

FIELD STUDY ON CRASH CAUSAL FACTORS OF CHASSIS MODIFICATIONS

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ABSTRACT

New vehicle types are extensively tested to check almost all factors that influence ride and handling. With reference to the Association of German Car Tuners' (VDAT e.V.) valuations, approximately 10% of all cars in Germany are being modified by their owners. 28 % of those modifications' sales are divergent wheel-tire combinations, 13 % are tuning measures on the chassis suspension or wheel spacers. In almost all cases the singular modifications present a general permission for specific vehicles they have been tested in. Combined tuning measures, however, are often checked by just one inspector, following a procedure of mostly subjective assessment criteria.

Today, critical attributes are only being observed, in case a vehicle is involved in an accident and the modifications are identified as crash causal factors or as a cofactor on the development of a crash. For the first time, a field study allows a survey of safety affecting chassis modifications.

The test layout has to comply with some basic conditions. Different vehicle concepts with a wide margin of modifications are required to get a high transferability of the results. A total amount of more than 150 tested vehicles serves the same purpose. The tests are limited concerning the installation time of measurement techniques and the requirement that no damage, defilement or immoderate wear of the vehicles are accepted by their owners. Due to such factors as well as the driver's acceptance, the vehicles are controlled by its owners instead of robots or test drivers. For keeping down the driver's influence, the lane has narrow boundaries and the driver has to drive in strictly adherence to the given instructions.

After gathering all modifications, as well as static and kinematic parameters like the toe and camber angle, dynamic testing of predominantly lateral dynamics is conducted. Besides standardized tests like the ISO 3888-2 (Obstacle Avoidance) or the ISO 14512 (Braking on Surfaces with Split Coefficient of Friction), to test the influence of modified kingpin offsets caused by wheel spacers, some deviant tests are conducted. Those are required due to the demand of objective test results for road tests with vertical induced stimulation of the chassis suspension. Hence, new tests on corner braking with and without vertical stimulation have been developed.

The interpretation of data includes thresholds, e.g. the maximum entrance velocity without hitting cones, on the one hand, and the analysis of characteristics of data concerning time and frequency range, "1-second values" and peak response times on the other hand. Besides the thresholds as indicators for the achievable velocities, which are mainly affected by friction coefficients, the vehicle reaction in the course of time characterizes the vehicle reaction in the threshold range and consequently the operational demands on the driver.

The field study has started and promises the first long-range analysis of chassis modifications. The results offer a basis for hypothesis and resultant further test layouts for oncoming studies of the identified critical tuning measures.

INTRODUCTION

The *Institute of Automotive Engineering at Technische Universität Darmstadt* and the *Federal Highway Research Institute* research on the safety of vehicles with modified chassis suspension. The research project includes an analysis of tuning measures, a field study on crash causal factors, and a detailed examination of the identified critical states by the use of vehicle simulation and an experimental vehicle. This paper concentrates on the results of the field study. The results of the systematical investigation are expected at the end of the year.

STATE OF THE ART

Today, the process of development includes comprehensive tests of prototype vehicles, both in dynamic testing and in simulation. Thereby, the main safety-regarding aim is to ensure the functional safety. All-embracing examination about the factor of vehicle modification is not covered by the analysis of functional safety. In addition to simulation, subjective and objective methods are used to assess both, safety and comfort of chassis suspension. The mentioned project analyzes just the safety-regarding aspects for the reason that costumers of tuning measures do not expect benefits in comfort.

Subjective Safety Criteria

The controllability of a vehicle gets specified by desired characteristics (cf. Heißing [1]):

- predictable vehicle reactions to the drivers input,
- high damping ratio of the yaw rate,
- well-defined approach to the limit of cornering grip,
- soft transfer behavior, and
- consistent driving with different loads as well as on surfaces with different friction coefficients.

The assessment of various criteria happens by the use of various assessment schemes. The subjective vehicle safety can be assessed by test drivers as well as by test persons.

Objective Safety Criteria

Objective safety criteria distinguish between thresholds and the view on characteristics in time or frequency range. Characteristics to describe the vehicle behavior as well as the conceptual design of the maneuvers are the topic of diverse scientific publications (e.g. Baumann [2], Richerzhagen [3])

CONSIDERATION OF THEORY

The consideration of theory includes a vehicle tuning analysis, the derivation of crash causal factors, and the definition of the test layout.

Vehicle Tuning Analysis

Vehicle tuning includes several measures on:

- wheel,
- aerodynamic,
- chassis suspension,
- engine,
- exhaust system,
- interior,
- audio system,
- steering wheel, and
- seat.

