Honda Research Institute EU
Honda Research Institute Europe GmbH
https://www.honda-ri.de/

New approach for improvement of vehicle performance by using a simulation-based optimization and evaluation method

Timo Friedrich, Martin Heiderich, Minh-Tri Nguyen

2016

Preprint:

This is a post-peer-review, pre-copyedit version of an article published in 7th International Munich Chassis Symposium 2016: chassis.tech plus (Proceedings). The final authenticated version is available online at: https://doi.org/10.1007/978-3-658-14219-3_21

New approach for improvement of vehicle performance by using a simulation-based optimization and evaluation method

Neuer Ansatz zur Verbesserung des Fahrverhaltens durch Verwendung einer simulations-basierten Optimierungs- und Beurteilungsmethode.

Vortragender:

Martin Heiderich, M.Sc.
Honda R&D Europe (Deutschland) GmbH
Mail: martin_heiderich@de.hrdeu.com

Co-Autoren:

Timo Friedrich M.Sc., Honda Research Institute Europe GmbH

Dipl.-Ing. Minh-Tri Nguyen, IVK – Institut für Verbrennungsmotoren und Kraftfahrwesen, Universität Stuttgart

1 Introduction

The early consideration of the overall vehicle performance as well as early subjective evaluation of predefined vehicle targets is very important. Due to the increasing vehicle complexity and growing customer demands, it is challenging to identify potentials for improvement and keep the predefined development time. Complex problems can be investigated and optimized in the early development process using simulation-based working environments. A particular advantage is the use of multi-objective optimisation algorithms which automatically calculate desired vehicle behaviour characteristics depending on defined objective criteria for individual driving situations. Additionally first subjective evaluations without real vehicles are possible utilizing virtual vehicle prototypes which are evaluated with Driver-in-the-Loop environments in driving simulators and on HiL test benches. The effective implementation is shown in figure 1.

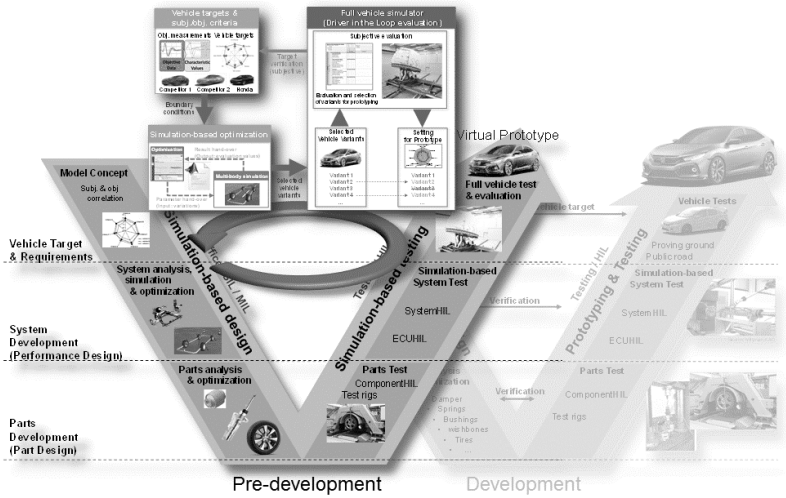


Figure 1: Optimization and Evaluation process within the development process

An important application of these virtual development processes is the investigation of vehicle stability at high speed which is one of the important factors for a European customer. High speed stability is usually tested in the later development steps by using real prototype vehicle. Especially at higher vehicle velocities up to v_{max}, the driver expects a stable, predictable and controllable vehicle. The vehicle behaviour is mainly influenced by the interaction of suspension components, the steering subsystem and

tire characteristics. This leads to a high number of adjustment factors and results in many possible variations depending on the vehicle targets. The trade-off between vehicle dynamics, ride comfort and road holding capability makes the definition of the perfect chassis setting challenging. Especially high speed driving in interaction with real road disturbances is important to meet the European customer requirements and should be considered in the early development process. Usually these type of tests are done in a later stage with road-registered prototype vehicles.

Within this paper a simulation-based method for optimization and evaluation is described. At first we will take care for the objectification. The subjective and objective targets are described, optimization requirements are set and necessary test scenarios are prepared. In a second step multi-objective optimization algorithms will be used in combination with defined objective criteria. Finally the optimization results are evaluated in a Driver-in-the-Loop environment and verified with actual vehicle tests.

