be able to compare the driving experience in the simulator with the Volvo FH truck they drive on a test track.

The applied parameter changes for the four modified trucks are described below. It should be noted that since the vehicle model structure remains unchanged, and only the model parameters are altered, the model validity holds for all the four modified trucks.

- *Parameter set 1 – Increased roll stiffness*: a 100% and 50% increase of the roll stiffness of the rear and front axle of the truck, respectively, coupled with a 100% increase on the frame torsional stiffness. These modifications lead to a stiffer ride with less roll, which is expected to be mapped to a feeling of increased stability.
- *Parameter set 2 – Decreased roll stiffness*: a 40% decrease on the rear axles roll stiffness. This introduces increased roll angles which are expected to be mapped to a feeling of decreased stability.
- *Parameter set 3 – Softer rear tyres*: a 25% decrease on the rear axle tyres cornering stiffness. This modification leads to an oversteered vehicle, which is expected to be mapped to a feeling of increased yaw motion.
- *Parameter set 4 – Increased roll understeer*: a roll steer coefficient of −0.45 is considered to model roll understeering, in contrast to a zero roll steer coefficient for the baseline vehicle. It means that 45% of the axles roll angle is added to the front axle steering angle, which creates understeering. This change is expected to be mapped to a feeling of an understeered vehicle.

The effects of 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 6. A higher/lower roll stiffness will decrease/increase the cabin roll angle as expected. Change of roll stiffness has a rather insignificant effect on the yaw rate gain and steering wheel torque, as can be seen in Figure 7. These plots are made for a truck speed of 70 km/h, which is the speed used in the simulator study.

The effects of changes in parameter sets 3 and 4 on the simulated yaw rate are illustrated in Figure 8. As expected, having softer rear tyres will make the truck oversteer more, which will result in a higher yaw rate gain. Increasing the roll understeering has almost an opposite effect.

The primary effect of parameter sets 3 and 4 is on the yaw behaviour of the truck; however, as shown in Figure 9, these changes will also affect the steering wheel torque and the cabin roll gain. The truck with softer rear tyres appears lighter to steer on-centre, due to the delayed build-up of aligning torque which results in less steering torque feedback on-centre; while the truck with higher roll understeer provides more steering torque feedback and appears heavier to steer on-centre. With respect to the cabin roll gain, the truck with softer rear tyres rolls a bit more compared with the baseline truck, but 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 a vehicle handling, even for skilled test drivers. This is a consideration which should be taken into account when analysing the results of the conducted driving simulator study.

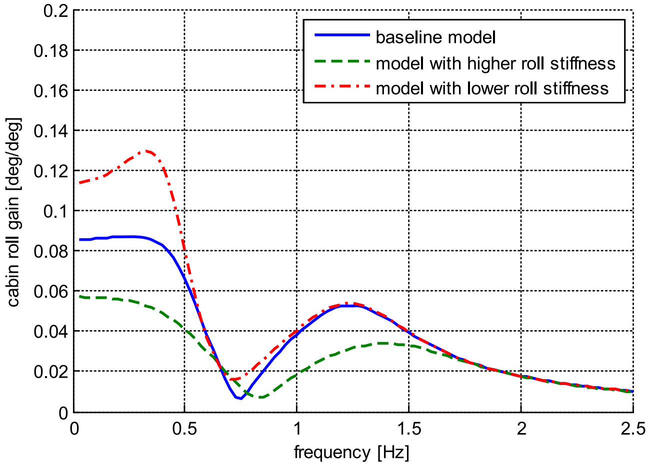

Figure 6. Cabin roll of the baseline truck in comparison with the trucks with parameter sets 1 and 2.

