Validation of a Moving Base Driving Simulator for Subjective Assessments of Steering Feel and Handling

G.L. Gil Gómez, C. Andersson Eurenius, J. Donnay Cortiñas & E. Bakker
Volvo Car Group, Vehicle Dynamics Centre, Gothenburg, Sweden

M. Nybacka & L. Drugge
KTH Royal Institute of Technology, School of Engineering Sciences, Dept. of Aeronautical and Vehicle Engineering, Division of Vehicle Dynamics, Stockholm, Sweden

B. Jacobson
Vehicle Dynamics, Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden

ABSTRACT: Moving Base Driving Simulators (MBDS) have a large potential to increase effectiveness in vehicle dynamics development. MBDS can reduce dependency on vehicle-prototypes by allowing subjective assessments (SA) of models. Little is, however, known about the relation of SA in MBDS and in physical vehicles. This paper aims to increase this knowledge, and proposes and implements a methodology to validate MBDS for SA of steering feel and handling. Firstly, vehicle models were generated from Kinematics & Compliance measurements of real vehicles. These models were validated versus objective tests, with steering robots, of the physical vehicles. These vehicles and their MBDS-models were assessed by expert drivers, using a scanned-test track in the MBDS. Comparison of the SA in both environments enabled the MBDS validation. Promising results, with higher SA accuracy for handling than for steering feel, indicates that the major improvement effort should focus on the steering model and its simulation in the MBDS.

1 INTRODUCTION

Moving base driving simulators (MBDS) are a key step towards a more effective vehicle dynamics development, reducing time and cost, and allowing engineers to focus, in a reliable way, on specific parameters by eliminating parasitic effects and external factors. (Mohajer *et al.* 2015 & Hjort *et al.* 2014)

Mohajer explains that reliable results require a high level of fidelity and accuracy, which is attained by means of motion, visual, sound and haptic cues (corresponding to vestibular, visual, auditory, and kinaesthetic sensory information). Depending on their fidelity, usability, complexity and costs, MBDS can be classified as high-, mid- or low-level. High-level simulators offer all kind of cues and normally include a wide field-of-view and a full cockpit. This cabin is often mounted on a hexapod coupled to a moving platform that increases the workspace on the horizontal plane. This configuration offers more than 6-DOF, as it is the case of the MBDS in Figure 1.

Murano *et al.* (2009) claims that to be felt as realistic and to avoid motion sickness, these horizontal platforms require to travel approximately the same distance as the simulated real vehicle. For example, to properly reproduce normal driving (0.3 g longitudinal and lateral accelerations) in an intersection, a movement capability of 35 x 20 m is demanded. For more advanced driving, the limitations in displacements and power of the actuator cannot normally reproduce full vehicle dynamics, therefore not matching the visual cueing. This reduced *physical validity* negatively affects *perceptual validity* (driver's perception of self-motion), which has to be increased by motion cueing, that is, a coherent coordination of all the available cues (Reymond & Kemeny, 2000). Unlike Murano, Berthoz *et al.* (2013) claim that drivers prefer the motion cue scaled down to 40-70%. However, no motion feedback severely degrades driver's performance in fast manoeuvres, because artificial environments disturb driver behaviour.

Behavioural validity is therefore conditioned to physical and perceptual validity; it means that drivers behave similarly in MBDS as in real traffic. This validity has been the main focus of previous research, as MBDS allows to study drivers' behaviour and interactions with active safety systems under stressful, dangerous, or non-legal situations (Blana, 1996; Burenger-Koch, 2005; Murano *et al.* 2009).

Figure 1. Driver-in-Motion simulator at Volvo Car Group.

However, according to Mohajer (2015), and to the best of the authors' knowledge, there is little research about subjective assessments (SA) of vehicle dynamics in MBDS. A pair of examples are: Cossalter *et al.* (2010), on a motorcycle simulator, and Hjort *et al.* (2014), who introduce a methodology for subjective and objective validation of MBDS for on-the-limit handling. Hjort maintains that MBDS seldom perform well in these situations; therefore, validated reliable models are required. However, as Hjort states, their method was not fully developed.

This paper proposes and implements a further developed validation methodology for MBDS regarding steering feel (controllability) and handling (stability), giving special focus to the relation of SA in real vehicles and in their respective MBDS-models.

2 MATERIAL AND METHODS

Figure 1 shows the Driver-in-Motion simulator, which has 9-DOF with three horizontal cylinders that move a hexapod (VI-Grade, 2015). This is the simulator validated in this study.