2 Objectification of real world driving situations

Not only limit handling maneuver are important to describe the stability of a vehicle, also customer-oriented situations which happen every day are essential. Suitable situations for the investigations of high speed stability are cornering scenarios with up to 0.4g lateral acceleration on highways and customer-oriented lane changes. In these situations the perception of the driver is influenced by a combination of yawing, rolling and vertical body motion.

Reasonable objectifications of related driving scenarios for the evaluation of the high speed stability are an important base for an effective full vehicle optimization. Especially the correlation of objective measureable values and the subjective evaluation criteria annotated by expert drivers are essential to define objective criteria and corresponding target values for the optimization. From previous investigations the following customer requirements are determined to describe good high speed stability and derive subjective evaluation criteria:

- Safe, stable handling and controllability in all driving situation up to v_{max}
- High level of driving safety including the stability limits
- Sufficient road and vehicle reaction feedback as well as predictable vehicle behaviour
- Steady, stable and comfortable straight-line driving behaviour (e.g. under crosswind, road surface profile irregularities)
- Comfortable and precise steering which provides good feeling for road condition

For the enhanced subjective evaluation of the high speed stability the Honda internal assessment sheet was extended by additional criteria. These subjective assessment criteria are created and extensively discussed by relevant vehicle dynamics experts for vehicle evaluation to reflect the above mentioned customer requirements. The evaluation criteria include the sensitivity of the vehicle motion on transverse joints, basic road disturbance sensitivities during cornering, body roll behaviour, lane change reactions, cornering and straight line traceability, cross wind sensitivity and others.

At the same time a set of related driving maneuverers are defined, which are used in real world testing and in the simulation-based test environment. Depending on the individual scenarios additional road surface information are implemented to reproduce real world road disturbance. For example there are several customer-oriented high speed situations with velocities over 160 km/h like lane change maneuver, driving on highways with road surface undulations and bridge joints, side wind scenarios and step steer maneuver.

All necessary information about the evaluation of high speed stability are listed and summarized in the Honda Secure Feel guideline. This guideline contains detailed specification of driving scenarios, necessary road surface conditions, subjective assessment criteria and assessment sheets as well as related objective criteria to describe and evaluate the vehicle behaviour. These objective criteria are additionally used as objectives for the subsequently explained optimization method.

In this paper two situations, the transverse joint during straight driving and during cornering, are exemplarily described. These are used for the illustration of the optimization process to improve the high speed stability of a reference vehicle. A description of the situations and their objectification follow below.

Transverse joints during straight driving

Typical situations for evaluation of high speed stability are transverse joints during straight driving at high speed. Such situations can be found while crossing bridges as shown in Figure 2 with a constant speed of 180 km/h.

By driving across these transverse joints the vehicle body receives a vertical excitation delayed in time between the left and right wheel, which leads to enhance body motion in vertical direction, roll motion and also may cause in a small lateral movement of the vehicle. According to the official definitions in [1], the described scenario is a closed loop scenario and the driver tried to compensate the lateral vehicle motion by steering corrections which should be as small as possible.

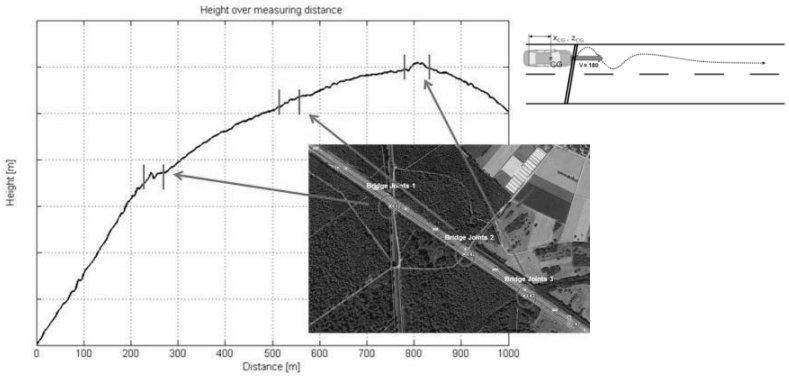


Figure 2: Transverse joints during straight driving maneuver

Extensive test person studies, subjective evaluations and objective vehicle measurements provided several correlation criteria. These criteria are calculated from the mean values of the measured vehicle reactions and driver steering inputs. Every driver has to perform at least three measurement turns per maneuver to get reliable measurement data. The measurement data are compared and analysed such as shown in figure 3.