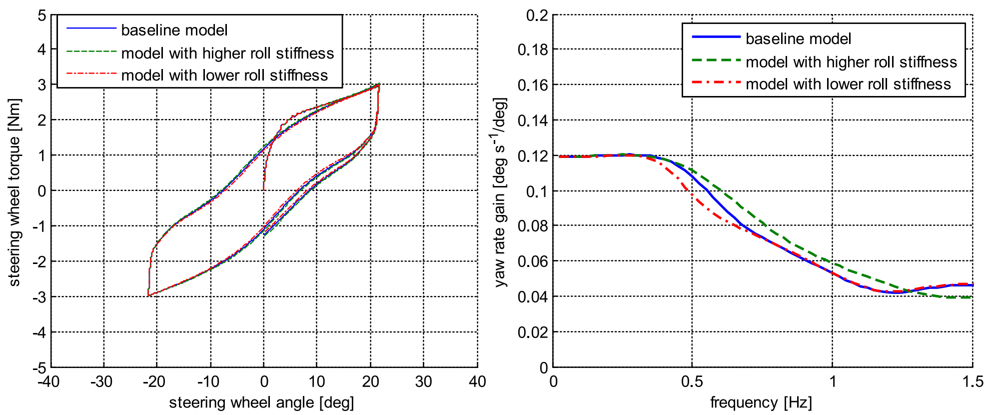

Figure 7. Effects of roll stiffness changes on steering wheel torque and yaw rate gain.

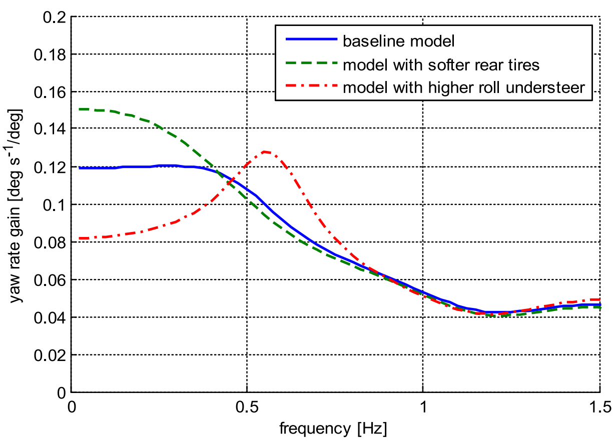

Figure 8. Yaw rate gain of the baseline truck in comparison with the trucks with parameter sets 3 and 4.

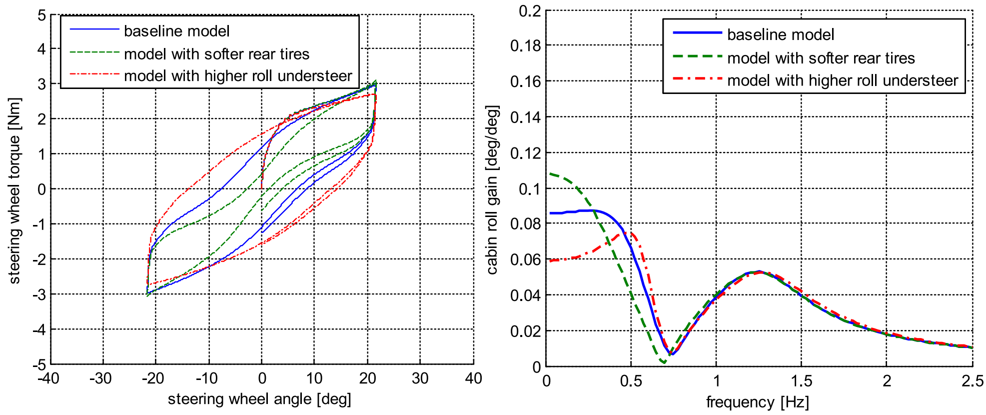

Figure 9. Effects of roll understeer and soft rear tyres on steering wheel torque and cabin roll gain.

4. Driving cues

Evidently, all cues contribute to the driving experience in a driving simulator; however, for vehicle dynamics testing, the following cues play a key role in the perceived realism:

- *Visual cues*, since they are the main cues used to orient a vehicle on the road.
- *Motion cues*, since they map the modelled vehicle motions into feedback to the driver's body (vestibular system and kinaesthetic sense)
- *Steering wheel torque feedback*, since it provides the driver with information about the contact forces between the tyre and the road and the vehicle handling.

Visual cue latency, which is the time between the driver's input to the vehicle and the visual display of the resulting motion in the simulator, should be kept low for improved perception of the motion. In an article overviewing literature on the effects of latency, it is concluded that maximum thresholds for delay acceptance range from 50 to 150 ms [5]. It is reasonable to assume that for vehicle dynamics testing, this value should be kept as low as possible to ensure high responsiveness of the visual cues. Furthermore, the accuracy of the position of the observer in the graphical representation relative to the body of the represented vehicle is important to guarantee that the driver perceives the displayed motions correctly.

