Controllability of superposition steering system failures

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Abstract

This paper describes the method und results of a study conducted to evaluate driver controllability in the event of failures of superposition steering systems. The research investigated the driver-vehicle-interaction during the occurrence of steering angle faults and aimed to explore whether limit values in terms of lateral vehicle motion parameters that are valid for different vehicles can be defined. To this end, four test vehicles which covered a considerable range of vehicle characteristics in terms of lateral dynamics were investigated. N=98 drivers took part in the study. The chosen methodological approach describes subjective disturbance ratings as a function of objective parameters of lateral vehicle motion. Regression analyses were used to identify those factors affecting subjective ratings. Limit values, which should not be exceeded in the event of system failures, were established.

1 Introduction

The evaluation of the functional safety of active steering systems considers technical aspects as well as driver behaviour in the event of system malfunctions. The latter is usually referred to as "controllability". Controllability deals with the question whether a vehicle can be handled safely by the driver in the event of a system failure (MISRA 2007, ISO WD 26262-3, 2007).

According to the recommendations of a Code of Practice that was developed in the EU project RESPONSE 2006, verification of controllability can be demonstrated by means of a trial with normal drivers. The Code's recommendations pose two fundamental questions:

- What is the adequate methodological procedure and which evaluation criteria should be applied in a trial?
- Is it possible to transfer the results gained from a specific set of vehicles in a safety study to other vehicles?

This paper particularly addresses the latter point and considers the issue in light of the results from a study on the controllability of superposition steering system failures.

Evaluation Methodology and Pass/Fail Criteria

Publications on the evaluation of steering system malfunctions are scarce. No standardized evaluation procedures are currently available that would specify appropriate driving situations (e.g. manoeuvres, speed, etc.) or required test environments (e.g. real driving vs. driving simulator). The same holds true for the criteria to be applied in the safety assessment.

Studies published so far use quite different methodological approaches. For example, Jamson, Whiffin & Burchill (2007) benchmarked active front steering system (AFS) failures against power-assisted steering system failures, assuming that the latter could be controlled by normal drivers.[1] The driving took place in a static driving simulator. Taking into account multiple subjective and objective indicators (such as steering wheel reversals or time to line crossing),

[1] The authors make the assumption that the breakdown of power steering is not safety critical and can safely be dealt with by normal drivers. However, there are no publications available in the scientific literature that test this assumption.

the authors concluded that drivers show a tendency to control AFS failures better than failures of the power-assisted steering. However, authors concede that transfer of findings from the simulator to real driving may be problematic.

Whereas Jamson et al. compared drivers' performance in compensating the failures of two different systems Freitag et al. (2001) used absolute criteria to assess driving performance. The study investigated drivers' reaction to the occurrence of malfunctions in a fail-silent designed steer-by-wire system. Using a driving simulator, the researchers recorded whether a system malfunction resulted in lane edge exceedance of more than 20 cm or 40 cm respectively. Obviously, this criterion is a very crude measure as the initial position of the vehicle is not controlled for.

Neukum & Krüger (2003) proposed an evaluation procedure for malfunctions of active steering systems which is essentially based on subjective criteria. The approach utilises a dedicated rating scale together with a standardized evaluation procedure (see chapter 2) and applies an upper tolerance limit that is derived from drivers' judgements.[2] The method was validated in a series of studies on BMW's Active Steering (Krenn & Richter, 2004). There was clear evidence that the subjective tolerance limit is markedly more conservative than a performance criterion of leaving the road, as used by Freitag et al.. The approach put forward by Neukum & Krüger has since been used to evaluate malfunctions of other steering and chassis systems (e.g. Klier, Kieren & Schröder 2007, Switkes et al. 2007).

Transferability of findings to other vehicles

As outlined above the second important question concerning the evaluation of controllability is whether and to what extent the findings from one safety study can be generalised and thus transferred to other vehicles.

Switkes et al (2007) for example investigated the effects of erroneous steering torques of a lane keeping system by using subjective driver ratings. In their discussion they emphasize that the results only apply to the vehicle under study. Neukum & Krüger (2003) similarly stress that their findings on failures of a superposition steering system are only valid for the study vehicle. They argue that the same nominal steering angle fault may lead to different outcomes in other vehicles, depending on a large number of factors such as different lateral dynamics, different steering systems, etc..

