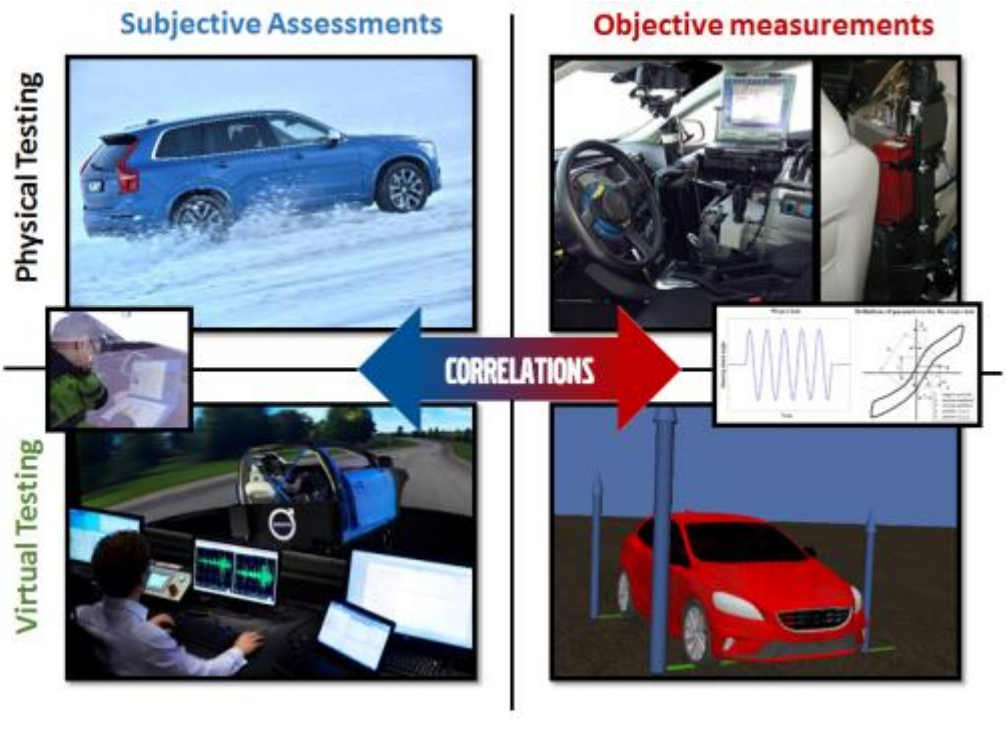
Final report

iCOMSA - Correlation of Objective Measures and Subjective Assessments: efficient vehicle dynamics evaluation and new intelligent concepts



FFI Fordonsstrategisk Forskning och Innovation

Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1 Sammanfattning

Fordonsdynamikutveckling är starkt baserad på subjektiva bedömningar (SA) av fordonsprototyper vilket är både kostsamt och tidsödande. Samtidigt i denna datorålder är det en stark drivkraft till att reducera beroendet av provning ute i fält. Men datorer är kända för sin enorma beräkningskraft och inte för sina känslor. Det är därför man behöver förstå SA innan de beräknas samt förstå deras relation till objektiva mätetal (OM) som kan beräknas genom simuleringar samt förstå hur denna kunskap kan möjliggöra en mer effektiv utvecklingsprocess. Huvudresultatet i detta projekt är utvecklingen av en metod som är kapabel till att prediktera SA från kombinationer av OM. Denna metod genererar först en självorganiserad karta av fordon som bara baseras på fordonens OM, vilket möjliggör kvalitativ prediktion av ett nytt fordons styrkänsla genom fordonets position i relation till närliggande fordon på kartan. Denna prediktion är utökad med beskrivande ordmoln som sammanfattar med få ord kommentarerna från expertförare för varje fordon i kartan. Sedan läggs ett lager på skapat av ett artificiellt neuralt nätverk som predikterar SA betyget för ett nytt fordon i kartan. Vidare kan denna metod också analysera effekten av toleranser på OM kravsättningar samt verifiera tidigare identifierat önskat OM område. Förutom korreleringar av SA-OM vid sommarväglag så har också arbetet i detta projekt doktorsavhandling haft som mål att effektivisera fordonsdynamikutvecklingen även under andra körförhållanden. För vintertester där objektiva tester ännu inte är färdigutvecklade så identifierar och definierar denna forskning robusta objektiva manövrar och OM i vinterklimat. Detta har gjorts genom att använda experimentell data tillsammans med datorstödda optimeringar och ANOVA för att optimera manövrar som sedan har verifierats genom experiment. För att förbättra kvalitén och effektiviteten kring SA har Volvos körsimulator validerats för fordonsdynamisk betygsättning av SA samt en applikation till en datorplatta tagits fram och validerats.
Sammanfattningsvis så har denna forskning tagit fram en omfattande metod för en mer effektiv och objektiv utvecklingsprocess för fordonsdynamik.