The proposed validation methodology follows the workflow shown in Figure 2. This workflow is divided in two parallel branches: a virtual and a physical branch. The former includes the models and the MBDS. The latter comprises the tests on the real vehicle, which were used to gather data for parameterizing the models and as the reference for the posterior validation of these models and of the MBDS. The steps in this methodology are presented below in order of appearance, from left to right, in Figure 2.

2.1 *Test vehicle configurations*

Three vehicle configurations were driven in both the MBDS and in reality. This amount was considered appropriate for a first case study, as it allows to compare, real-SA and MBDS-SA, per configuration; and to evaluate, in addition, how these SA evolve between different configurations in these two test environments.

These three set-ups were a Volvo V40 in: (i) its standard configuration, (ii) without the front antiroll bar (ARB), and (iii) without the rear ARB. These extremely simple modifications greatly influence characteristics such as roll control or understeering coefficient, and therefore steering feel and handling.

Moreover, ARB tuning is an integral part of vehicle dynamics development. Although removing an ARB is not within the realistic tuning range, the authors consider this approach appropriate, because going from large to smaller changes allows to easily identify the limitations of the MBDS.

An extra model was generated from MSC Adams. This process represents the real development workflow, in which real vehicles are not available in early stages and therefore, the MBDS models are obtained from more complex multibody dynamics models.

2.2 *Generation of the vehicle models*

MBDS require real-time capable models. In this project, VI-CarRealTime was used. This software performs at real-time by being based on look-up tables, which can be obtained from Kinematics and Compliance (K&C) tests. These tests accurately describe the kinematics characteristics of the vehicle suspen-