According to a study by VDAT [4] from 2005, the sales of German tuning manufacturers reach a yearly amount of 4.6 bn Euro. Thereby, young drivers have a higher purchase intention for such parts but a smaller budget. For that reason more and more parts of very inferior quality get sold to costumers with scarce technical knowledge (cf. DVR [5]). Within the study, modifications on chassis suspension get analyzed.

Tuning measures on chassis suspension Chassis modifications can be realized by the replacement, the adjustment, or by the installation of additional components. The parameters (cf. Causemann [6]) of the chassis suspension thereby interact with each other (See Figure 1).

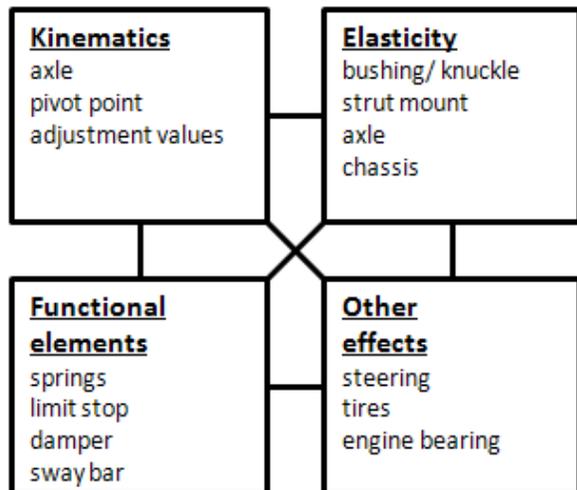


Figure 1: Scheme of the parameters of chassis suspension

Typical chassis modifications are:

- change of wheels/ tires,
- track extensions, and
- change of the chassis suspension.

The change of wheels and tires includes wide-base or low-section tires as well as changes of the rim contour and the tire filling with nitrogen. Beside a loss of comfort, influences on the steering behavior and on the sensitivity to ruts can occur.

Track extensions typically extend the track width about two to four percent. This extension gets realized by wheel spacers or by a lower rim offset. A modified track width changes the scrub radius. Thus, the directional stability changes particularly with regard to braking on a track with partially low friction (cf. Betzler, Reimpell [7]).

Changes of the chassis suspension include shorter and stiffer springs, stiffer sway bars, and dampers with a stiffer characteristic.

Life-cycle Several partners are involved in the tuning market. The participants in the life-cycle of modifications are separated in four closely connected groups with different interests (See Figure 2).

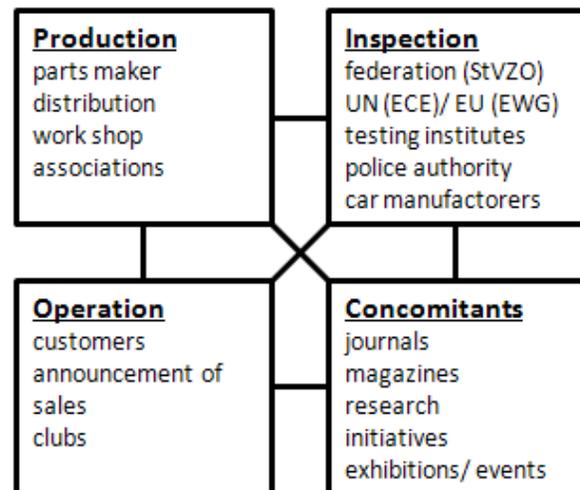


Figure 2: Scheme of the partners in the life-cycle of tuning

Regulations The motor vehicle licensing in Germany requires a type approval. Single tuning measures with a type approval do not need an acceptance test. Combined tuning measures or large-scale changes require a test to keep their operating license (cf. Konitzer, Wehrmeister [8]).

Crash Causal Factors

According to the three-level-model of Donges [9], the task of driving includes navigation, tracking and stabilization. Concerning safety-matters, the effects on the stabilization-level of the vehicle are being analyzed. Parameters to describe the risk of accidents are defined as:

- vehicle-caused malfunction,
- sensitivity to malfunction, and
- feasibility to correct an impact on the controllability.

Vehicle-caused malfunction Within the study, vehicle-caused failures are not considered. The exclusion of this parameter is based on the consumption that the participating vehicles, as well as the modified parts, had passed the technical inspection or approval by a technical inspection authority (e.g.: TÜV [10], Dekra [11]).

Vehicle-caused malfunction also includes effects that may occur currently, or more often with modified

vehicles. An exemplary malfunction is hitting the damper stop. Vehicle-caused malfunction has not been identified within the field study.

Sensitivity to malfunction The sensitivity to malfunction is represented by open-loop maneuvers. On the one hand, reactions to transient stimulations and on the other hand response functions are instrumental in assessing the safety relevant parameters.