2 Executive summary

The vehicle industry needs to strengthen the knowledge concerning driver/vehicle interaction and the connection between SA and OM. This project aimed to find methods that will enable an efficient process for objective vehicle dynamics evaluation for both early development and during vehicle validation. Based on the detailed knowledge of the correlation between Objective Measures (OM) (from vehicle data) and Subjective Assessments (SA) (from driver rating) the aim was also to develop new intelligent vehicle systems built around the driver.
The main result from this project is the development of a method capable of predicting SA from combinations of key OM. Firstly, this method generates a classification map of vehicles solely based on their OM, which allows for a qualitative prediction of the steering feel of a new vehicle based on its position, and that of its neighbors, in the map. This prediction is enhanced with descriptive word-clouds, which summarizes in a few words the comments of expert test drivers to each vehicle in the map. This project focused on OM-SA correlations in summer conditions, but also aimed to increase the effectiveness of vehicle dynamics development in general. For winter conditions, where objective testing is not yet mature, this research initiates the definition and identification of robust objective manoeuvres and OM. Furthermore, a tablet-app to aid vehicle dynamics SA was developed and validated.
Combined this research encompasses a comprehensive method for a more effective and objective development process for vehicle dynamics.

3 Background

There is a strong drive in the vehicle industry to improve the efficiency and quality of the development process. At the same time the complexity of the vehicles increases. Design and development of vehicles is very much a collaborative effort in-house and with suppliers, where all need to keep in mind the requirements of sustainability, safety, economy, and customer satisfaction. Understanding people, customer and/or users is hard since what can be expressed are not only facts but also often perceptions and interpretations. One important method in achieving the desired development improvements is to move from physical to virtual testing. Physical testing is costly and time consuming due to the need for prototype vehicles and testing of multiple variants. Even though virtual testing is extensively used during vehicle development there is a lack of knowledge on how to capitalize on the SA and make use of them in the early development. Here further studies on how to link SA to OM from vehicles is needed to be able to build a good process and tools that can be used for early development in simulation software and hardware in the loop.

The first identified publications in the research area date back to the 1970s, namely the work of Walter Bergman at Ford Motor Co. and the work of Friedrich O. Jaksch at Volvo Car Corporation. Both authors focused on control qualities of the vehicle: On the one hand, Bergman (1973) indicated that the most important vehicle-handling quality is the ease of control (and not the level of vehicle performance). This study was based on the physical and mental effort required by the driver to control the vehicle. On the other hand, Jaksch's (1979) study was based on theoretical and experimental tests related to the steering control quality and the performance of the system driver-vehicle regarding their ability to follow a predefined course. Later, at the transition from the 20th to the 21st century, the interest in the subject increased with the development of objective tests standards (such as ISO 4138:1996, ISO 15037-1:1998, ISO 3888-1:1999) and with the move into objectivising vehicle dynamics evaluations. Moreover, better computer capabilities enabled deeper studies to understand the relation between OM and SA. David C. Chen and David A. Crolla aimed to establish a bridge between OM and SA using linear regression. Their goal was to identify what characteristics to pursue in the design phase, and to utilise computer modelling to achieve these characteristics as early and as efficiently as possible in the process (Chen, 1997; Crolla et al., 1997 and 1998; Chen and Crolla, 1996 and 1998). Afterwards, Howard A. S. Ash and Crolla took a step forward by including in the study non-linear relations, by means of artificial neural networks. This allowed obtaining an insight into the preferred ranges of vehicle handling OM (Ash, 2002; King et al. 2002)

The research on the steering feel continued with the contributions of Peter E. Pfeffer, Manfred Harrer and Nigel Johnston. They defined evaluation routines for objective testing methods with the help of steering robots (Pfeffer *et al.* 2008b), and developed a model of the steering system to evaluate steering feel on-centre. Using the simulation results of this model, subjective feel was predicted using identified links between OM and SA (Harrer *et al.* 2006). Although only linear regression methods were applied, identifying preferred ranges was made possible by including a sign in the SA (indicating the desired direction of change of the OM by the driver) followed by a non-linear transformation of the SA. Pfeffer *et al.* (2008a) pre- sented some examples about how these results can be used together with CAE simulations to predict expected SA. Simultaneously, Guo Konghui performed some studies related to OM and SA evaluations for vehicle handling and steering feel. In this case most of the tests were not performed in real vehicles but in a MBDS (Guo, K. H. *et al.* 2002; Zong, D. *et al.* 2007; Zheng, H. *et al.* 2013). Furthermore, in collaboration with Crolla, they also investigated which OM should be used in the search of OM-SA correlations in the field. (Yan B., *et al.* 2010). Also, simultaneously, Marcus Agebro performed another MBDS-based study on driver preferences of steering characteristics and on their influence on drivers' performance (Agebro, M. 2007). Abebro's work was continued by Malte Rothhämel, who investigated the OM-SA correlations for steering feel and handling of heavy trucks using both physical vehicles and MBDS (Rothhämel et al., 2008 and 2010). In these studies, he characterised steering feel and implemented the acquired knowledge into active steering systems (Rothhämel 2010 and 2013). Rothhämel also generated a word pool, to identify the main dimensions for describing steering and handling for heavy trucks (Rothhämel et al., 2011).