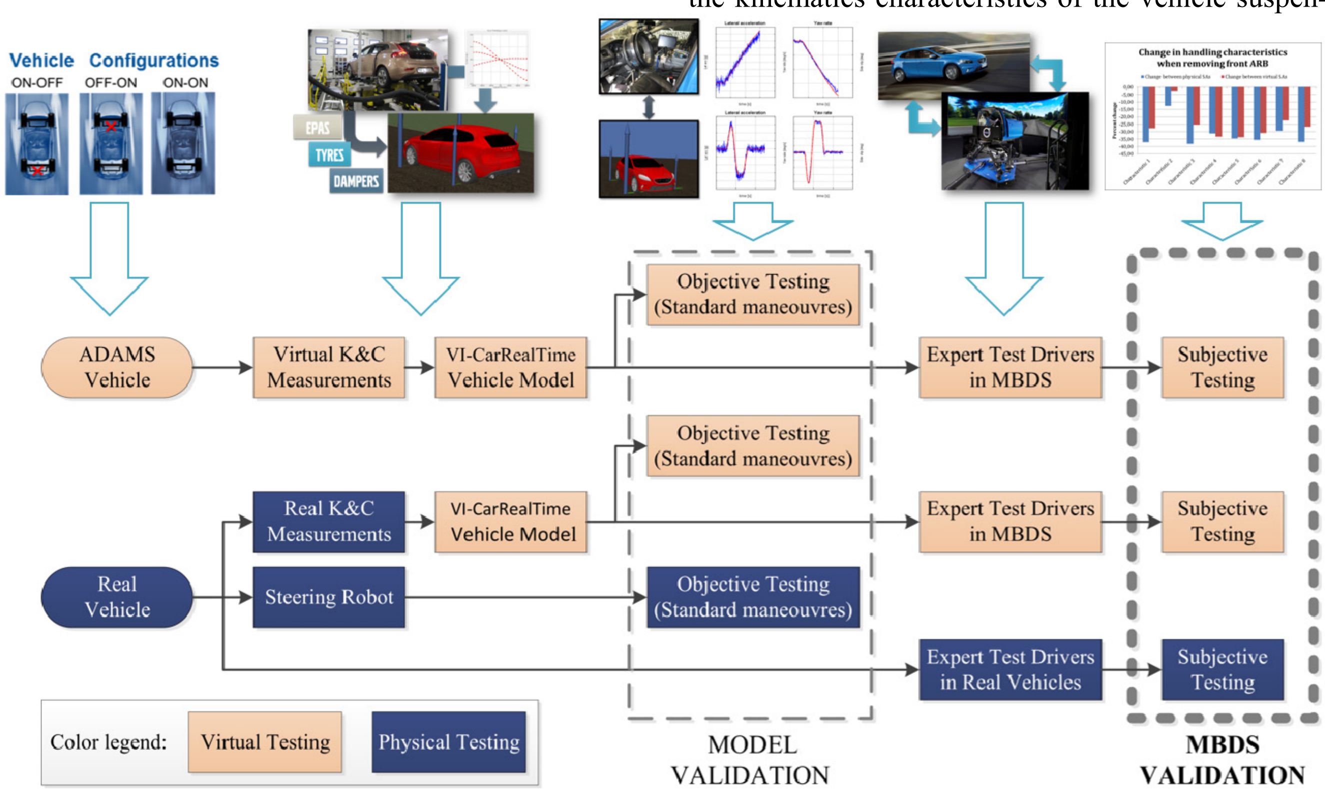

Figure 2. Workflow of the methodology proposed and implemented to validate the MBDS.

sion and steering geometries, the compliance characteristics of their components, and the centre of gravity and moments of inertia of the vehicle. Virtual and real K&C tests were performed in this study:

- The virtual K&C tests were run in MSC Adams, to represent model-based development.
- The real K&C tests were done in an Anthony Best Dynamics' SPMM 4000 machine, to ensure the best possible parameterization of VI-CarRealTime.

To model the non-linearity of the system, these tests included: single-event tests; asymmetric left-right bounce-level tests; and measurements at three bounce levels. The intermediate level corresponded to curb weight plus a driver and a passenger, which corresponds to the weight, on the passenger seat, of the required equipment in later objective testing.

The steering characteristics were measured with the help of a steering robot, which implemented a limit-to-limit sweep of the steering rack. A braking robot was also mounted, and applied when required.

These quasi-static tests were complemented with the curves of the characteristics of the dampers and of the power steering system; as well as with the tire model, for which the magic formula was used, parameterized by the tire manufacturer.

2.3 *Validation of the models*

After their generation, the models were verified (for executability, stability and robustness) and validated by comparison and adaptation at different loads, operating ranges and time scales, i.e., steady state, slow and fast transients (Klemmer et al. 2011). This was done by back-to-back objective tests, executed in the real vehicles and in VI-CarRealTime. Different operating cases were achieved by using different standard manoeuvres: on-centre handling (ISO 13674), swept steer (SAE J266), frequency response and step input (ISO 7401), constant radius (ISO 4138), and sine with dwell (Forkenbrock, 2007).

These open-loop manoeuvres were programmed on a steering robot to test the real vehicle configurations. This method eliminates driver's influence and increases test repeatability (Harrer et al. 2006, Pfeffer et al. 2008). The selected steering robot, from Anthony Best, was equipped with angle and torque sensors; with a throttle actuator; and with a differential GPS and an OTS Inertial platform, RT3002, to measure the current states of the vehicle.

In the virtual-environment case, the manoeuvres were initially programmed in CarRealTime. However, as it is practically impossible to reproduce the same manoeuvres in the physical and virtual environments (Cossalter et al. 2010), time-vectors recorded in the physical tests were used as model inputs. This ensured that the models were exactly exposed to the same stimulus as in the physical testing. These inputs were the steering wheel angle (SWA) and the longitudinal velocity.

The validation was done comparing: (i) time series data of relevant steering and handling measurements: lateral acceleration, yaw rate, sideslip angle, roll angle, and steering wheel torque (SWT) (Mohajer et al. 2015); and (ii) key metrics as the described in the standards. According to Klemmer, the comparison was done for the highest and lowest tested inputs, to ensure the validity of the models for a wide operating range. Note that non-linear effects lead to simulation results being generally only valid within a limited input window (Garrott et al, 1997).

2.4 *MBDS validation*

To validate the MBDS, drivers' SA obtained first in the real vehicle were compared to those obtained later in the MBDS. This test order was followed by Hjort *et al.* (2014) and recommended by Molino *et al.* (2005): "If simulation is an abstraction of reality, it is better to let nature to be first instructor"

Three expert drivers participated in this study (see Table 1). More drivers were planned, but around ¾ of the physical test had to be cancelled, or rescheduled, due to poor weather conditions. Furthermore, Driver A could unfortunately not complete the tests in the MBDS due to motion sickness.

Table 1. Detailed test drivers' information.