Steering wheel torque feedback 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 tyres and the road. Reproduction of realistic steering torque feedback places demands on the steering system model, as well as actuators used to generate the torque.

A driving simulator cannot represent the full array of vehicle motions due to its physical constraints which limits the ranges of accelerations and rotations that can be presented to the driver. However, with the help of different motion cueing strategies, the simulator motion can be tuned to improve the fidelity of the motions of interest.

4.1. Motion cueing algorithm

Motion cueing algorithms are responsible for mapping vehicle motions into simulator motions. One of the most common motion cueing algorithms is the classical washout algorithm, which is also used in the utilised driving simulator, as presented in [6]. In a classical washout algorithm, the frequency contents of the motion are separated using filters and are partly reproduced through platform translational and partly through platform tilt. In tilt coordination, roll and pitch rotations are used to simulate sustained lateral and longitudinal accelerations, respectively [7].

Before running the study, the motion cueing algorithm of the driving simulator was tuned with help from a small group of test truck drivers, to improve the motion fidelity. The tuning was performed subjectively, which is a common approach, by adjusting the gain and frequency contents for each degree of freedom. It should be noted that there can be different approaches for tuning of motion cueing algorithms. For instance, in a study which is focused on relative comparison of different vehicle setups by a few expert test drivers, the motion cuing algorithm can be tuned differently for each expert driver to enhance the individual driving experience. However, the objective of this case study was to investigate if a driving simulator can be used to analyse and compare the perceived performance of different heavy vehicles by a larger group of truck drivers. Thus, one motion cueing algorithm was used through the whole study, tuning of which is explained in the following paragraphs.

Tilt coordination for longitudinal motion was removed and the gain for longitudinal accelerations was set to a lower value than what was used for lateral accelerations. This was done to increase the hexapod capacity for generation of lateral and vertical motions, and to avoid possible false cues. This choice was motivated by the nature of the manoeuvres of the simulated tests which excite lateral and vertical dynamics, predominantly.

For the lateral accelerations, the tilt coordination was kept so that the sustained accelerations in the curves can be simulated. However, the reference acceleration for tilt coordination was scaled differently than its lateral translation counterpart since the drivers pointed out that the rotation was noticeable, generating a false cue.

Pitch rate was presented almost in an unbounded state, only missing a small part of the lower end of the frequency range. Pitch rate presentation was considered important in this study, since it gives the driver an impression of the truck cabin movements on rough roads.

Yaw was not represented; no combination of gains or frequencies was depicted by drivers to be better than not representing yaw. One probable reason is a wrong rotation point in the visual representation of the motion, which could not be verified in this study. It should be emphasised that the decision for not representing yaw in the motion cueing was made by the subjective evaluation; since none of the tested yaw gains or frequencies improved the driving experience realism perceived by the drivers.

Tuning of the roll motions was coupled to the lateral accelerations; these signals are linked given the nature of the lateral manoeuvres. Early efforts showed that it was important to match the cut-off for low frequencies in lateral acceleration with the cut-off frequency of high pass filter of the roll rate, so both were set to 0.2 Hz. For the same reason, both signals were also affected by an equal scaling factor of 0.5 This resulted in an improvement in the responsiveness of the vehicle perceived by the drivers.

5. Results

Ten skilled test drivers were recruited from Volvo testing and chassis engineering to participate in the study. These test drivers are often engaged in the evaluation of concepts affecting the handling quality of heavy vehicles at Volvo. Two of test drivers could not complete all parts of the study due to motion sickness. Drivers were instructed to stop driving as soon as they felt any discomfort. This means that those who were considered to be affected by motion sickness in this study had a rather mild state of sickness. Therefore, the provided answers by the test person who was affected in the first part of the study, TP2, are provided within parenthesis in Table 1 as extra information. However, TP2 answers are not considered in the calculated average and standard deviation values.

Given the small amount of test persons in this study, it is hard to evaluate whether these tests are more prone to cause motion sickness or not. The occurrence of motion sickness in the driving simulators is mainly due to the mismatch between the visual cues and motion cues transmitted to the simulator driver. Some degree of motion sickness is inevitable in any simulator study and a 10% incidence of sickness appears to be the norm [8]. It is possible that in a test setup where the dynamics of the simulated vehicle are constantly being excited, the drivers are more often exposed to situations where the simulation shortcomings are accentuated. In the remaining part of this section, the achieved results from the simulator study are discussed.