Mikael Nybacka continued this work for passenger vehicles, analysing drivers' ratings tendencies and OM-SA correlations using both linear and non-linear methods, which allowed to identify the drivers' preferred range for some OM (He, X. and Su, Z., 2012; Nybacka et al., 2014a-b). He also presented how these ranges could be used in CAE simulations to parameterise and optimise an electric power assist steering system (Ljungberg, M. 2014).

In parallel, Saskia Monsma studied the correlations of simultaneously measured OM and SA for tyre evaluation using linear and non-linear methods (general regression neural network), and analysing the physical and mental effort required by the driver (Monsma, S. 2015).

Regarding commercial products in the context of driveability, objective evaluation, calibration, and real-time adaptation of the character of the vehicle to the driving style was presented by Schöggl (List and Schoeggl, 1998; Schoeggl and Ramschak, 2000; Schoeggl et al., 2001).

Summarizing, expert test drivers are a key to bring in early reports of subjective data (feelings, perceptions, interpretations and so forth), while there are limitations to link the test drivers' feelings to the measured vehicle performance. If SA and OM can be correlated during tests it is possible to:

- **frontload**, using the subjective/objective correlation in early development phase, e.g. simulation and Hardware-In-the-Loop, thus reducing hardware related tests,
- **provide added value for end customers** with vehicle behaviour targeted to customer groups,
- **achieve standardized test and development process** since the rating of the behaviour will follow a predefined method,
- **use knowledge of correlation** between subjective and objective data when developing new active systems for the vehicle, e.g. active steering, torque vectoring, drive-by-wire that are set up for a specific subjective profile,
- **reduce end customer's complaints** or dissatisfaction by tighter connection of tests and development,
- **benchmark the competitors' vehicles** making sure that your own vehicles behave better or in a predefined way,
- **communicate targets** in early development within the company and to suppliers and thus reduce costly redesigns.

4 Purpose, research questions and method

The vehicle industry needs to strengthen the knowledge concerning driver/vehicle interaction and the connection between SA and OM. The proposed research on subjective and objective correlations will enable an efficient development process concerning vehicle dynamics, active safety systems and how the driver interact with the vehicle. VCC develop safe cars with good winter properties where vehicle dynamics is important for safe and secure behaviour in both regular driving and critical situations. Today the vehicles are component wise very similar, i.e. sharing components from same supplier. This means that it is the integration of these components that gives the vehicles individual character and status among buyers, thus the subjective evaluation is very important in the development of new vehicles. Also, there is a strong need to improve the development efficiency by testing fewer variants in hardware in less time. Both the Voice of the Customer and much of the hardware development and testing is based on SA and since simulation requires OM it is important to find correlations between SA and OM to make use of that knowledge in the front end of development but also during testing.
Regarding the vehicle development process, the vehicle manufacturers usually incorporate as much technology content as possible already from the start of production of a new car model. This demands higher efficiency than before to implement the fundamental content in the vehicle and give engineers more time to understand and integrate the new technology. Having access to the test engineers' subjective knowledge in the early development during simulation will save considerable time when integrating these new technologies and optimizing for a perfect vehicle character. This effective development process will ensure a competitive advantage.

4.1 Research question

The following research question was studied during the project:

- *How can the increased knowledge about the correlation between subjective assessment and objective measures enable an efficient vehicle dynamics evaluation, and how can this knowledge be used in new intelligent concepts?*

5 Aim

The project aims to find methods that will enable an efficient process for objective vehicle dynamics evaluation for both early development and during vehicle validation. Based on the detailed knowledge of the correlation between Objective Measures (OM) (from vehicle data) and Subjective Assessments (SA) (from driver rating) the aim was also to develop new intelligent vehicle systems built around the driver. The underlying assumption is that these methods will increase the ability to move from physical testing to virtual simulation methods. This in turn is essential to improve the efficiency and quality in the vehicle dynamics development of new vehicles.

The project has focused on the following:

- Further develop vehicle test methods for objective vehicle dynamic evaluations (concerning handling, dynamic active safety and steering).
- Develop methods to correlate SA to OM regarding vehicle handling.
- Establish and validate the objective and subjective correlation by physical testing during summer and winter and with driving simulator.
- Gain increased knowledge of the connection between driver and vehicle regarding vehicle dynamics.
- Gain increased knowledge of drivers' ability to assess vehicle properties and behaviour in a driving simulator.
- Strive to reduce the number of load cases and variants that is measured and tested with hardware using correlated subjective and objective data in early development (CAE).
- Develop new intelligent vehicle systems capitalizing on the increased knowledge of driver vehicle interaction and methods for subjective objective correlations.
- Acquire a database for subjective objective correlations to be used during project and after for further research and development.