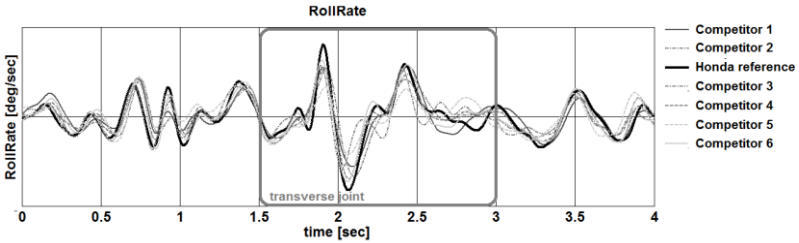


Figure 3: Roll behaviour comparison at a transverse joint

In this chart the better rated vehicle showed less roll motion after crossing the transverse joint. Almost all test persons associate lower roll motions with better high speed stability. The reason behind is a reduced sensitivity towards road surface excitations and consequently smoother body motions. Additional assessment criteria based on the perception of the drivers are heave and pitch motions. The body heave motion should be well balanced between front and rear axle with less pitch motion. Small pitch angle are evaluated positive.

Based on the measurement data characteristic values such as maximum, minimum, gradients, root mean square, variances and peak to peak values are calculated automatically. For correlation of subjective and objective criteria the Pearson correlation coefficient is used. It is a standard correlation method to determine linear correlations. The correlation coefficients are calculated by covariance of input (subjective evaluations of the test persons) and output (calculated characteristic values) divided by standard deviation of the input and output (Eq. 1) [2].

$$\rho = \frac{Cov(x,y)}{\sigma(x)\sigma(y)}$$
$$Cov(x,y) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \qquad \text{Eq. 1}$$
$$\sigma(x) = \sqrt{Var(x)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

For the above mentioned maneuver “transverse joints during straight driving” the following calculated objective criteria show a good correlation. As a result some of the calculated amplitudes and rates are used to define target ranges for future optimization described in the next chapter. The defined target ranges are figured in the following correlation plots.

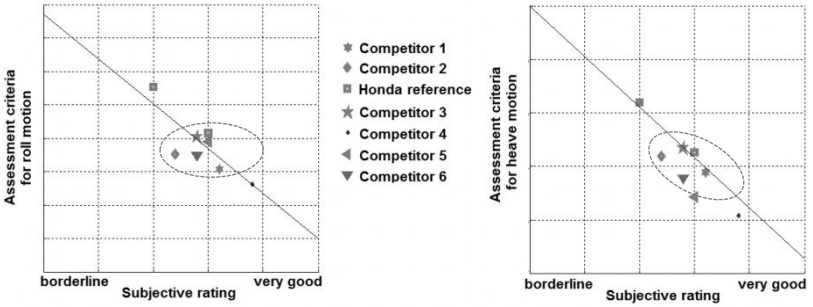


Figure 4: Correlations plots for transverse joints during straight driving

Transverse joints during cornering

The second situation is defined as crossing bridge joints during cornering at 180km/h with lateral accelerations up to 0.4g and is shown in figure 6. Right after passing a transverse joint during cornering the vehicle body receives additional vertical excita-

tions. The driver can feel a combination of lateral acceleration, yawing, rolling and vertical body accelerations.