If the aim is to generalise conclusions on the controllability of steering malfunctions, these must not refer to a tolerable failure that is defined in technical terms. Rather, the only way to allow transfer of findings from one vehicle to another is to express the tolerable failure in its effects on the driver (see also Parkes, 1995). Therefore, a suitable safety criterion must be based on parameters which are relevant for drivers' perception and behaviour.

An earlier study on superposition steering system failures demonstrated that participants' ratings of driving disturbance can be plotted as a function of fault-induced lateral vehicle motions (Neukum & Reinelt, 2005). Objective parameters considered in the study were the extreme values of yaw rate and lateral acceleration. The subjective disturbance ratings allowed the differentiation between failure-induced effects that are tolerated by drivers and effects that are regarded as safety critical. The findings showed that the upper subjective tolerance limit for the

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[2] Subjective data can not be the only criterion applied and have to be complemented by objective data (also see Neukum & Krüger, 2003).

yaw rate depended on driving speed, whereas the tolerance for lateral acceleration did not. However, as the study included only one vehicle no conclusions could be drawn as to whether the same principles apply to other vehicles.

Questions addressed in this study

The present study on the controllability of steering angle faults in superposition steering systems addresses the issue of transferability of findings to other vehicles. It investigates, if driver ratings of failure-induced effects can be related to objective parameters describing the vehicle response and if so, in how far these associations between subjective and objective indicators can be generalised across different vehicles. Four vehicles with distinctly different vehicle dynamics were included in the study (for further details of the test vehicles, see Wesp et al. in this volume).

2 Method

Failure characteristic and driving manoeuvres

In the following we concentrate on so-called irreversible steering angle faults.[3] During irreversible faults, steering inputs of the system occur, which in amount and direction do not correspond with the movement of the steering wheel. The driver initially perceives a brief increase of steering torque that results in a change of the steering wheel angle (if the steering wheel is not fixated). Complementary dynamic reactions of the vehicle follow.

Figure 2-1 depicts an example of steering torque, steering wheel angle and yaw rate over time. The onset of compensatory action by the driver starts at approximately 250 ms and is completed after 1.5 s, when the driver carries on straight with an offset in steering wheel angle and deactivated system. The following analyses exclusively consider fault-induced effects during the primary reaction phase. The focus is on extreme values for steering torque, yaw rate, lateral acceleration and roll rate.[4]

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3 Several other types of failure were investigated in the study; however, these are not considered in this paper.

4 Further analyses were carried out on drivers' compensatory actions in reaction to system failures. These findings are reported elsewhere."

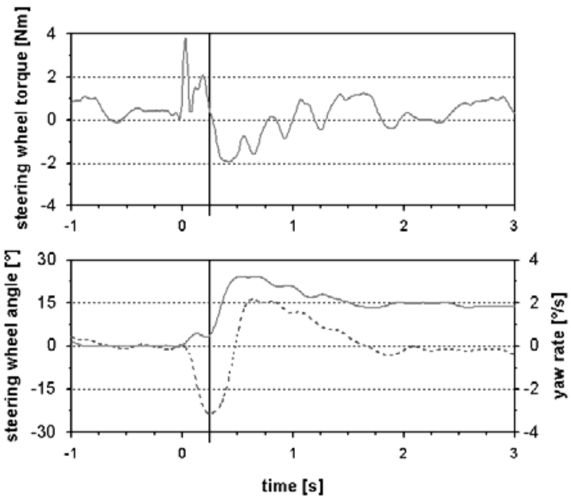

Figure 2-1: Steering torque, steering wheel angle and yaw rate (broken line) over time with the occurrence of an irreversible steering angle fault at time point t=0. The vertical line denotes the point in time where the driver initiates compensatory action.

Experimental design and participants

A total of N=98 subjects took part in the study. The sample included three driver groups:

- N= 86 participants with average driving skills: this sample was balanced for gender and age (25-30, 31-45, 46-60, >60 years) and split to drive one of the four test vehicles (between factor);
- N=8 novice drivers with a maximum of three month driving experience;
- N=4 expert drivers.

The test scenario chosen was straight lane driving. In low and medium speed conditions the driving lane was artificially narrowed by pylons to simulate driving through road works. In the 50 km/h conditions the lane width was restricted to 2.50 m, in the 100 km/h condition to 3.00 m (Schönborn & Schulte, 1995). For the high speed condition the lane width was restricted to 3.75 m.