6 Results and deliverables

The main result from this project is the development of a method capable of predicting SA from combinations of key OM. Firstly, this method generates a classification map of vehicles solely based on their OM, which allows for a qualitative prediction of the steering feel of a new vehicle based on its position, and that of its neighbors, in the map. This prediction is enhanced with descriptive word-clouds, which summarizes in a few words the comments of expert test drivers to each vehicle in the map. Then, a second superimposed ANN displays the evolution of SA-ratings in the map, and therefore, allows one to forecast the SA-rating for the new vehicle (Figure 1). Moreover, this method has been used to analyse the effect of the tolerances of OM requirements, as well as to verify the previously identified preferred range of OM.

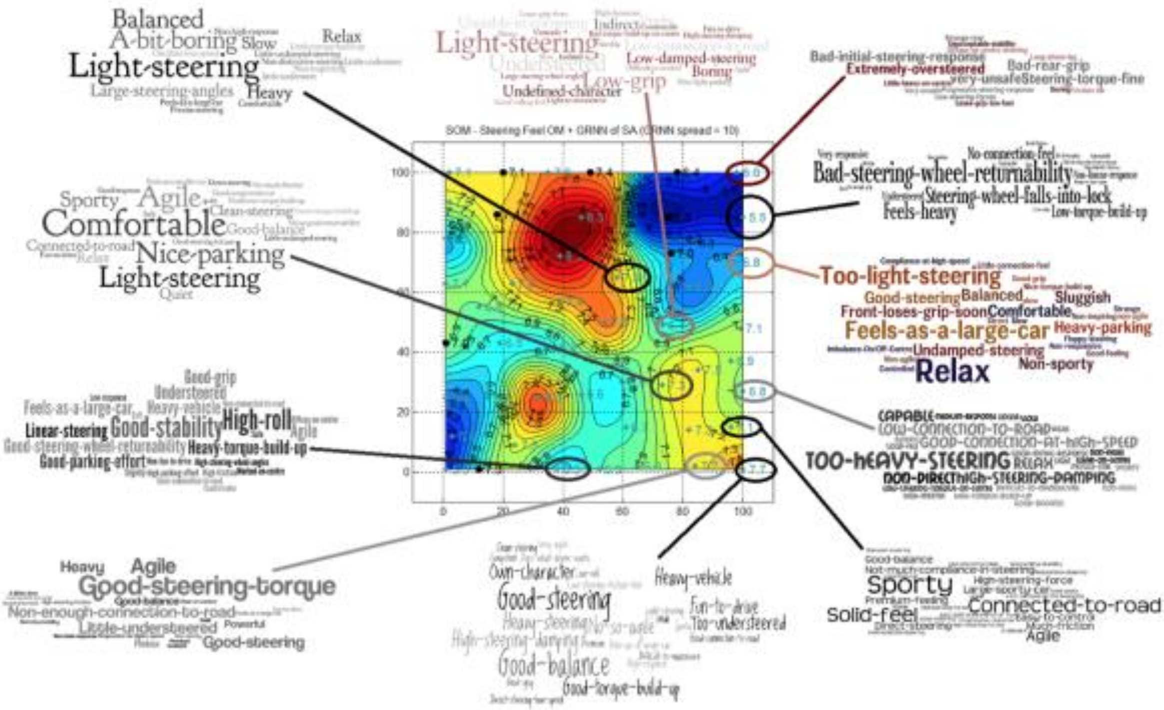


Figure 1. A SOM + GRNN map complemented with word-cloud descriptions of each vehicle

This project focused on OM-SA correlations in summer conditions, but also aimed to increase the effectiveness of vehicle dynamics development in general. For winter conditions, where objective testing is not yet mature, this research initiates the definition and identification of robust objective manoeuvres and OM. Experimental data were used together with CAE optimisations and ANOVA-analysis to optimise the manoeuvres, which were verified in a second experiment. To improve the quality and efficiency of SA, Volvo's Moving Base Driving Simulator (MBDS) was validated for vehicle dynamics SA-ratings (Figure 2).

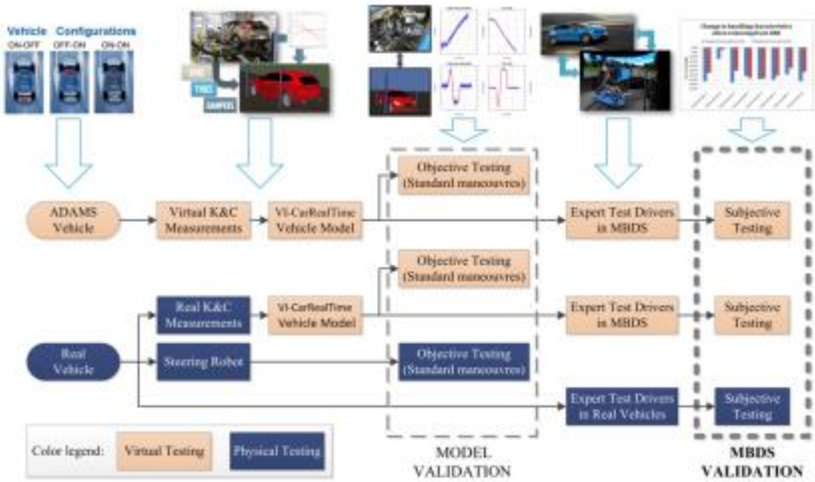


Figure 2. Workflow of the methodology proposed and implemented to validate the MBDS.