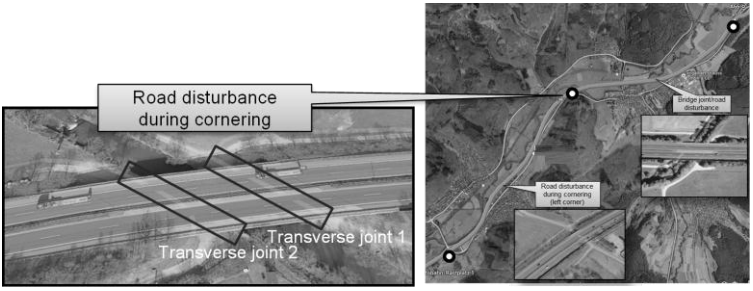


Figure 5: Transverse joints during cornering

The main influencing subjective impressions for the assessment of this cornering situation are body roll behaviour, vertical motions and steering corrections. A vehicle with high sensitivity against road excitation requires the driver to apply additional steering corrections. After analysis of the objective measurements and subjective evaluations rolling, yawing and heave motion show the strongest correlation. The better evaluated vehicles show higher yaw rate amplitudes and roll motion root mean square values. The roll motion criteria in this situation are contrary to the roll motion criteria in the situation described before (transverse joint during straight driving). During cornering an increased roll motion is preferred by the test persons. The roll motion differences and the yaw rate examples are shown in figure 6.

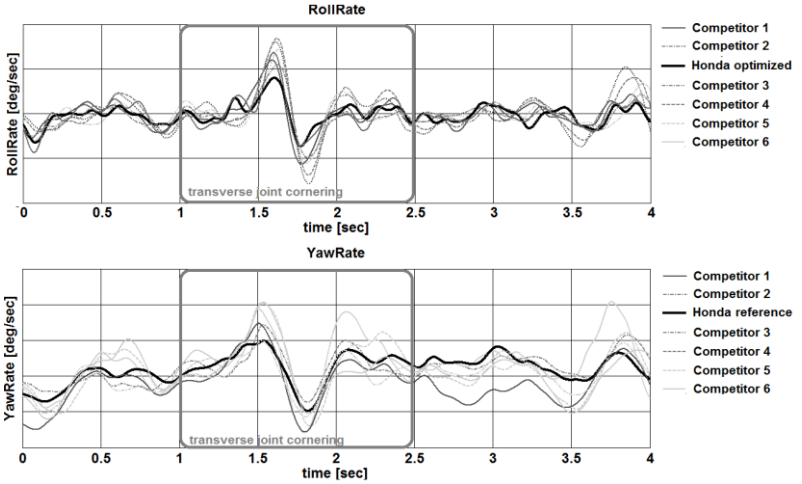


Figure 6: Roll rate and yaw rate plots at a transverse joint during cornering

The following correlation plots visualize two of the best matching results for the calculated Pearson coefficients according to Eq. 1 and are based on the measurements shown in figure 6.

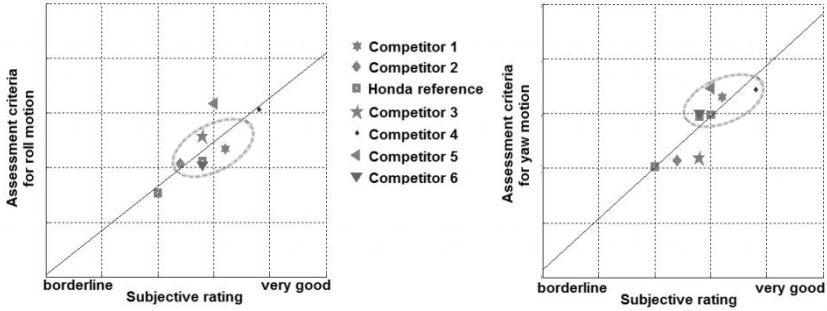


Figure 7: Correlations for transverse joints during cornering

Virtual Road surfaces

With respect to a high comparability to real road situations, related road surfaces of the above mentioned highway maneuvers are measured, digitalized and used for the offline and online simulations. Figure 8 displays the measured .crg (curved regular grid) road surface information. The transverse joints are visualized darker.

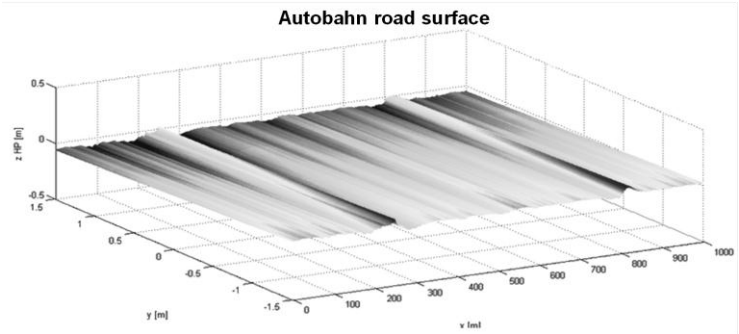


Figure 8: Autobahn road surface and transverse joints

The road surface is measured with a resolution of 10mm in the longitudinal and lateral plane as well as 1mm in vertical direction. With respect to the measured surface width of 1.80 m the road surface provides different excitations sizes on the left and the right contact patch.