The range of steering angle faults was tested during piloting and subsequently selected in such a way that small as well as considerable faults were included. All drivers were exposed to all faults (within factor). The sequence of the faults was randomised across all driver groups. The disturbances were induced under single-blind conditions. All participants completed all driving speed conditions (within factor).

Disturbance Rating Scale

Drivers had to rate the effects of the steering angle faults by means of the disturbance rating scale (Fig. 2-2), following a two-step procedure. Firstly, drivers had to select the verbal category (e.g., “dangerous”) that described the fault-induced effects best. Subsequently, drivers had to use a more fine-graded numerical rating within the chosen verbal category. The scale is characterized by a unique, defined tolerance limit. Drivers are instructed to rate disturbances which are not tolerable with scale values ≥7[5]. The aim of the scale is to specifically represent fault-induced effects on driving. This cannot be achieved by established scales measuring workload, safety or task difficulty. Ratings on these scales are strongly influenced by individual driver characteristics or by features of the driving task. Additionally, those scales are not able to provide a tolerance limit (e.g., what does “medium safe” mean?).

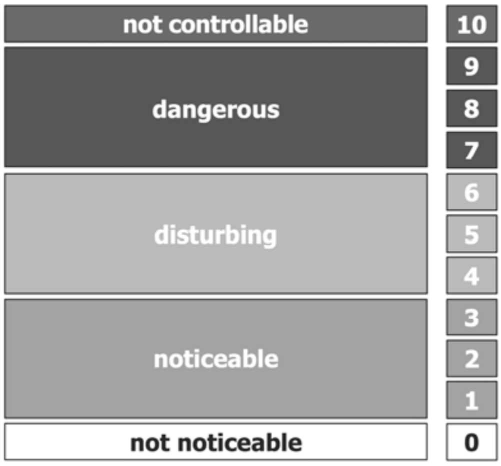

Figure 2-2 Disturbance Rating Scale (Neukum & Krüger, 2003).

In order to get a common understanding of the scale, drivers were intensively instructed about the procedure and the meaning of the categories. The verbal categories of the scale were described in the following way:

- The category „noticeable“ (scale points 1-3) comprises disturbances that are noticed by the driver, but which have only small effects on the driving task (if at all). The main effect of the disturbances may be a decrease in driving comfort. Compensatory action by the driver – if at all required – is negligible.
- The category „disturbing“ (scale points 4-6) refers to erroneous steering interventions which require (by way of vehicle motion and lateral displacement) a marked compensatory effort from the driver. This effort, however, is still judged by the driver as tolerable.
- The fault is rated as „dangerous“ (scale points 7-9) if its compensatory effort is considerable and is regarded as not tolerable by the driver. The system failure thus results in safety critical situations.

5 The disturbance rating scale is similar to the Cooper-Harper-Scale (Cooper & Harper, 1969) with regards to its underlying structure, however, not with regards to its content.

3 Results

3.1 Dependency of parameters on nominal steering angle faults

Objective Parameters

Depending on vehicle dynamic properties steering angle faults of the same nominal amplitude lead to different outcomes in the test vehicles under study. Figure 3-1 provides an example of this finding for the 100 km/h condition in the closed loop trials. Means of the extreme values of each parameter, including steering torque, yaw rate, lateral acceleration and roll rate are shown for each nominal steering angle fault, (please also refer to Wesp et al. (in this volume) for further details on measurements in open-loop conditions). The figure shows distinct differences between the four vehicles, particularly for the steering torque. Considerable differences are also found for lateral acceleration and roll rate. Differences between vehicles become more pronounced on all four parameters for increasing steering angle faults. Fault-induced changes in yaw rates are similar in all four test vehicles.