Furthermore, a tablet-app to aid vehicle dynamics SA was developed and validated.

Combined this research encompasses a comprehensive method for a more effective and objective development process for vehicle dynamics. This has been done by increasing the understanding of OM, SA and their relations, which enables more effective SA (key SA, MBDS, SA-app), facilitates objective requirements and therefore CAE development, identifies key OM and their preferred ranges (see Table 1), and which allow to predict SA solely based on OM.

Table 1. Identified preferred OM. DS1: C-, D- & E-class. DS2, DS3 and King. et al. (2002): only D-class. Values in (): correlation without high confidence level. Values in []: middle values for level-5 (Lv.5) SA.

No	Objective measure	All DS	DS2	DS1	King et al. (2002)
1	Window [°]	< 3.5 Lv.5 [4]	<3.7		
2	Response Gain Straight Path [°/s/100°SWA]	> 25	29.5-33.5	25-30	20-25
3	Lateral Acc. Resp. Gain [g/100°SWA] low speed	> 1.1	>1.125		>1.25
4	Lateral Acc. Resp. Gain [g/100°SWA] high speed	> 1.7	>1.8		
5	Gain Linearity [-]	(<1.4)			
7	Roll Control Straight Path [°/s/g]	< 31.25	<30.5		
8	Torque Deadband [°]	1.2-2.0 Lv.5 [2]	<1.6	<2.2	
9	Torque Build-up [Nm/100°SWA]	30-40 [31.5]	30-38		
10	Friction Feel [Nm]	1.2–1.7 Lv.5 [2.2]			
11	Yaw Response Gain [°/s/100°SWA]	> 28	30.5-34	28-32	12-20
12	Response Gain Understeer [°/g]	< 2.75 (1.5-2.0)	1.6-2.1		>0
13	Yaw Gain Linearity [%]	< 100 (85-100)			
14	Rel. Yaw Gain @ Max. Lat. Acc. [°/s/100°SWA]	(> 55)			
15	Yaw - SWA Phase Time Lag @ 4m/s^2	(70-90)	62-75		
16	Ay-SWA Phase Time Lag @ 4m/s^2	> 80 (80-150)			
17	Ay – Yaw Phase Time Lag @ 4m/s^2	< 30			

18	Roll Control Cornering [°/g]	(< 4.6)	<4.2		
19	Torque Build-up into Corner [Nm/100°SWA]	> 18 Lv.5 [16]	>16.5		
20	Torque Build-up Cornering [Nm/g]	> 2.5 Lv.5 [2.1]	>2.7	4-6	
21	On-centre Hysteresis [°]	---	11.5-14.5		
22	Off-centre Hysteresis [Nm]	1.5-2.6	2.1-2.6	1.5-2.2	
23	Effort Level [Nm]	3.7-4.3	4.2-4.8	3.6-4.5	
24	Low Speed Response Gain [°/s/100°SWA]	(> 28)	>25.5		20-25
25	Low speed torque build-up [Nm/100°SWA]	14-20			
26	Parking Effort Standstill [Nm]	< 3.7	<4	<3.3	
27	Parking Effort Rolling [Nm]	< 2.8 (1-2.8)	<3.2	>1.5	

7 Dissemination and publications

7.1 Knowledge and results dissemination

How have or is the project results planned to be used and distributed?	Mark with X	Comments
Increase knowledge within area	X	Project have generated 13 scientific publications and been presented in several internal and external events.
Carry on to other advanced technical development projects		
Carry on to product development project	X	Methods and tools will be implemented in product development process.
Introduced to the market		
Used in investigations/policy/political decisions		

7.2 Publications

Gil Gómez, G.L. (2017): Towards efficient vehicle dynamics development: From subjective assessments to objective metrics, from physical to virtual testing. PhD Thesis, KTH Royal Institute of Technology, TRITA-AVE 2017:12.

Gil Gómez, G.L., Lönnergård, A., Asher, M. H., Nybacka, M., Bakker, E. & Drugge, L. (2017): Analysis and optimisation of the objective vehicle dynamics testing in winter conditions. *Published in Vehicle System Dynamics: Int. J. of Vehicle Mechanics and Mobility*, January 2017. D.O.I. 10.1080/00423114.2016.1278248.