Feasibility to correct an impact on the controllability The driver and the vehicle represent a closed loop control. The feasibility to correct an impact on the controllability is characterized by the vehicles' response time as well as the transfer function.

This criterion includes:

- the time delay of the vehicle reaction after the drivers input, and
- the transfer function between the drivers input (steering angle, the position of throttle and brake pedal) and the vehicle motion.

The extract of a closed loop control circuit (See Figure 3), based on Mitschke and Hei3ing [12], [13] illustrates the time delay between the driver input and the vehicles reaction.

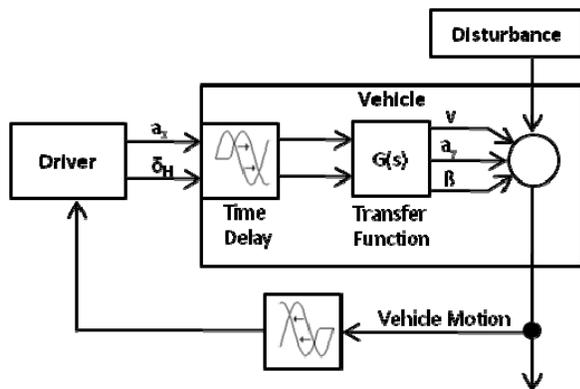


Figure 3: Scheme of the closed loop control of vehicle stabilization

Test Layout

Dynamic parameters regarding to safety, affect the lateral dynamics. Concerning this matter, the focus concentrates on the:

- lateral dynamics,
- combined longitudinal and lateral dynamics, and
- combined vertical and lateral dynamics.

With reference to this test design, an applicable test layout has to be defined. An established method therefore is the derivation of basic maneuvers and the superposition of these maneuvers (cf. Janßen [14]).

Hereby, the maneuver is defined by the initial state of the vehicle, the basic maneuver and the combination of basic maneuvers (See Table 1).

Table 1.

Derivation of longitudinal and lateral maneuvers

Maneuver		
initial state	initial state of track	- straight - curve
	initial state of movement	- speed - lat. acceleration - sideslip angle
basic maneuver	load cycle changes	
	braking	
	acceleration	
combined maneuver	steering	- jump - ramp - sinus
	superposition of basic maneuvers	
	sequence of basic maneuvers	- periodical - extensive

Lateral and vertical stimulation offer a supplementary variation of the basic maneuvers. Beside the stimulation by wind, transient, periodic, and aperiodic stimulation by road affect the vehicle dynamics (See Table 2).

Table 2.

Derivation of stimulation types

Stimulation		
track	transient	- one-sided - two-sided
	periodic	
	aperiodic	- deterministic - random
other	wind	

The test conditions offer an additional parameter next to the definition of the maneuver. Within the study, the track conditions are particularly important with regard to the vehicle safety, necessary to ensure the assignability of the test results. The derivation of test conditions includes the weather as well as the track conditions (See Table 3).

Table 3.

Derivation of test conditions

Test conditions		
weather	rainfall	- fog
		- rain
		- snow
		- hail
	ambient temperature	
light		- glare
		- twilight
track	friction coefficient	surface temperature
		- dry
		- wet
		- humid
		- ice
		- snow
		- μ -split
		- μ -jump

The final test layout represents the relevant standardized tests and deviant test layouts to address the expected crash causal factors of vehicle modifications.

FIELD STUDY

The main objectives of the field study are:

- the analysis of safety-affecting single tuning measures,
- the research into the effects of multiple modifications, and
- the identification of capable test layouts.

The results of the study offer an overview about the trend of dynamic effects, as a function of the tuning measures' extend.

Within the field study, the vehicle owners drive their own cars. By this approach to the vehicle guidance, the real-case scenario is represented as good as possible. In addition to that reason, the vehicle owners' acceptance to the test raises.

Testing Requirements

In face of the involvement of conventional vehicles and their owners in dynamic testing maneuvers, exceptional requirements have to be fulfilled.

Safety The safety needs to be ensured for:

- occupants,
- the test vehicle, and
- the testing infrastructure.

An adequate reaction in case of critical maneuvers cannot be expected within a study with ordinary drivers. The implementation of safety zones as well as crash-permissive targets and cones into the test layout attend this requirement.

Instrumentation The installation of the instrumentation takes place in different vehicle types. A central unit needs to be fixed and calibrated in the rear trunk; an adapter gets mounted on the steering wheel, and the speed sensor gets attached to the towing lug. The assembly needs to happen fast and easily. The measuring setup works self-sustaining and needs to be removed without leaving any damage at the vehicles.

Configuration of vehicles Different vehicles with a wide range of modifications offer an adequate survey. Vehicles without ABS or ESC systems and non-modified vehicles get tested for the same reason.