Driver	Gender	Age	Experience (years)
A	Male	54	30
B	Male	35	7
C	Male	29	0.5

To ensure that the drivers were exposed to similar experiences in both environments, great effort was invested on keeping the tests alike: For instance, in the real-vehicle tests, tire pressure was checked to reflect the model. The vehicle weight was kept at curb plus two (as the objective tests emulates this configuration), by having a test leader as passenger in each real drive. This test leader drove the cars to the test track, where test drives were limited to three laps, and he also gave support with the SA questionnaire, which is presented in Table 2. The MBDS-tests used a V40 cockpit and the same test track, which had been laser scanned, and to avoid motion sickness, again only three laps were allowed.

Table 2. A subset of the SA questions*.

Level 2	Level 3	Level 4	Level 5
		Response	Window
		Roll Control	
Steering Feel	Straight-ahead Controllability		Deadband
		Torque Feedback	Build-up
			Friction
			Damping

* further detail can be found in Gil Gómez et al. (2015).

To avoid including a bias, the real-vehicle tests were always executed in the same order: 1st) configuration *ii*, 2nd) configuration *iii,* and 3rd) configuration *i*. To analyse SA repeatability (an issue identified by Gil Gómez et al. 2015), the test series in the real vehicle were blind and repeated twice. That is, configurations *ii – iii – i* were tested followed by a pause and configurations *ii – iii – i* again. The second time, the SA was done using a tablet version of the questionnaire (Gil Gómez et al. 2016).

In the MBDS the test-sequence was similar, but with no model repetition. Instead, as it is difficult beforehand to identify the best model (Hjort *et al*. 2014), different parameterizing technics were studied: First, the models obtained by real-K&C measurements of configurations *ii, iii* and *i*. Second, configurations *ii* and *iii* obtained by virtually removing ARB in the model *i* obtained from real-K&C. Last, model *i* derived from virtual-K&C in MSC Adams.

The SA in the MBDS was answered in the tablet (to reduce transcription time), and complemented by an interview about general driving feel and improvements suggestions in the vehicle configuration.

The comparison of the SA (MBDS vs. real vehicles), and the outcome of the interview, were used to validate the performance of the MBDS. The results were firstly studied car by car. However, it was observed that a relative analysis led to better results. That is, analysing how SA changed (for each driver) between different vehicle configurations.

3 RESULTS AND DISCUSSION

3.1 *Objective validation (model validation)*

Figure 3 shows that the initial model was already realistic. However, this model, directly obtained from the K&C tests, was not considered good enough. The responses of the model were normally too low for the lowest SWA inputs, whereas too high for the highest. Moreover, some mechanical properties of the steering system, such as stiffness and inertia of the components of the steering column, were missing, as they are not measured by the K&C test. Furthermore, as shown in Figure 4 (left), activating the power steering model led to unstable results.

Therefore, a fine-tuning iteration of the model was performed:

- For the tires, the lateral and longitudinal peak friction coefficients were increased to 1.0 (they were initially set to 0.8), to allow for larger lateral accelerations. The relaxation length was modified to decrease tire oscillations (Luty, W. 2001), and therefore reduce stability issues, although this strategy alone did not lead to large improvements.

- For the ARB, theoretical parameters were used, as the values obtained by K&C seemed to be non-symmetrical, too stiff, and vehicle-roll was too low.

- For the steering system, the mechanical properties of its components were included; and a simpler Simulink-model was used for the power steering. It calculated SWT as function of SWA, steering rack force, longitudinal velocity and lateral acceleration. Figure 4 (right) shows that this simpler solution led to a significantly higher numerical stability.

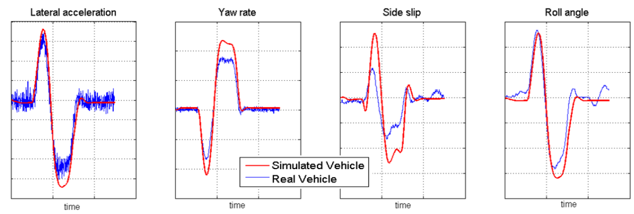

Figure 3. Example of the initial model validation. Comparison of real and simulated sine with dwell tests of configuration *i*.

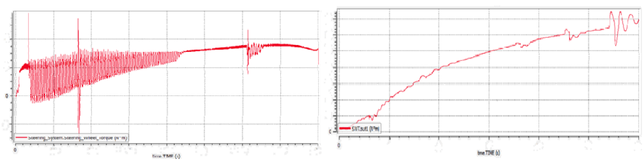
Figure 4. SWT during constant radius test. Numerical instability of the initial model vs. the stable simpler Simulink model.