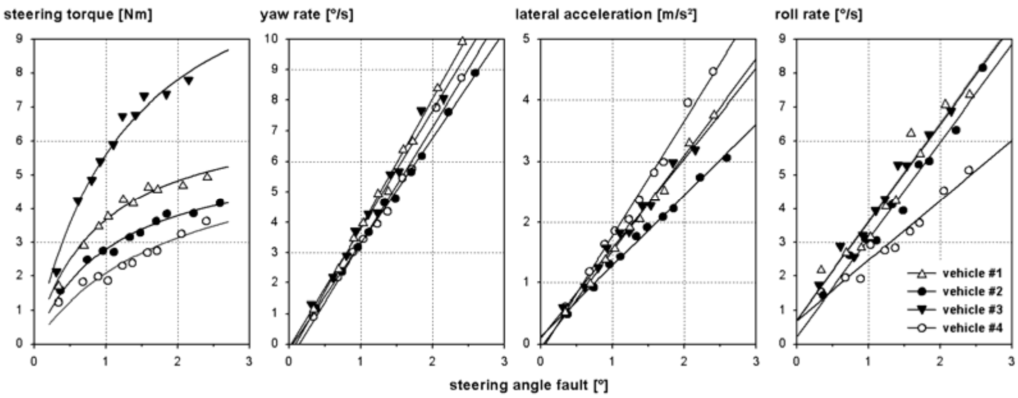

Figure 3-1 Means of the four objective parameters plotted against nominal steering angle faults in the 100 km/h condition.

Subjective Ratings

Whereas pronounced differences are found on the objective parameters, the disturbance ratings as functions of the nominal steering angle faults are very similar for all four vehicles. Figure 3-2 depicts the mean disturbance ratings for the four vehicles in the 50, 100 and 150 km/h condition. It reveals that for the same nominal steering angle fault, drivers' ratings of the disturbance increase as a function of driving speed.

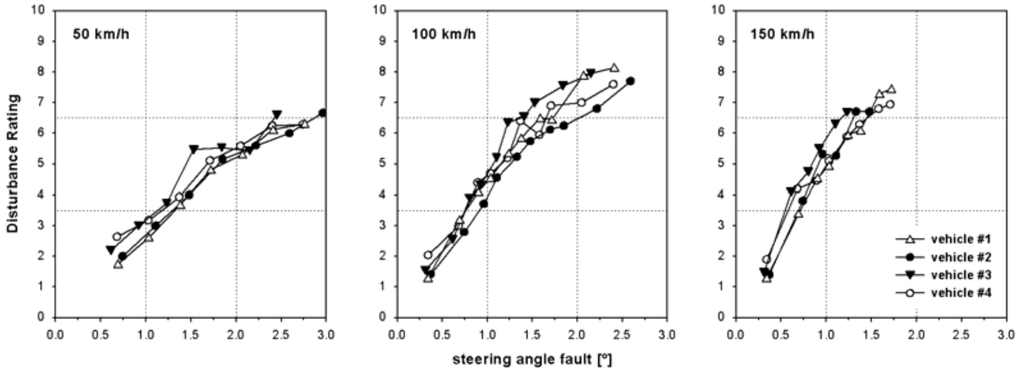

Figure 3-2 Means of subjective disturbance ratings plotted against nominal steering angle faults in the 50, 100 and 150 km/h condition.

Driver characteristics and habituation

Further analyses were carried out to check for systematic differences between participants. No systematic differences were found for age, gender or driving experience (novice, normal and expert drivers).

Resulting from the repeated measurement design of the study, each participant carried out approximately 60 drives. To test whether increasing experience with the experimental situation affected the disturbance ratings, the very first presentation of a steering angle fault was compared to the same fault presented in a later phase of the experiment. Figure 3-3 shows the results. No significant differences were found for the 50 km/h condition. In the 100 and 150 km/h condition, small but significant effects were found between the first and the later presentation of the same fault in the trial. In both conditions, participants rated the second presentation to be more disturbing than the first one (v=100 km/h: t=3.58, p=.001; v=150km/h: t=2.12, p=.037). The findings suggest that habituation in the sense of increased tolerance of faults does not take place.

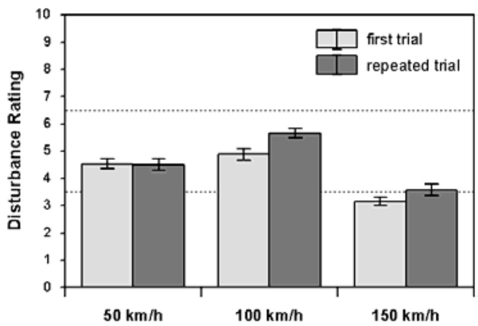

Figure 3-3 Means and standard errors of driver ratings for the first (light grey) and subsequent (dark grey) presentation of steering angle faults.