Registration of vehicle parameters The characterization of the vehicles occurs by the registration of additional vehicle parameters beside the measurement data. The following data are necessary to calculate parameters and to classify the vehicle:

- position of the gravity center,
- wheel base,
- position of the sensors,
- present tuning measures,
- tire data, and
- track conditions.

Test Environment

The field study takes place on the proving ground of the TUD. The area offers a track-width of 20 m, two dynamic pads with a diameter of 40 m and a straight braking track with a watered low friction surface (See Figure 4).



Figure 4: Braking maneuver on a low friction surface

Test Design

The test design covers critical states of maneuvers as well as tests to assess the feasibility and the sensitivity. Therefore four categories of testing compose the layout.

Calibration The test vehicle passes a basic layout to calibrate the sensors and to identify the sensor offsets, including:

- 5 s offset-adjustment,
- 100 m straight to adjust the sideslip angle,
- 360° quasi-static cornering, and
- 10 m straight to calibrate the speed sensor.

A light barrier is mounted to trigger the signals.

Lateral dynamics The lateral dynamics are represented by:

- lateral transfer function,
- steady-state cornering, and
- obstacle avoidance.

Thereby, the lateral transfer function is tested in a slalom maneuver with 15 m distance between the cones. The several runs get passed with 40 km/h, 50 km/h and with the maximum speed. This test refers to ISO 7401 [15]. The steady-state cornering (cf. ISO 4138 [16]) starting with 10 km/h and raising about 10 km/h each run until reaching the maximum possible maneuver-speed takes place on a skid pad with 50 m radius. Within this test, the understeer gradients as well as the maximum lateral acceleration get tested. The ISO 3888-2 [17] obstacle avoidance test requires a high controllability and a predictable vehicle behavior.

Combined lateral and longitudinal dynamics

The combined lateral and longitudinal dynamics are represented by:

- braking in a turn,
- braking on surfaces with split coefficient of friction, and
- brake-/ evade test maneuver.

Braking in a turn (cf. ISO 7975 [18]) and the non-standardized brake-/ evade test maneuver distinguish between the initial state of track. Braking on a track with split coefficient of friction represents an open-loop test and it is comparable to ISO 14512 [19].

Combined lateral and vertical dynamics For reaching a high acceptance rate of the participants, regarding the maneuver, a single vertical stimulation is the highest imposition for the vehicle. For that reason, an open loop test with a transient two-sided vertical stimulation is implanted into the test layout.

Signals and Data Quality

To achieve the testing requirements of objective results, a package of sensors gets adapted to each vehicle of the field study.

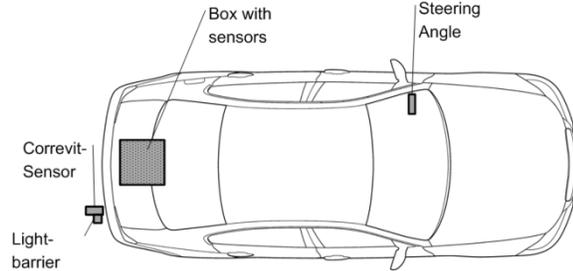


Figure 5: Scheme of sensor configuration

The sensor package includes a high-precision optical 2-axis speed sensor, a light barrier for trigger, a sensor to measure the steering angle, and a box with a 3-axis acceleration, and 3-axis angular motion measurement (See Figure 5). To cover as many vehicles as possible, the sensor package is a stand-alone system. The data recording frequency of 250 Hz was selected for a 10-time oversampling of the safety-relevant chassis motion and the eigenfrequency of the wheel, which are lower than 25 Hz (cf., Mitschke, Wallentowitz [20]). The real-time data checking and logging takes place with the measurement-notebook onboard by the test instructor.

Table 4:

Signals, resolution and accuracy of the mounted sensors

Signal		Resolution	Accuracy
long. speed	v	0.04 km/h	0.1%
lat. speed	v _q	0.04 km/h	0.1%
long. acceleration	a _x	0,0025 m/s ²	2%
lat. acceleration	a _y	0,0025 m/s ²	2%
vert. acceleration	a _z	0,0025 m/s ²	2%
yaw rate	ψ'	0.2 °/s	1%
pitch rate	θ'	0.2 °/s	1%
roll rate	φ'	0.2 °/s	1%
steering angle	δ _H	0.1°	1%
light barrier		Trigger	Trigger

The signals (See Table 4) get offset-adjusted and calibrated during the test runs.

TEST RESULTS

Results of selected tests are specified in the following.