The first part of the study was focused on the absolute realism of the driving experience. The questionnaire results show that the average ranking of both motion and steering feel perception by the drivers is between 3 and 4, in a 5-grade scale, in all road sections, except the steering feel during lane changes which has an average ranking of 2.8. The overall realism ranking is quite high as well, with an average of 3.6 which means that the test persons think the simulator realism is better than moderate. More importantly the average ranking of the usefulness of the driving simulator for vehicle dynamics testing is 4.2, 1 being not useful at all and 5 very useful. This means that the test persons think that such a motion-based driving simulator is a useful tool for vehicle dynamics testing. The results of the first questionnaire are provided in Table 1. The standard deviation is also provided in addition to the average values. However, since the limited number of participants constrains the statistical analysis, the answers of all test persons are provided for a better overview of the results.

In the last part of the study, the drivers drove four modified versions of the truck model, which were to be compared with the baseline truck, to investigate if the drivers could correctly deduce the vehicle changes associated with each parameter set. Evaluation of the

Table 1. Drivers' ranking of the realism of the perceived motions and steering feel in the driving simulator at different parts of the scenario, as well as their ranking of its usefulness for vehicle dynamics testing.

	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10	Average	Std
Lane change – motions	2	(3)	3	4	4	4	4	4	4	3	3.6	0.7
Lane change – steering feel	2	(4)	2	4	3	3	3	2	2	3	2.7	0.7
Curves – motions	2	(4)	3	3	4	4	–	4	3	3	3.2	0.7
Curves – steering feel	2	(4)	4	4	3	3	–	3	3	3	3.1	0.6
Uneven road – motions	3	–	4	5	4	–	5	3	3	4	3.9	0.8
Uneven road – steering feel	3	–	2	5	4	–	3	3	3	3.25	3.3	0.9
Uneven – visual vs. ride	3	–	3	4	3	–	5	3	3	3.25	3.4	0.7
Overall realism	2	(4)	4	4	4	–	4	4	3	3.75	3.6	0.7
Usefulness	3	(5)	5	4	5	4	4	5	–	3.75	4.2	0.7

Notes: TP stands for test person; the empty cells are for the test persons who either missed to fill in all the questions (TP6 & TP7) or did not complete the first part of the study due to motion sickness (TP2: Note that the answers of TP2 are not considered in the calculated statistics but are provided as extra information to the reader).

Table 2. Acceptance categories for the drivers' description based on the utilised words.

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

Table 3. The correctness, or lack thereof, of the drivers' deduction on the applied changes on the vehicle model, ranked according to Table 2.

	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10	Average
Parameter set 1 – Increased roll stiffness	0	–	1	0.5	1	0.5	1	1	–	1	0.75
Parameter set 2 – Decreased roll stiffness	1	–	1	0.5	0.5	1	1	1	–	0	0.75
Parameter set 3 – Softer rear tyres	1	–	0.5	1	1	1	1	1	–	0.5	0.875
Parameter set 4 – Increased roll understeer	1	–	0.5	1	0.5	0.5	0.5	1	–	1	0.75

Notes: TP stands for test person; the empty cells are for the two test persons who did not complete the second part of the study due to motion sickness.

answers was done based on the drivers' description of the perceived differences with the baseline truck. The drivers' descriptions were scrutinised for words or expressions which fall in acceptance categories, see Table 2. These categories were defined considering the actual parameter changes and are based on the expected perception of the vehicle dynamic behaviour. It should also be noted that their answers on the effect of the parameter changes on the vehicle motion, i.e. negative or positive effect on the vehicle handling, were used to assist the grouping for the cases with unclear words or expressions. The driver's descriptions of the changes were partitioned in three categories: correct (1), quite correct (0.5), or incorrect (0). Results equal or above 0.5 are considered as satisfactory results, since it shows that the driver could perceive the applied changes on the truck. As shown in Table 3, the average results for all the cases are above the acceptance level of 0.5.