Gil Gómez, G.L., Nybacka, M., Drugge, L. & Bakker, E. (2016): Machine learning to classify and predict objective and subjective assessments of vehicle dynamics: the case of steering feel. *Submitted for international journal publication,* December 2016.

Gil Gómez, G.L., Nybacka, M., Bakker, E. & Drugge, L. (2016): Correlations of subjective assessments and objective metrics for vehicle handling and steering: A walk through history, *International Journal of Vehicle Design*, Vol. 72, No. 1, pp. 17-67.

Gil Gómez, G.L., Nybacka, M., Bakker, E. & Drugge, L. (2016): Objective metrics for vehicle handling and steering and their correlations with subjective assessments, *International Journal of Automotive Technology,* Vol. 17, No. 5, pp. 777-794.

Gil Gómez, G.L., Andersson Eurenius, C., Donnay Cortiñas, J., Bakker, E., Nybacka, M., Drugge, L. & Jacobson, B. (2016): Validation of a moving base driving simulator for subjective assessments of steering feel and handling. *Proceedings of the 13th International Symposium on Advanced Vehicle Control, AVEC'16,* Munich, Germany, 13-16 September 2016.

Gil Gómez, G.L., Vestlund, J., Bakker, E., Berger, C., Nybacka, M. & Drugge, L. (2016): Improving subjective assessments of vehicle dynamics evaluations by means of computer-tablets as digital aid. *SAE Technical Paper 2016-01-1629.*

Gil Gómez, G.L. (2015): Towards Efficient Vehicle Dynamics Evaluation using Correlations of Objective Metrics and Subjective Assessments. Licentiate Thesis, KTH Royal Institute of Technology, TRITA-AVE 2015:28.

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*. Vol. 53, Iss. 10, pp. 1416-1438.

Gil Gómez, G.L., Bakker, E., Nybacka, M. & Drugge, L. (2015): Analysing vehicle dynamics objective and subjective testing in winter conditions, *Proceedings of the 24th Symposium of the International Association for Vehicle System Dynamics (IAVSD 2015),* Graz, Austria, 17- 21 August 2015. pp. 759-768.

Ljungberg, M., Nybacka, M., Gil Gómez, G., and Katzourakis, D. (2015): *Electric power assist steering system parameterization and optimisation employing computer-aided engineering*, SAE World Congress, April 21-23, Detroit, USA.

Nybacka, M., He, X., Gil Gómez, G., Bakker, B. and Drugge, L. (2014): *Links between subjective assessments and objective metrics for steering*, International Journal of Automotive Technology, ISSN: 1229-9138, vol. 15, no. 6, pp. 893-907.

Nybacka, M., He, X., Gil Gómez, G., Bakker, B. and Drugge, L. (2014): *Links between subjective assessments and objective metrics for steering, and evaluation of driver ratings*, *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*. Vol. 52, Iss. sup. 1, pp. 31-50.

8 Conclusions

To allow for correct objective requirements, this research has defined the range of preferred OM for a good steering feel. This has been achieved by identifying the OM-values that are associated to high SA ratings in the field. Objective requirements leads to a more efficient development, for example by enabling CAE optimisations. *Right* objective requirements leads to effective development, in this case a vehicle offering the desired driving experience.

However, objective requirements are reliant on OM, which were not available for winter conditions, despite vehicle handling evaluation on icy roads being fundamental in the development process. Consequently, an initiative has been taken in this research to define and identify robust winter objective manoeuvres and OM. Main conclusions are that to allow for comparable results, the test vehicle needs to be measured simultaneously with a reference vehicle and that not to saturate the vehicle response, the manoeuvres inputs needs to be adapted by lowering power of the inputs, that means not only lower input levels but also larger time constants.

On the other hand, it cannot be forgotten that the current development process is still strongly based on SA. Therefore, it is important to increase both its efficiency and its effectivity. For the former, this thesis has developed a tablet-based SA application, which mainly reduces transcription time, avoids forgotten ratings, increases rating resolution and opens a whole new range of possibilities to enhance SA. Moreover, this thesis has also analysed how MBDS can be used for vehicle dynamics SA, by further developing validation methods of MBDS for vehicle dynamics SA-ratings and by applying this method to the new MBDS at Volvo Car Group. Comparing SA in the MBDS versus SA in a real vehicle, the results indicated a good correlation for steering feel and a very high correlation for handling. Regarding effectivity, this thesis has examined drivers' SA repeatability, the effect of drivers' rating tendency on SA and on how normalization can be applied to mitigate this issue.

Furthermore, the introduction of a first impression test demonstrates that a short predefined test can be used to reduce testing time, with almost the same results as that of the long standard subjective testing method. However, no clear improvement in drivers' rating spread can be associated with driving predefined manoeuvres, in comparison to free driving.