3.3 Subjective ratings of the fault-induced vehicle response

In Figure 3-4 the means of drivers' disturbance ratings are plotted against the means of the objective parameters for all four test vehicles in the 100 km/h condition. Whereas linear regression functions are the best fit to describe the relationship between subjective and objective variables for steering torque, disturbance ratings follow a degressive function on the lateral vehicle dynamics variables. For these parameters, sigma-functions (y = a/(1+(b/x)^c) were fitted.

For each of the four vehicles, objective parameters and subjective ratings are closely related. However, overlaps of the functions for different vehicles are only found for the yaw rate and the lower quadrants for the lateral acceleration. In both cases, similar effects on vehicle lateral motion in different vehicles result in similar disturbance ratings. The goodness of fit is expressed by the determination coefficient of the regression; for both, yaw rate and lateral acceleration in the 100 km/h condition R^2=.95. For the remaining driving speed conditions, 50 km/h and 150 km/h, the R^2s ranges between .90 and .98 and thus signifies that at least 90 percent of the variance in the ratings can be explained by these two objective parameters.

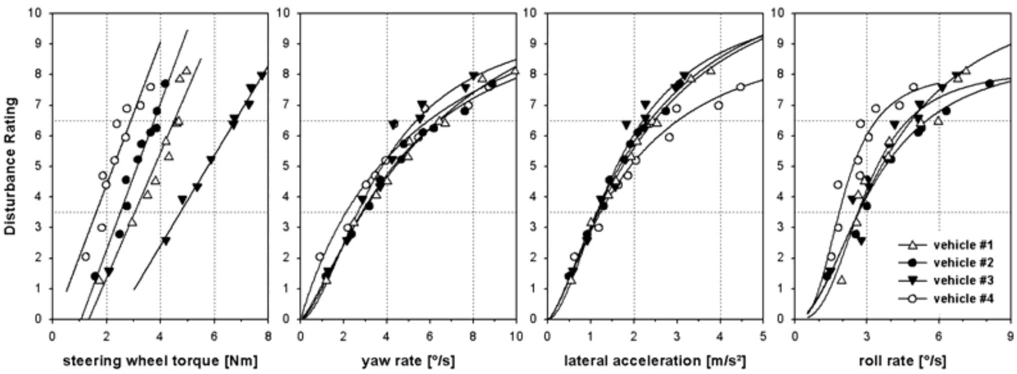

Figure 3-4 Regression functions for each of the four test vehicles in the 100 km/h condition.

Considerably lower R^2s were found for fault-induced roll rates as a predictor for disturbance ratings (range R^2= .64 and R^2= .81. The fact that quite different roll rates were rated as equal in their effect on driving suggests that the roll rate does not play a significant role in the assessment of failure effects. This finding was in line with results reported in the relevant literature.

The most striking differences between vehicles were found for the extreme values of the steering wheel torque. As Figure 3-4 illustrates, differences on the objective parameters in the four vehicles did not find an expression in the subjective ratings (R^2 ranged between .13 and .39). This indicates that the fault-induced steering wheel torque is of limited relevance for the subjective assessment of failure effects (within the value range investigated in this study).

3.4 Establishing tolerance limits

As outlined above, the regression functions of yaw rate and lateral acceleration were almost identical and thus allowed pooling of data from the four test vehicles. For further analysis, yaw rate and lateral acceleration were grouped ex post into classes (class range for yaw rate: 0.5°/s; class range for lateral acceleration: 0.25m/s²). The aim of the grouping was to achieve an adequate differentiation of ratings across the parameter space of interest whilst ensuring that the resulting classes contained sufficient data for robust analysis. Mean and standard errors of the disturbance ratings for each category were calculated and are displayed in Figure 3-5.

As Fig. 3-5 illustrates the resulting functions between objective and subjective parameters can be described nearly perfectly with degressive sigma functions. The findings show that drivers rate fault-induced yaw rate changes of the same amplitude as more critical with increasing driving speed. On the other hand driver ratings as a function of lateral acceleration are not influenced by driving speed.