The test drivers can perceive the implemented change in the truck rather well. For parameter set 3, 75% of the drivers guessed the parameter change completely correct while the remaining drivers also had a quite correct deduction. The results for the other three parameter changes are also very promising. There are only 2 incorrect answers, out of a total of 32. Considering the fact that altering a truck parameter can affect several handling characteristics, which will make identification of the primary change difficult, the achieved results are quite significant.

5.1. Correlation between drivers' perception and objective data

Some of the logged data such as driver steering input, yaw rate and cabin roll angle during manoeuvring were studied to verify the correlation between the driver's perception of the vehicle performance with objective data. For instance, in Figure 10, the cabin roll angle

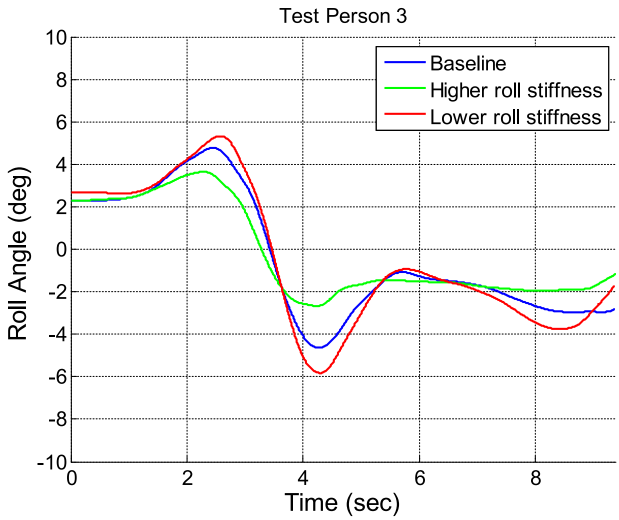

Figure 10. Cabin roll angle in a lane change for the trucks with different roll stiffness.

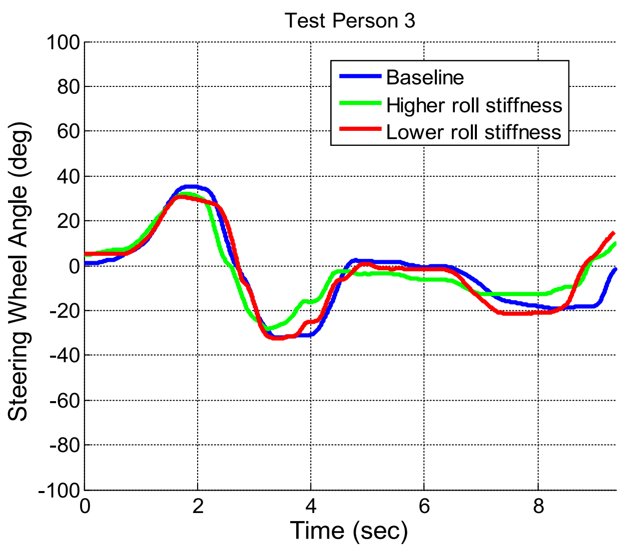

Figure 11. Driver input during the lane change, for the trucks with different roll stiffness.

during the lane changes performed by the driver is plotted for the baseline vehicle and parameter sets 1 and 2, where the roll stiffness is changed. The example curves are for test person 3 who had correctly deducted the changes applied on the truck. As expected, the cabin roll is reduced/increased for the truck with higher/lower roll stiffness in comparison with the baseline truck; changes which are correctly perceived by the driver.

Figure 11 confirms that the driver, test person 3, is performing rather similar lane changes with each truck. The steering wheel amplitude for the truck with higher roll stiffness is 32° and 28° in each half of the sinus-shaped cycle, while it is 31° and 32° for the truck with lower roll stiffness. Thus, the steering input amplitude difference is only 10–15%, while the difference in maximum cabin roll angle is 60% (5.8° versus 3.6°). This confirms that the