Transient Vertical Stimulation

The first test-layout represents an open-loop maneuver including lateral and vertical dynamics. The initial state is a steady-state cornering maneuver with a radius of R=20 m and an initial speed of v=40 km/h. The initial lateral acceleration and the basic yaw rate can be calculated (Equation 1, 2).

$$a_y = \frac{v^2}{R} \approx 6.2 \frac{\text{m}}{\text{s}^2} \quad (1)$$

$$\psi_0 = \frac{2\pi}{360^\circ} \frac{v}{R} \approx 31.8 \frac{^\circ}{\text{s}} \quad (2)$$

To analyze the sensitivity to failures, the course of the yaw-rate offers the relevant criteria to specify the stability. The two-sided transient vertical stimulation is designed as a linear ramp with an angle of 2.5°. The target gets overtraveled with a steady steer angle and constant speed to ensure the open-loop properties.

The maneuver starts at t₁ with the first touch of the ramp by the front tires (See Figure 6). At t₂ the front tires jump off the ramp, at t₃ the rear tires hit the ramp, and at t₄ the rear axle jumps off the ramp. The following absorption of the yaw rate represents the criteria for the sensitivity to malfunction.

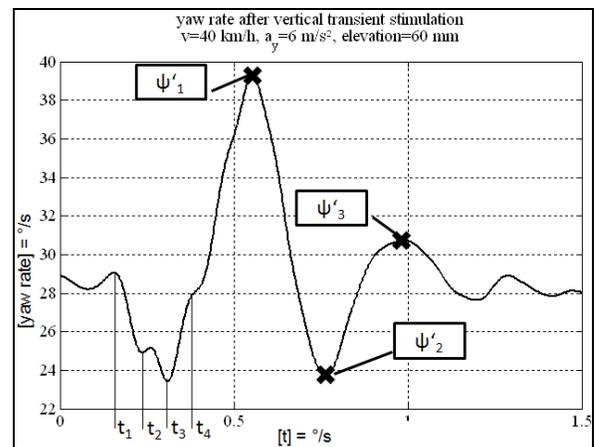


Figure 6: Exemplary course of the yaw-rate

To assess the self-contained damping of the yaw rate, the reduction of the yaw rate has to be independent from the understeer gradient. Therefore, the relative change of the yaw rate gets calculated (Equation 3).

$$OR_{\psi} = \frac{\dot{\psi}_3 - \dot{\psi}_2}{\dot{\psi}_1 - \dot{\psi}_2} \quad (3).$$

To analyze the influence of chassis modifications, on the one hand, serial cars are getting tested, and on the other hand, sports cars are examined (See Figure 7).

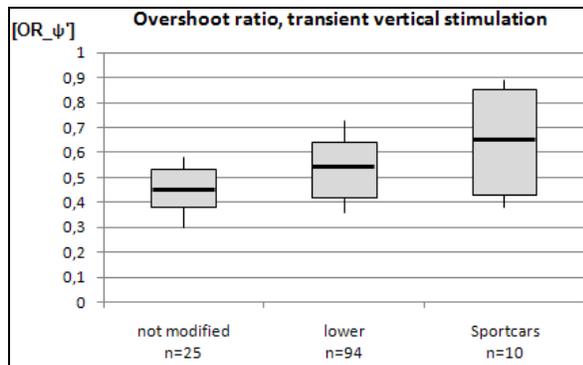


Figure 7: Overshoot ratio of the yaw rate after a transient vertical stimulation in course of steady-state cornering.

The results of the tests are displayed in the boxplot-view. The upper and lower limits tag the 90% and 10% limits. The boxes tag the 25 and 75 percentile. The median is tagged by the bold line in the box.

In the course of the tests no vehicle reached critical excited states of the yaw rate. Over the test time the serial vehicles achieved the best overshoot ratio with a mean ratio of 0.45. Lowered vehicles reached a mean ratio of 0.54; sports cars reached a mean ratio of 0.64 in contrast to that. As a result of that investigation, lower vehicles achieve a significant worse overshoot ratio than non-modified vehicles. Thus the overshoot ratio of the yaw rate is not associated with the measure of lowering (See figure 8), the overshoot ratio basically changes with the damper ratio.

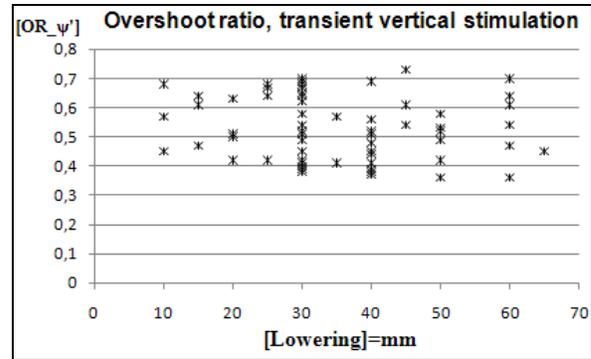


Figure 8: Overshoot ratio of the yaw rate dependent on lowering

This assumption gets verified in outstanding tests by the use of a test vehicle with various damper settings.