Additionally, because numerical inputs are required for correlation methods, most of previous studies have focused only on the analysis of SA-ratings. However, the author considers that test drivers feel more confident with giving a subjective description of the tested vehicle than a numerical rating to it (probably, the former is also more robust than the latter). Therefore, in this thesis, some research has been dedicated to SA-interviews and to verbal analysis of their transcriptions. This analysis has been used to generate SA vehicle descriptions and to identify a word-cloud with the most important factors in vehicle steering and handling in passenger cars. The results did agree with those using SA autocorrelations.

Finally, the main result of this project is a new method that is capable of predicting SA from combinations of OM by producing a self-organised map or classification of vehicles in two dimensions (2D), which can be visualised. This method groups together vehicles with nearby OM and one interesting result is that vehicles from the same manufacturer and/or from the same vehicle class appear together in the map. This objectively demonstrates that there is a brand and a vehicle class identity (at least for steering feel). Furthermore, this map allows to calculate the position of a new vehicle in the map and consequently, the neighbours of this new vehicle generates a prediction about which SA should be expected for the new vehicle. This prediction is complemented with the aforementioned SA word-cloud descriptions, offering a direct explanation about how the vehicles were subjectively perceived by the test drivers. Consequently, although the map only presents objective information, the relationship of a vehicle with its neighbours implicitly carries subjective information: *If you like the attributes of the neighbours of the new vehicle, you should probably like the new vehicle, or vice versa.*

Besides, the map can be combined with a surface regression of the SA associated to each vehicle. The strength of this combined method is that it makes it possible to understand in the 2D map how the SA rating evolves. This is a great feature, especially if considering that 17 OM (dimensions) were used as inputs to the method (27 OM before the multicollinearity reduction). Altogether, this method allows to: set right objective requirements, analyse their tolerances and to predict SA from OM (from objective requirements, CAE simulations or objective tests).

Moreover, previous methods focused on simple single-input-single-output OM-SA correlations that allowed visualising the OM-SA relation, but did not allow to consider the combination effect of different OM or on more complex models with multiple inputs that required large datasets and did not allow the visualisation of the OM-SA correlations, which made it difficult to understand the SA-ratings predictions or the effect of varying OM. The classification map presented in this research joins the best of both methods: considering the combination effect of different OM and allowing one to visualise the evolution of the SA; moreover, this can be done with relatively small samples.

In addition, previous methods were strictly based on the relation between OM-SA. Considering that SA surely change constantly, for example with time, these methods need to be continuously trained and are cursed to small datasets. Oppositely, the map here is solely based on OM, which should be time-independent; therefore, larger datasets can be built through time.

9 Participating partners and contact persons

Volvo Cars:
Egbert Bakker, Acting manager Vehicle Dynamics Integration and Technical Leader Vehicle Dynamics at Volvo Cars, have been the project leader of this work as well as the industrial supervisor of Gaspar Luis Gil Gómez.
+46-31-595962, egbert.bakker@volvocars.com

Gaspar Luis Gil Gómez have been the industrial PhD student in this project and have been the main contributor to the project results.
+46-31-3250365, gaspar.gil.gomez@volvocars.com

KTH Royal Institute of Technology:
Mikael Nybacka, Associate Professor in Vehicle Dynamics, have been the main academic supervisor of Gaspar Luis Gil Gómez.
+46-8-7907638, mnybacka@kth.se

Lars Drugge, Associate Professor in Vehicle Dynamics, have been academic supervisor of Gaspar Luis Gil Gómez.
+46-8-7907604, lards@kth.se

10 References

Agebro, M. (2007). *Driver preferences of steering characteristics*. Licentiate thesis. KTH Royal Institute of Technology, Stockholm, Sweden.

Ash, H. A. S. (2002). *Correlation of subjective and objective handling of vehicle behaviour*. PhD Thesis. University of Leeds, Leeds, UK.

Bergman, W. (1973). Measurement and subjective evaluation of vehicle handling. In: *Auto- mobile Engineering Meeting*. Detroit, Michigan, 14-18 May, 1973. Society of Automotive Engineers. Warrendale, Pa. doi:10.4271/730492.

Chen, D. (1997). *Subjective and objective vehicle handling behaviour*. PhD Thesis. Universi- ty of Leeds, Leeds, UK.

Chen, D. C. and Crolla, D. A. (1996), A comprehensive study of subjective and objective vehicle handling behaviour, In: *14th IAVSD Proceedings, Suppl. to Vehicle System Dynam- ics*, vol. 25, Swets Publishing Service, Holland.

Chen, D. C. and Crolla, D. A. (1998). Subjective and objective measures of vehicle handling: drivers & experiments. *Vehicle System Dynamics,* vol. 29, 576-597.

Chen, D. C., Whitehead, J. P., Crolla, D. A. and Alstead, C. (1997). Collecting subjective vehicle handling data. *IMechE Seminar Publication*, vol. 1, 199-208.