3 Simulation-based optimization

For the previous described high speed stability real world driving scenarios, virtual test maneuvers are created within a multi-body simulation tool and linked with MATLAB. Within this optimization environment desired chassis characteristics can be defined as optimization input parameter. These chassis characteristics are for example stiffness of springs and stabilizers, steering ratio, topmount stiffness as well as nonlinear characteristics curves of damper and bushing. Instead of using a typical trial and error approach, DOE or sensitivity analysis, a multi objective optimization algorithm is applied to calculate the best matching suspension settings to reach the desired target performance. A developed script controls the multi-body simulation, receives and analyses the simulation results and finally visualize the optimization results. During this project two optimization algorithms are tested, the NSGA2 and the SMS EMOA. Both algorithms show similar results for the individual driving situations.

Vehicle model and optimization parameter

The required vehicle model accuracy is very important. Due to the future planned driving scenarios and the bandwidth of influencing frequency ranges on human perception, it is necessary to use a full vehicle model with most possible degree of freedom. Additionally real-time capability is important since the model is used for both, the offline optimization as well as for the further Driver-In-the-loop evaluation. The reference vehicle is built as a real-time multi-body model with an extended vertical damping subsystem. This subsystem includes a detailed description of the shock absorbers in interaction with their topmounts. The parameterization is based on comprehensive damper and topmount subsystem measurements. The used MBS axles provide a dynamic calculation of kinematics and compliance, which specifically reflect a more realistic feeling in the Driver-in-the-Loop assessments. Due to real time restrictions, a validated empirical Pacejka MF-Tyre model dataset [3] is used. The steering system is represented by a simplified Pfeffer model [4] but still includes necessary stiffness and friction effects. Detailed aerodynamic information based on wind tunnel measurements are used as a consequence of the high speed maneuver requirements. Finally the vehicle dynamics of the vehicle model coincides with the original reference vehicle.

As already mentioned before, high speed stability is highly influenced by several chassis components. To show the potential of a simulation-based multi objective optimization method within the described two maneuvers the suspension parameters spring stiffness FA/RA, stabilizer stiffness FA/RA and the steering ratio are used as input variables for the optimization.

Optimization results

In chapter 1 the required objective criteria for the optimization are determined. The optimization algorithm estimates the optimization direction and calculates necessary variations by changing the defined input parameters. In our two example scenarios the objectives in the following table should be achieved by the multi-objective optimization algorithm:

Transverse joints straight driving	Transverse joints cornering
• roll rate reduction and less roll angle • increased heave motion • decreased vertical acceleration amplitudes	• higher roll angle amplitude and roll rate • higher yaw rate gain • increased heave motion

Table 1: objective criteria for multi objective optimization

The optimization of the driving scenarios provide individual solutions visualized for the single events in data tables, Pareto plots, parallel coordinate plots and objective curves. These plots shown in figure 9 in interaction with an implemented cross evaluation are a support for the decision making on the final variant selection.

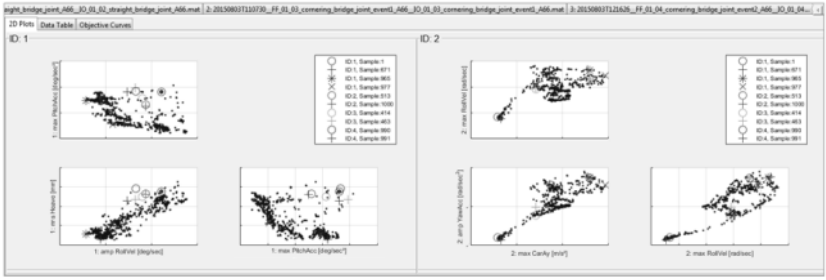


Figure 9: Optimization results software implementation

The analysis of both driving situation provide several vehicle variants with slightly different input parameter variations. These variants show similar results in the offline simulation and are tested in a virtual evaluation process described in the next chapter.