Severe Lane-Change Maneuver - Obstacle Avoidance

Within the study, the delay time of the lateral acceleration after a drivers steering input is addressed by the ISO 3888-2 “Test track for a severe lane-change maneuver, Part 2 Obstacle avoidance” [17]. Beside the delay time, the maximum yaw rate as a measure for the sensitivity to a drivers input gets analyzed (See Figure 9).

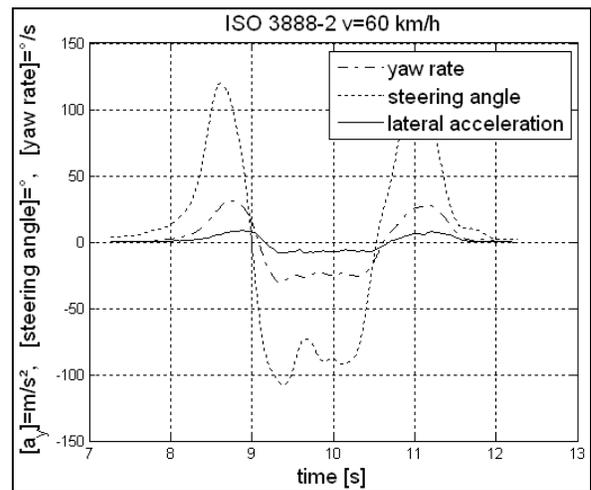


Figure 9: Yaw rate, steering angle and lateral acceleration at ISO 3888-2

The delay time (DT) is defined as the mean phase shift between the steering angle and the lateral acceleration. Therefore a correlation analysis between the steering angle function ($f_{\delta}(t)$) and the function of the lateral acceleration ($f_{a_y}(t)$) gets operated (Equation 4).

$$\rho(\tau_i) = \int_{t=0s}^{4s} f_{\delta}(t) \cdot f_{a_y}(t + \tau_i) dt \quad (4).$$

τ rises stepwise until 0.5 seconds. The delay time gets identified by (Equation 5):

$$DT = \max(\rho(\tau_i)) \quad (5).$$

The spreading of the different wheel types and road conditions is nearly uniformly distributed between the lower vehicles and the serial vehicles.

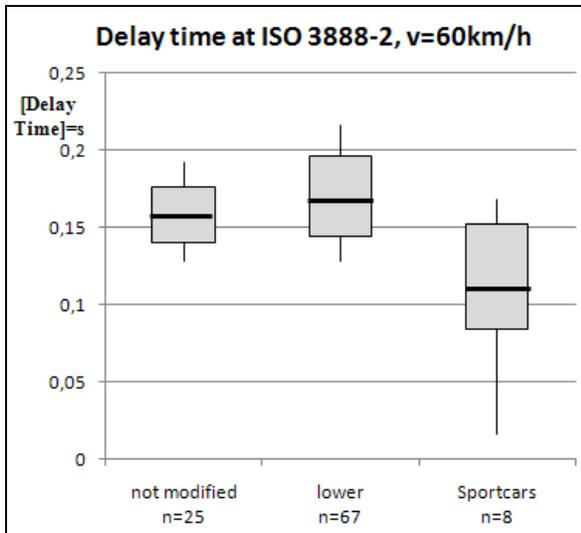


Figure 10: Delay time at ISO 3888-2 for different vehicle types

The delay time between steering angle and lateral acceleration mainly depends on road conditions and the cornering stiffness of the tire (See Figure 11). Thus, no significant differences between lower and not modified vehicles occur (See Figure 10). Within the field study, the tested sport cars drove with slick or semi-slick tires with a very high cornering stiffness. In addition with the short wheel base, the delay time is highly significant shorter.