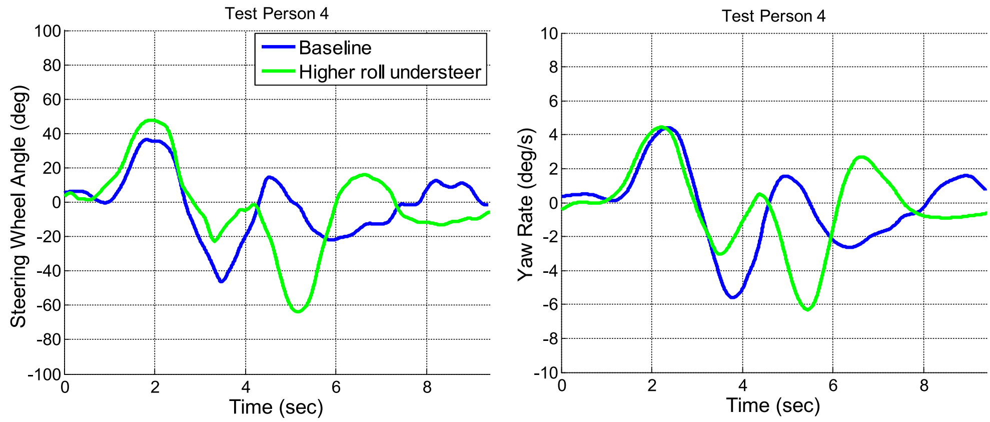

Figure 12. Driver input and the yaw rate for baseline truck vs. truck with roll understeer.

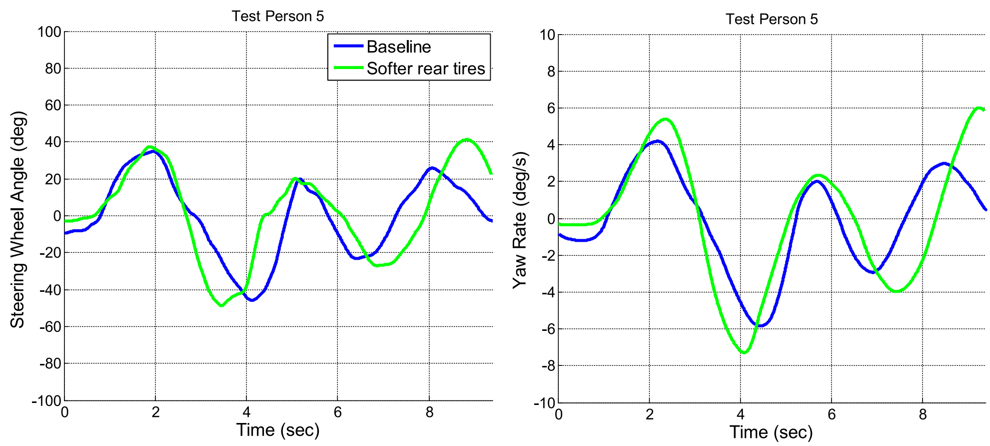

Figure 13. Driver input and the yaw rate for baseline truck vs. truck with softer rear tyres.

differences in cabin roll angle are mostly due to the different vehicle setups rather than the driver input.

Another example is illustrated in Figure 12, where the driver must steer considerably more to achieve similar yaw motion for the truck with higher roll understeer, relative to the baseline truck. The steer input peak is 39% higher for the truck with higher roll understeer, while the resulting peak yaw rate is only 12% larger for that truck. Again, the driver, test person 4, correctly perceives the changes in the vehicle motion.

The last example, for parameter set 4, is shown in Figure 13. The truck with softer rear tyre has larger yaw rate values compared with the baseline truck (25% larger peak value), although the driver is providing similar steering input (only 6% difference in peak values). The driver, test person 5, detects this oversteering behaviour correctly.

6. Conclusions

The presented case study investigates the suitability of a moving based driving simulator for dynamics tests focused on the evaluation of a heavy vehicle handling. A driving scenario was setup where skilled test drivers were asked to drive the 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 simulation has the capability to provide the drivers with satisfactory feedback; sufficient to enable them to correctly deduce the vehicle changes associated with each parameter variations. The attained results, even though not statistically significant, can encourage further research in this area.

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 a complementing tool in the existing test chain. It should be noted though that designing driving scenarios should be performed by care to mitigate the unwanted effects of increased safety of a driving simulator on the driver behaviour.

The average ranking of the usefulness of the driving simulator for vehicle dynamics testing by the drivers participated in this study is 4.3 out of 5. This is significant, considering that the truck drivers who participated in the study are skilled test drivers whose task is to drive and evaluate different truck designs on test tracks.

Disclosure statement

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