4 Driver-in-the-Loop evaluation

The optimization method provides improved vehicle suspension settings, which are typically evaluated later in the development process by using prototype vehicles. Instead of performing real world tests first subjective evaluation can be done with a virtual prototype in a full vehicle driving simulator to reduce time and cost. By using driving simulators, the vehicle variants and different suspension settings can be assessed in the predefined and already offline applied test scenarios. The used real-time model and the driven virtual maneuver including the measured road surface profiles are the same, which were used within the optimization process. The subjective evaluation of the driving behavior enables an assessment of the achieved status of the target performance. Additionally a benchmark with virtual competitor vehicles is possible. The differences between the benchmark vehicles, the desired target performance and the optimization results can be evaluated. Other great advantages of the virtual evaluation are the eliminated safety risks during high speed testing and the possibility of testing many different test situations in a short time.

The following figure 10 shows the driver in the loop evaluation environment, in which the drivers interacts with the virtual scenarios and evaluate different chassis settings.



Figure 10: Driving simulator vehicle mock-up and scenario visualization [Source: FKFS]

Driving Simulator study

A simulator study was done to evaluate if a full vehicle driving simulator is suitable to evaluate the offline optimized suspension settings compared to the base setting. For this driving simulator study the Stuttgart Driving Simulator is used. It is an 8 DOF vehicle simulator with a full vehicle mockup included in the simulator dome. The driver is located in a regular vehicle interior with full functionalities allowing the most realistic perception of the vehicle and the environment.

The study is done with several test persons who assessed four different vehicle settings. Analogous to the real world vehicle assessments the test persons evaluated according to the Secure Feel evaluation sheet to give an extensive subjective feedback. Moreover the drivers had to rate and nominate the vehicle with highest stability. As indicated in figure 11, finally all test persons were able to clearly identify the optimized vehicle variants, which generate the best feeling for stability at high speed within the underlying vehicle variants. The optimized vehicle variant 3 provided the best stability in the tested driving situations transverse joint during straight driving and cornering. This vehicle setting has a reduced stabilizer stiffness at the front axle by 13%. At the rear axle the spring stiffness is reduced by 7% and the stabilizer is increased by 20%.Within the driving simulator study the optimization results and the corresponding expectations could be confirmed. In additional tests using a lane change scenario and free driving on a two-lane highway the improvement of the controllability and predictability of the driving behaviour was subjectively confirmed.

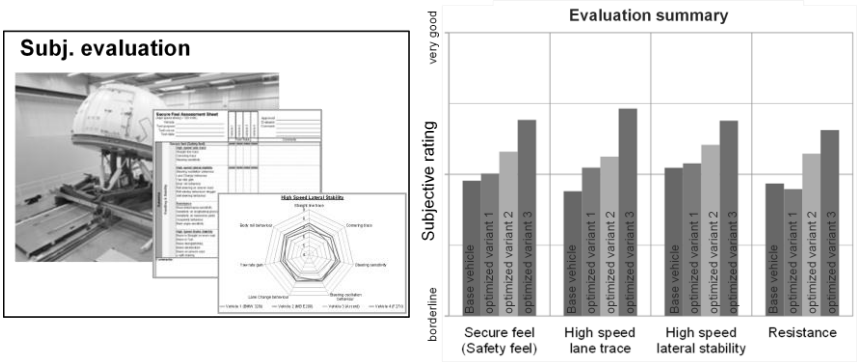


Figure 11: subjective evaluation process and evaluation results

5 Real world verification of the optimization results

The optimization and evaluation method is finally verified in real world tests with a modified prototype vehicle, equipped with the final selected suspension part characteristics. This vehicle was evaluated on the measured real road surfaces, which were used during the optimization and evaluation procedure.

Test results and subjective evaluation – transverse joints straight driving

Figure 12 shows the result of the optimized suspension setting using the example of the measured roll rate data. As already seen in the optimization results and subjective evaluated in the driving simulator environment, the optimized vehicle with modified spring and stabilizer stiffness visualized as the solid black line generates less roll rate.