Figure 5 shows that these modifications clearly improved the simulation results. In general, the modified model represents the physical testing more accurately than the initial model. The figure also illustrates that the K&C-based models are better than the non-modified model obtained from Adams. This trend is repeated for all manoeuvres.

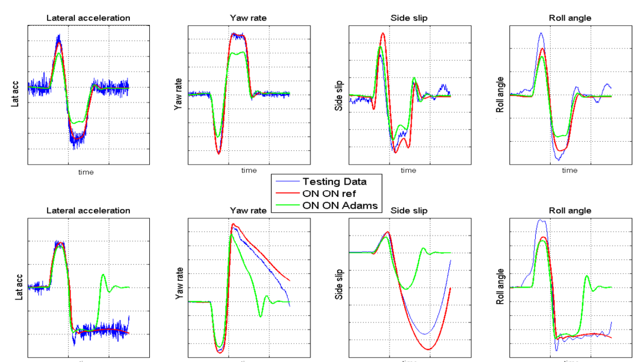

Figure 5. Final validation. Comparison of configuration *i* (ON-ON): modified real-K&C model (ref) vs virtual-K&C model during a sine with dwell. Top: low SWA. Bottom: high SWA.

Figure 6 presents results for the two models of configuration *ii.* The one obtained by removing, virtually, the rear ARB from the standard configuration model; and the one obtained from real K&C measurements of the vehicle without the rear ARB. The former does not perform so well as the latter for the sine with dwell. However, the two models show smaller differences for the rest of the manoeuvres. Additionally, the differences between these two models are slightly larger than for the two non-front-ARB models, because this latter modification affected less the K&C results.

To complete the validation, the objective metrics (OM) were also compared. Comparing absolute values did not result in an effective method; however, the comparison of the OM between all vehicle configurations allowed to identify that 83% of the selected handling OM (62% for steering) changed in the same direction in the model as in reality, with an average deviation of 15.9% (6.3% for steering). This relative evaluation is considered important because the MBDS is intended to properly represent the direction of the changes in vehicle response.

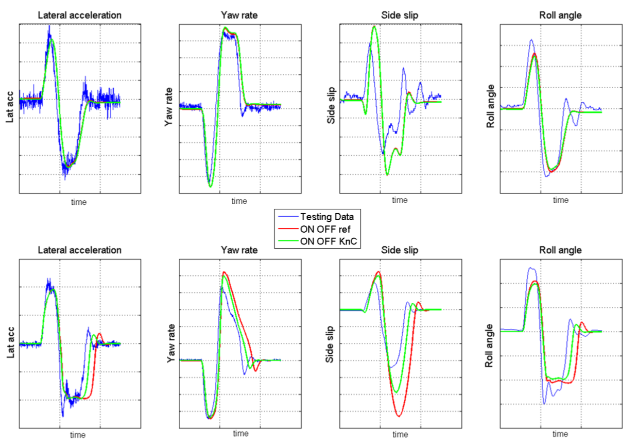

Figure 6. Results of the "ON-OFF ref" and "ON-OFF KnC" models. The former is derived from the model in Figure 5 removing, virtually, the rear ARB. The latter is the model derived from measuring the real vehicle without rear ARB in the real K&C rig. They are compared with the data gathered from the physical testing during two sine with dwell manoeuvres.

3.2 *Subjective validation (MBDS validation)*

Regarding the SA in the MBDS, bad weather conditions led to a low number of drivers completing the tests. This affects the statistical significance of the results. However, it is nevertheless a good example of a motivation for validated MBDS, where tests are non-dependent of weather conditions.

Furthermore, a first result is that one driver could not complete the tests in the MBDS due to motion sickness, which is caused by lack of physical validity and/or by poor model/motion-cueing harmonisation. This reduces drivers' performance and motivation, and is therefore an issue that needs to be taken into consideration. Some methods to help avoiding it are presented in literature, e.g.: ReliefBand (a medical device), which seems to offer some simulator sickness relief against increased MBDS exposure; independent visual background (IVB) (Mollenhauer et al. 2004) and the better performing "natural" IVB, which uses "meaningful" objects, such as clouds, as fixed background (Lin et al. 2002).