Crolla, D., Chen, D., Whitehead, J. and Alstead, C. (1998). Vehicle handling assessment us- ing a combined subjective-objective approach. In: *International Congress and Exposition*. Detroit, Michigan, 23-26 February, 1998. Society of Automotive Engineers. Warrendale, Pa. doi:10.4271/980226.

Guo, K. H., Zong, C. F., Kong, F. S. and Chen, M. L. (2002). Objective evaluation correlated with human judgment: an approach to the optimisation of vehicle handling control system. *Int. J. Vehicle Design*, vol. 29, no. 1-2, 96-111.

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

He, X. and Su, Z. (2012). *Links between subjective assessments and objective metrics for steering*. Master Thesis in Vehicle Engineering. KTH Royal Institute of Technology, Stockholm, Sweden.

Jaksch, F. O. (1979). Driver-vehicle interaction with respect to steering controllability. In: *Passenger Car Meeting*. Hyatt Regency, Dearborn, 11-15 June, 1979. Society of Automo- tive Engineers. Warrendale, Pa. doi:10.4271/790740.

King, R., Crolla, D., Ash, H. and Whitehead, J. (2002). Identification of subjective-objective vehicle handling links using neural networks for the foresight vehicle. In: *SAE World Con- gress*. Detroit, Michigan, 4-7 May, 2002. Society of Automotive Engineers. Warrendale, Pa. doi:10.4271/2002-01-1126.

List, H. and Schoeggl, P. (1998). Objective evaluation of vehicle driveability. Society of Au- tomotive Engineers. Warrendale, Pa. doi:10.4271/980204.

Ljungberg, M., Nybacka, M., Gómez, G. G., and Katzourakis, D. (2015). Electric power as- sist steering system parameterization and optimisation employing computer-aided engineer- ing. *SAE World Congress*, April 21-23, Detroit, USA.

Monsma, S. and Defilippi, E. (2011). Artificial neural networks for the assessment of driver judgement. 22nd Symp. Int. Association for Vehicle System Dynamics. Taylor & Francis. London, UK.

Nybacka, M., He, X., Su, Z., Drugge, L. and Bakker, E. (2014a). Links between subjective assessments and objective metrics for steering, and evaluation of driver ratings. *Vehicle System Dynamics*, vol. 52, suppl. 1, 31-50.

Nybacka, M., He, X., Gómez, G. G., Bakker, E. and Drugge, L. (2014b). Links between sub- jective assessments and objective metrics for steering. *Int. J. Automotive Technology*. vol. 15, no. 6, 893-907.

Pfeffer, P. E., Harrer, M. and Johnston, D. N. (2008a) *Interaction of vehicle and steering sys- tem regarding on-centre handling*. Vehicle System Dynamics, 46 (5), pp. 413-428.

Rothhämel, M. (2010) *Capturing steering feel - A step towards implementation of active steering in heavy vehicles*, Licentiate thesis, KTH Royal Institute of Technology, Stock- holm, Sweden.

Rothhämel, M. (2013) *Characterisation and utilisation of steering feel in heavy trucks*, Doc- toral thesis, KTH Royal Institute of Technology, Stockholm, Sweden.

Rothhämel, M., Drugge, L. and IJkema, J. (2010). On a method to generate a word pool for the description of steering feel. In: *10th International Symposium on Advanced Vehicle Control (AVEC 10)*. Loughborough, UK, 22-26 August 2010.

Rothhämel, M., IJkema, J. and Drugge, L. (2008). On the correlation between steering feel and handling in heavy trucks. In: *FISITA World Automotive Conference 2008.* Munich, Germany, 14-19 September 2008.

Rothhämel, M., IJkema, J. and Drugge, L. (2011). A method to find correlations between steering feel and vehicle handling properties using a moving base driving simulator. *Vehi- cle System Dynamics*, vol. 49, no. 12, 1837-1854.

Schoeggl, P. and Ramschak, E. (2000). Vehicle driveability assessment using neural net- works for development, calibration and quality tests. Society of Automotive Engineers. Warrendale, Pa. doi:10.4271/2000-01-0702.

Schoeggl, P., Ramschak, E. and Bogner, E. (2001). On-board optimization of driveability character depending on driver style by using a new closed loop approach. In: *SAE World Congress*. Detroit, Michigan, 5-8 March, 2001. Society of Automotive Engineers. Warren- dale, Pa. doi:10.4271/2001-01-0556.

Yan, B., Guan, H. and Crolla, D (2010). Vehicle handling dynamics – an evaluation of objec- tive metrics. In: *AVEC 2010*.

Zheng, H., Zong, C., and Yu, L. (2013) Road feel feedback design for vehicle steer-by-wire via electric power steering. Society of Automotive Engineers. Warrendale, Pa. doi: 10.4271/2013-01-1898.

Zong, C., Na, H. , Hu, D., Wang, d. et al.. (2007). Study on steering effort preference of driv- ers based in driving simulator. Society of Automotive Engineers. Warrendale, Pa. doi: 10.4271/2007-01-3575.