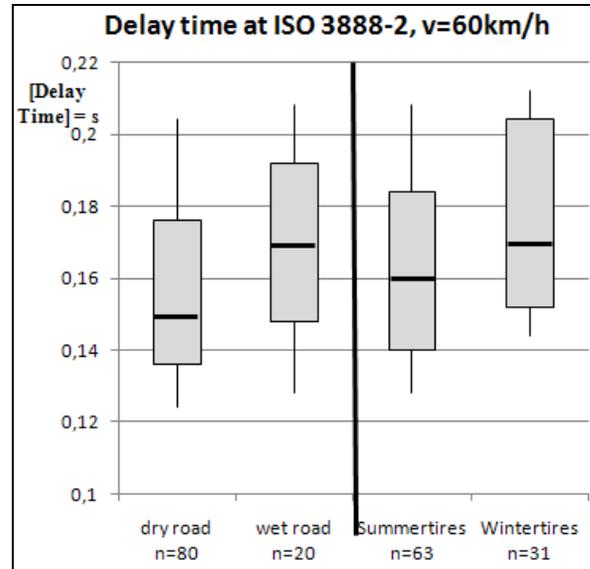


Figure 11: Delay time at ISO 3888-2 for different tires and road conditions

Beside the delay time, the maximum yaw rate describes the controllability of the vehicle by its owner.

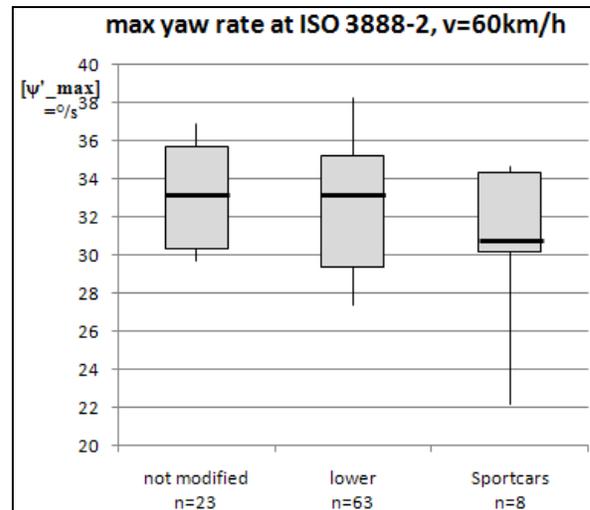


Figure 12: Maximum yaw rate at ISO 3888-2 for different vehicle types.

Thereby, lower cars show a wider range of maximum yaw rates, but the mean value is nearly equal to the median of the maximum yaw rate of serial vehicles (See Figure 12). The highly significant different maximum yaw rate of sport cars is mainly affected by the tires and their driver's experience.

The relation of the maximum yaw rate and the delay time is a matter of particular interest beside the significant differences of various tire and road conditions.

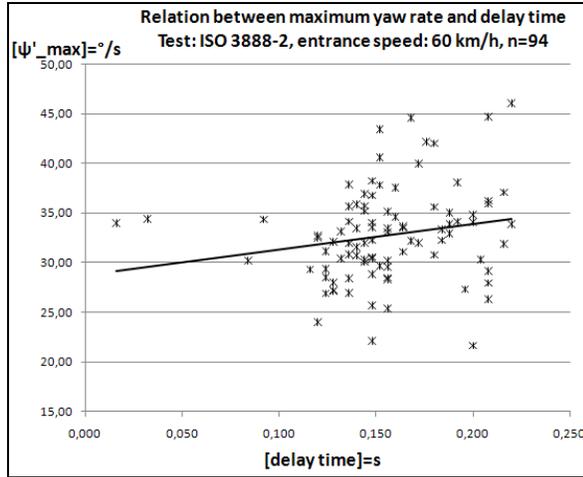


Figure 13: Relation between the maximum yaw rate and delay time at ISO 3888-2

The correlation of the maximum yaw rate and the delay time (See Figure 13) supports the assumption, that a high delay time negatively affects the controllability and consequently the safety of the vehicle.

Combined Brake- and Evade Test

With the combined brake and evade test, the vehicle reaction during a simultaneous brake and evade maneuver gets analyzed.

Therefore, the vehicle drives into the start lane with a constant speed of 70 km/h. After passing the start lane, the driver starts a full braking and evading maneuver (See Figure 14).

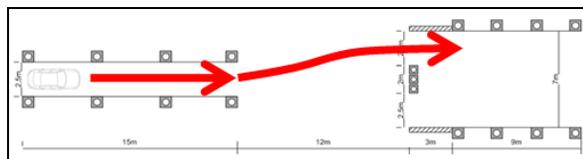


Figure 14: Combined brake- and evade test

Basing on the maximum combined lateral and longitudinal acceleration, the safety assessment takes place. Therefore, the maximum combined acceleration of the filtered signal gets calculated (Equation 6).

$$a_{\text{Combined}} = \max(\sqrt{a_{x_i}^2 + a_{y_i}^2}) \quad (6).$$

Thereby the traction is mainly affected by the tire and road conditions, as well as by the traction control systems. Thus, vehicles without ABS brake system (See Figure 15, (triangle)) have lower traction during the braking maneuver. Lower vehicles (quadrates) and serial vehicles (rhomb) do not differ significantly. The maximum combined mean acceleration of both types is nearby 10 m/s².