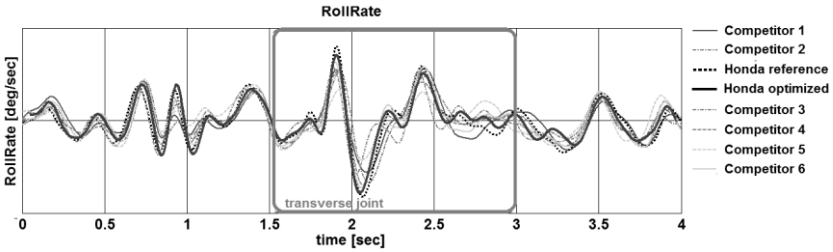


Figure 12: Optimized roll behaviour comparison at a transverse joint

Additionally the roll angle amplitude as well as the roll acceleration are reduced. Due to the higher body stability the vehicle was evaluated by the test drivers as more stable with less sensitivity to road disturbance. By additional optimization of compression and rebound forces of the damper a further improvement would be possible. These effects are already tested in the driving simulator and the verification with a separate prototype vehicle is planned.

Test results and subjective evaluation – transverse joints during cornering

Similar to the results of the driving simulator study the optimized chassis setting provides an increased roll motion at the real world test drive. Furthermore an increased yaw rate gain similar to the competitor vehicle was measured, which gives the driver a more neutral cornering behaviour.

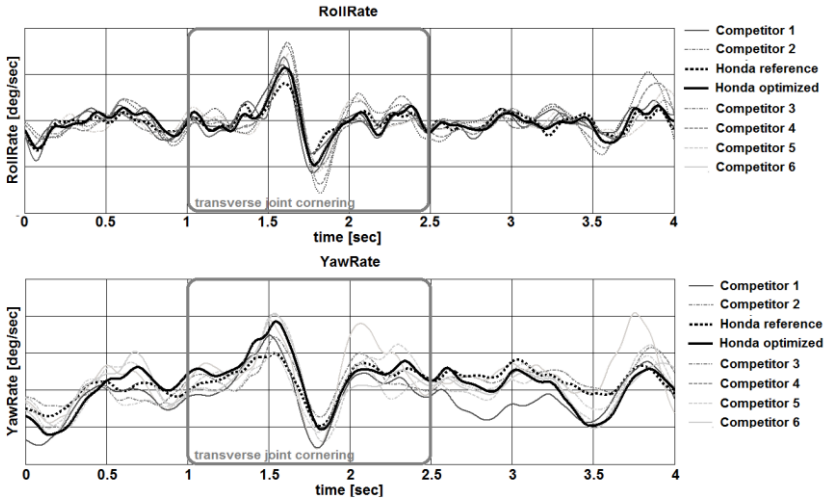


Figure 13: Optimized roll behaviour comparison at transverse joint during cornering

6 Summary and Outlook

In this publication a simulation-based method for optimization and evaluation of defined driving scenarios derived from real driving conditions was introduced. The method allows an initial investigation of the effects of basic suspension settings and the determination of optimized suspension specifications by using multi-objective optimization algorithms. Already at this point basic specifications of components like stabilizers and springs as well as more complex interactions like bushings and dampers can be determined. The assessment of the optimization results is done by Driver-in-the-Loop evaluation in a full vehicle driving simulator. A crucial part of this work is the use of a complex real-time full vehicle model combined with real world driving maneuvers for both, the offline optimization and real-time evaluation in a driving simulator. These enable a direct comparability of the results, an interactive selection and cross evaluation. Furthermore different chassis settings can be virtually exchanged and evaluated very quickly. This new method supports the decision making on variants and aims also to a reduction of prototype vehicles. This leads to cost and time savings. The successful optimization of high speed stability and the subjective evaluation in the driving simulator were verified with real world tests.

In future additional driving scenarios will be implemented to optimize the full vehicle characteristics.

References

[1] Heißing B., Ersoy M., Gies S.: *Fahrwerkhandbuch.* Springer Vieweg Verlag, 2013

[2] LeBlanc D.: *Statistics – Concepts and Applications for Science*. Jones and Bartlett, 2004

[3] Pacejka H. B.:*Tire and Vehicle Dynamics*. Butterworth-Heinemann, 2012

[4] Pfeffer P., Harrer M.: *Steering Handbook*. Springer Verlag, 2015