On the other hand, another driver did seem completely unaffected by motion sickness, thus completing the six tests without a break. However, testing so many cars (even only for three laps) during a single test day was identified as a high demanding task, thus complicating for the drivers to keep high level of concentration. This agrees with Blana (1996), who claims that simulator testing is more physically/effort demanding and more frustrating than driving on a similar real driving condition.

Regarding the interviews, the results were promising. All drivers assessed the standard configuration as being the best, not identifying any obvious improvement to be implemented in the vehicle. In contrast, for the other configurations, the main concerns were detected, and increasing ARB stiffness in the axle where it had been removed was normally suggested. Improvements on steering feel were also desired. This agrees with the results of the SA study.

The comparison of the SA ratings between all vehicle configurations allowed to identify if the drivers felt that the vehicle behaviour changed in a similar way in the real car and in the MBDS. Figure 7 shows that for handling 94% of the SA (78% for steering) changed in the same direction, with an average deviation of 6.3% (18.7% for steering). This outcome reflects the results previously obtained for the OM, where handling metrics offered better results too. This is probably due to the steering model, which had to be simplified because of numerical instabilities; and for which some parameters could not be directly obtained from the K&C measurements.

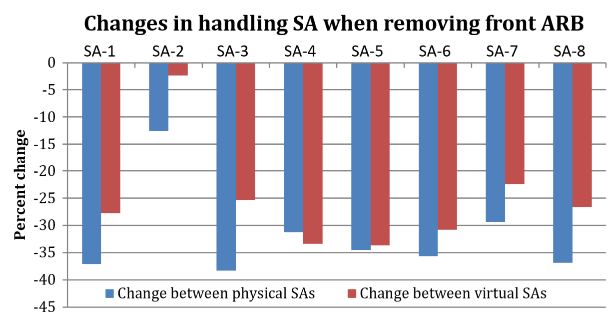

Figure 7. Example of the relative change in SA for test in the real vehicles and in the MBDS, in this case between the standard configuration and the configuration without the front ARB.

4 CONCLUSIONS

In summary, the following conclusions can be listed:

- The model derived from real K&C gave results closer to the real objective tests than the model derived from virtual K&C (MSC Adams). Furthermore, measuring all configurations in the real K&C was generally better than simply removing, virtually, the ARB from the standard configuration model.

- In virtual objective testing, in the model, using recorded inputs from real testing improved the validation, as the model is consequently excited with exactly the same inputs as the reference real test.

- The comparison of OM did not give as good results as the comparison of time signals. This might have been caused by the OM adding more complexity because of the post-processing tools.

- The longer the drivers tested in the simulator the more comfortable they felt doing virtual evaluations. There might be an effect of adaptation to the MBDS, indicating that training sessions in the MBDS can be beneficial for vehicle dynamics development.

- Despite of blind testing, the expert drivers normally suggested to increase the stiffness in the axle without ARB. Whereas, for the production vehicle, no clear suggestions were identified. This is a promising result towards development in the MBDS.

- The validation of the SA in the MBDS also led to very positive results, specially for handling. Further work in the development of the MBDS should therefore focus on the development of the steering model in VI-CarRealTime, and of the method to gather steering parameters from the real vehicle.

- As future work it is left, therefore, the study of how to improve the models of the steering feel and the steering assistance; as well as, how to properly modify ARBs in the model without real K&C.

Finally, as MBDS are continuously upgraded with new features, to identify if these upgrades improved the simulator, validations have to be performed periodically against field-testing in natural environments. (Molino et al. 2005; Blana 1996) The method proposed here allows to keep the models and the real-SA as calibration references for motion cueing validations. That is, for a second validation only a new SA session in the MBDS is required. Thus, increasing the effectiveness of the validation.

ACKNOWLEGDES

The authors would like to acknowledge gratefully the financial support from FFI - Strategic Vehicle Research and Innovation [2012-04609].

The authors would also like to extend their thanks to the vehicle dynamics, CAE and vehicle and rig testing teams at Volvo Car Group for their participation and all their support and help in this project.

REFERENCES

Andersson Eurenius, C. & Cortiñas, J. 2015. Validation of a Moving Base Driving Simulator for Subjective Assessments of Steering and Handling. Göteborg: Chalmers University of Technology (*Diploma work* - nr: 2015:69).

Berthoz, A. Bles, W. Bülthoff, H.H. Grácio, B.J. et al. 2013. Motion scaling for high-performance driving simulators. *IEEE Transactions on Human-Machine Systems,* 43(3): 265-276.