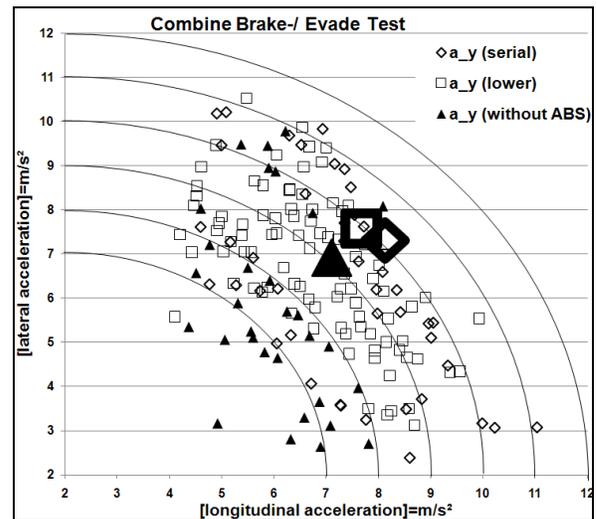


Figure 15: Maximum combined longitudinal and lateral acceleration at the brake- evade test with an entrance speed of 70 km/h.

μ-split Brake Test

The brake test on surfaces with split coefficient of friction (μ-split) was originally destined as an open loop maneuver. Within the study, only few drivers hold the steering wheel in position. Through this, the mean deceleration in a one-second interval is the relevant assessment criteria regarding the vehicle safety. The mean deceleration mainly depends on the tires and on the quality of the ABS-controller (See Figure 16).

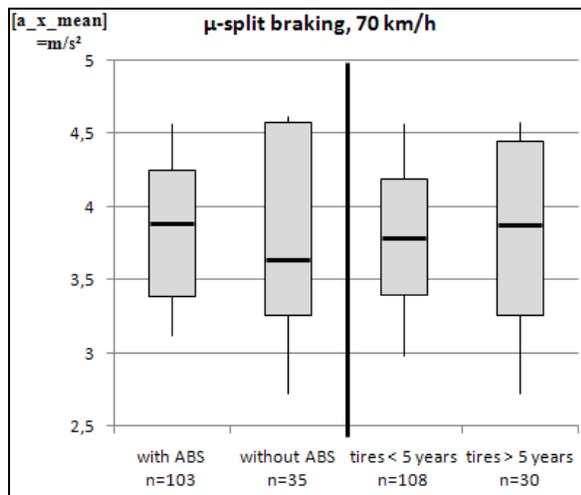


Figure 16: Equation of mean acceleration at braking on a straight μ -split track with an entrance speed of 70 km/h

The modifications of the track width affect the scrub radius. Thus, the braking behavior on μ -split surfaces changes. This behavior is represented by higher steering forces and it is an integral part of outstanding tests.

Within the tests, modified vehicles had a significant lower mean deceleration (See Figure 17).

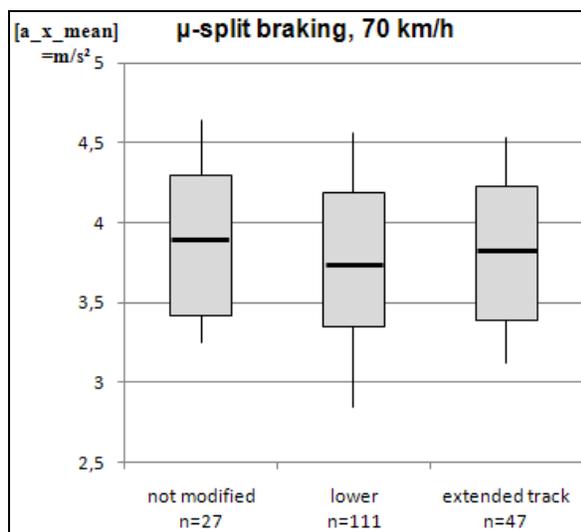


Figure 17: Equation of mean acceleration at braking on a straight μ -split track with an entrance speed of 70 km/h

The changed parameters of the chassis suspension system can possibly influence the effectiveness of the ABS and ESC system at this.

CONCLUSION

The test layout of the field study with modified vehicles is proved to be applicable to identify safety relevant states of driving. Particularly with regard to vertical stimulation, differences in the controllability are identified.

The driver's influence hindered the verification of assumptions in some tests. The results of the fields study offer a useful basis for hypothesis and resultant further test layouts for oncoming studies with reference vehicles and by using simulation programs.

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- [20] Mitschke, Wallentowitz: „*Dynamik der Kraftfahrzeuge*“. Springer, 2004, p. 282-284.