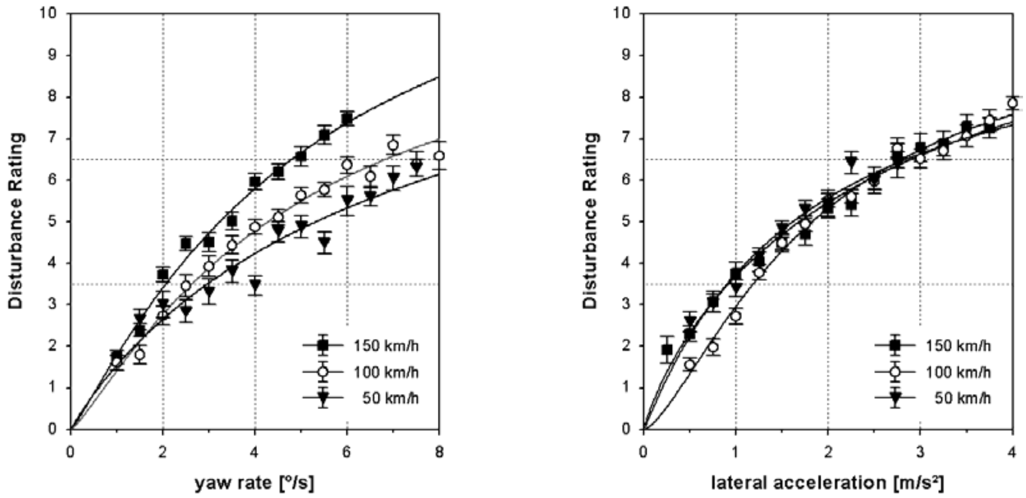

Figure 3-5 Disturbance ratings plotted against yaw rate and lateral acceleration for the three speed conditions, 50, 100 and 150 km/h.

The empirical distribution of ratings within each class was used to establish tolerance limits. A sequential procedure was developed which is primarily based on subjective judgements but also includes objective data to safeguard against the effect of erroneous ratings. In a first step, the class was selected where 85% of the subjective ratings were below point 7 on the disturbance rating scale. This scale point marks the transition from "disturbing" to "dangerous". In a second step it was checked in how far the 15% of the "dangerous" ratings actually corresponded with a safety-critical driving situation. For this purpose the distribution of objective parameters (in this case the distribution of maximal yaw rates) during the compensation phase was reviewed. If the objective value (in this case for yaw rate) corresponding with a "dangerous" rating fell into the distribution of objective values corresponding with the 85% non-critical ratings, the "dangerous" rating was deemed irrelevant.

The outlined procedure resulted in the definition of the following tolerance limits which should not be exceeded in the event of steering failures:

- The maximal admissible change in yaw rate caused by steering failures is speed-dependent. The following limits should not be exceeded:
  - Speed: 50 km/h, limit: 4.0°/s
  - Speed: 100 km/h, limit: 3.0°/s
  - Speed: 150 km/h[6], limit: 2.5°/s.
- The maximal change in lateral acceleration caused by steering failures should not exceed $1.25 m/s^2$. This limit applies for all three speed conditions, 50, 100 and 150 km/h.

4 Summary and Discussion

The aim of the study was to draw generalisable conclusions on the controllability of superposition steering system failures, based on a large driver sample. The underlying thought is that a safety criterion that can be applied to different vehicles needs to be based on drivers' perception. Therefore, relevant safety-limits must be established on the basis of the noticeable effects of a steering system fault rather than on technically defined failure values.

Four test vehicles with different dynamic vehicle characteristics were included in the study to investigate which factors affect driver ratings. The findings showed that the prediction of subjective ratings of the effects of system failures by fault-induced yaw rates and lateral accelerations are very good, whereas steering wheel torque and roll rate are less important. No significant differences between vehicles were found for yaw rate and lateral acceleration. Thus, tolerance limits for these parameters were established on the basis of the subjective disturbance ratings, which should not be exceeded in the event of system failures.

The proposed tolerance limits solely refer to the fault-induced effect; therefore, test trials with participants to ensure compliance with the limits are not necessary. Instead, testing can be carried out under open-loop conditions (for further details on the testing procedure, see Wesp et al., 2008, in this volume).

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[6] Test drives under high speed conditions (up to 250 km/h) were exclusively conducted with expert drivers. The results form these test show that the tolerance limits established for 150 km/h also apply to higher driving speeds.

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