Blana, E. 1996. Driving simulator validation studies: A literature review. *Working paper 480. Institute of Transport Studies, University of Leeds, Leeds, UK.*

Bruenger-Koch, M. 2005. Motion parameter tuning and evaluation for the DLR automotive simulator. *Proc. Driving simulation conference, North America 2005.*

Cossalter, V. Lot, R. & Rota, S. 2010. Objective and subjective evaluation of an advanced motorcycle riding simulator. *European Transport Research Review* 2(4):223-233.

Forkenbrock, G.J. & Boyd, P.L. 2007. Light vehicle ESC performance test development, *In proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles*, Paper Number 07-0456, Lyon, France.

Garrott, W.R. Grygier, P.A. Christos, J.P. Heydinger, G.J. Salaani, K. Howe, J.G. & Guenther, D.A. 1997. Methodology for validating the National Advanced Driving Simulator's Vehicle Dynamics (NADSdyna), *SAE Tech. Paper* 970562.

Gil Gómez G.L. Nybacka, M. Bakker, E. & Drugge, L. 2015. Findings from subjective evaluations and driver ratings of vehicle dynamics: steering and handling. *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*, 53(10):1416-1438.

Gil Gómez, G. Vestlund, J. Bakker, E. Berger, C. et al. 2016. Improving subjective assessment of vehicle dynamics evaluations by means of computer-tablets as digital aid, *SAE Technical Paper 2016-01-1629.*

Harrer, M. Pfeffer, P. E. & Johnston, D. N. 2006. Steering feel: objective assessment of passenger cars analysis of steering feel and vehicle handling. *FISITA World Automotive Conference*. Yokohama, Japan, 22-27 October 2006.

Hjort, M. Kharrazi, S. Eriksson, O. Hjälmdahl, M. 2014. Validating on –the-limit properties of a driving simulator. *Proc. New development in driving simulation design and experiments: Driving simulation conference Europe 2014*

ISO 4138, 2012. Passenger cars – Steady-state circular driving behaviour – Open-loop test methods (ISO 4138:2012, IDT), *International Organization for Standards*.

ISO 7401, 2011. Road vehicles – Lateral transient response test methods – Openloop-test methods (ISO 7401:2011, IDT), *International Organization for Standards*.

Klemmer, J. Lauer, J., Formanski, V. et al. 2011. Definition and application of a standard verification and validation process for dynamic vehicle simulation models. *SAE Int. J. Mater. Manuf.* 4(1):743-758.

Lin, J.J.-W. Abi-Rached, H. Kima, D.-H. et al. 2002. A natural independent visual background reduced simulator sickness. *Human Factors and Ergonomics Society Annual Meeting Proceedings* 46(26):2124-2128.

Luty, W. 2011. An Analysis of Tire Relaxation in Conditions of the Wheel Side Cornering Angle Oscillations, *Journal of KONES Powertrain and Transport*, 18(1):325-332.

Mohajer, N. Abdi, H. Nelson, K. & Nahavandi, S. 2015. Vehicle simulators, a key step towards road vehicle dynamics improvement, *Vehicle System Dynamics,* 53(8):1204-1226.

Moline, J.A. Katx, B.J., Opiela, K.S. & Moyer, M.J. 2005. Validate first; simulate later: A new approach used at the FHWA higway driving simulator. *Proc. Driving simulation conference, North America 2005.*

Mollenhauer, M.A. & Romano, R.A. 2004. The evaluation of a motion base driving simulator in a cave at tacom. *Proc. 24th Army Science Conference.*

Murano, T. Yonekawa, T. Aga, M. & Nagiri, S. 2009. Development of high-performance driving simulator. *SAE Int. J. Passeng. Cars – Mech. Syst.* 2(1):661-669.

Pfeffer, P. E. Harrer, M. & Johnston, D. N. 2008. Vehicle dynamics measurements. *Proc. of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 222(5):801-813.

Reymond, G. & Kemeny, A. 2000. Motion cueing in the Renault driving simulator. *Vehicle System Dynamics,* 34(4): 249-259.

SAE J266, 1996. Steady-state directional control test procedures for passenger cars and light trucks. Surface vehicle recommended practice. *SAE International.*

VI-Grade. 2015. DiM – Driver-in-motion brochure. 2 April 2015 [ONLINE] Available at: http://www.vi-grade.com/index.php?pagid=download_det&did=1224*. [Accessed 26 May 2016].*