# Compatible Measuring Systems – Synchronous Measuring of Different Driving Dynamics Tasks

In the past, individual suppliers were only able to cover partial spectrums of the technology required to determine all the relevant characteristics for evaluating vehicle dynamics. Customers had to make their own selections of the requisite sensors and measuring systems as well as performing installations, corrections or the interconnection of the systems themselves. Aiming to offer turnkey solutions, five companies joined forces in 2007 by founding the Driveability Testing Alliance (DTA). The central data acquisition and analysis system is one of the DTA's core competencies. It is the first system enabling the synchronous acquisition of data from various measuring systems, which now – for the first time as well – are compatible, as proven by an initial vehicle dynamics project.

## 1 Introduction

With Kistler Instrumente AG joining in 2007, the Driveability Testing Alliance (DTA) now comprises five companies (Corrsys-Datron, Dewetron, GeneSys, Kistler and TÜV SÜD Automotive) who have joined in the DTA's collaborative effort of providing customers with turnkey solutions for measuring technology - from individual to complete systems - for evaluating characteristics relevant to driving dynamics. DTA sensors acquire the external forces and moments acting on the vehicle by means of measuring wheels, all movements and angle positions of the wheels and the vehicle body by means of potentiometric and optical sensors as well as a fiber-optics inertial measuring system, and deliver the DGPS-supported vehicle position during each vehicle maneuver. The centerpiece of the DTA components is the central data acquisition and analysis system. In the vehicle project presented in this article it was used to configure over 230 measuring channels, with totally synchronized logging of the signals.

To this day, incompatibilities of the measuring systems frequently cause valuable development time to be lost due to the need for complex adaptations and synchronization of the various measuring systems.

At the end of 2007, the DTA decided to set up a measuring project of its own. On the one hand, the project aimed to document that complex measuring configurations and system structures can basically be simplified by creating standardized interfaces and data formats and, on the other – after the performance of select vehicle maneuvers - to provide answers to the following questions:

- What are the performance capabilities of the DTA-developed sensors and systems in complex interactions?
- What results can be derived from the vehicle measurements for the DTA and for customers?
- What benefits does a customer gain by operating a well functioning, well coordinated total system?
- Are the measured results comparable to textbook data?

For the measurements of select vehicle maneuvers, the driving dynamics course of Robert Bosch GmbH's Proving Ground in Boxberg was selected, and for data acquisition of load populations, the Nürburgring-Nordschleife.

A vehicle was procured and included in the fleet of TÜV SÜD Automotive, allowing it to be used for new and evolutionary tasks as well.

## 2 Preparation of the Test Vehicle

In addition to chassis development, TÜV SÜD Automotive's core competencies include the analysis of chassis and driving dynamics characteristics. TÜV SÜD

**Figure 1:** Exterior view of the measuring instrumentation installed on the vehicle

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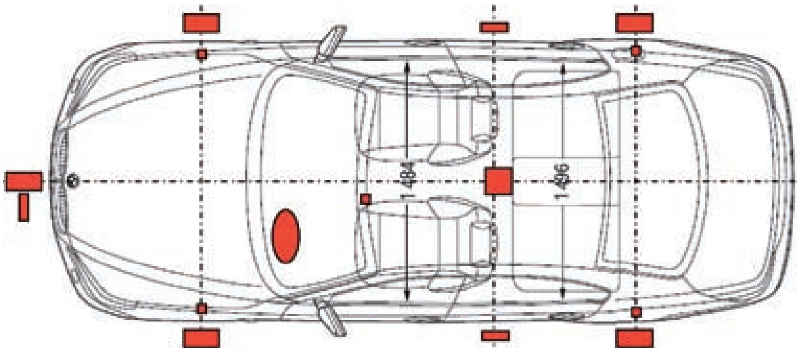

**Figure 2:** Geometric configuration of the sensors on the vehicle

equipped the vehicle with measuring technology and performed the test drives for the alliance partners.

While performing the connections for the various measuring instrumentations, **Figure 1**, particular attention was paid to laying the cables and fastening the individual components in a professional manner. Loose cables were to be avoided, and all connections to be marked and documented. All cables will remain in the vehicle after completion of the test series, allowing the entire system to be taken into operation and made functional again within a few days, even if the sensors were removed and used for other purposes.

All cables were laid by a team of application engineers from each of the partner firms.

## 3 Instrumentation Installed

The following measuring instrumentation for the test vehicle was provided by the alliance partners:

- Correvit S-350 Sensor: slip-free longitudinal and transversal dynamics with calculation of the vehicle's attitude angle [1]
- Correvit SFII Sensor: slip-free measurement of longitudinal and transversal dynamics with calculation of tire slip angle [1]
- HF-500C Sensor: height measurement at 3 vehicle positions with calculation of roll and pitch angle [1]
- RV-4 Sensor: mechanical wheel vector determination through simultaneous calculation of wheel travel in x-, y- and z-directions as well as toe and camber angle [1]
- MSW/S Sensor: measurement steering wheel (steering speed, torque and angle) [1] pedal force sensor [1]
- GPS/Inertial System ADMA: (Automotive Dynamic Motion Analyzer) [2] vehicle acceleration, vehicle speed, vehicle angle and vehicle position, x, y, z turning rates and angles (pitch, roll, yaw and attitude angles)
- Measuring wheel Roadyn P650 System 2000: piezoelectric measurement of wheel forces and moments as well as wheel turning angle [3]
- Acceleration sensor PiezoStar: measurement of 3-axial hub carrier acceleration [3]
- Acceleration sensor K-BEAM: measurement of tri-axial acceleration at the driver's seat rail [3]
- T³M temperature sensor: measurements of temperature in the tire tread [4].

The measurement set-up was complemented by additional control cable travel sensors positioned parallel to the suspension strut. The vehicle CAN bus data (e.g. vehicle speed, longitudinal acceleration or accelerator pedal angle) was picked up and logged. Due to the parallel logging of rough sensor data and the values derived from this data the engineers recorded a total of 234 measuring channels in the central data acquisition system [5] in parallel.

While laying the cables for the instrumentations and during the mechanical/electrical start-up, the alliance partners gathered valuable findings, which they are archiving and keeping available in a lessons-learned log for the evolution of the measuring systems. To the DTA , the realization of this vehicle project within the available time frame of only six weeks posed a huge challenge and certainly proved to be a profitable learning process for both manufacturers and customers.

For measuring pitch and roll angle, three optical height sensors (positioned at the side and at the front), which measure the distance between the road surface and the vehicle, are used. The measuring accuracy of the sensor is significantly determined by the geometric configuration of the sensors on the vehicle. In this context the rule of thumb applies that the greater the distance between the sensors, the higher the measuring accuracy.

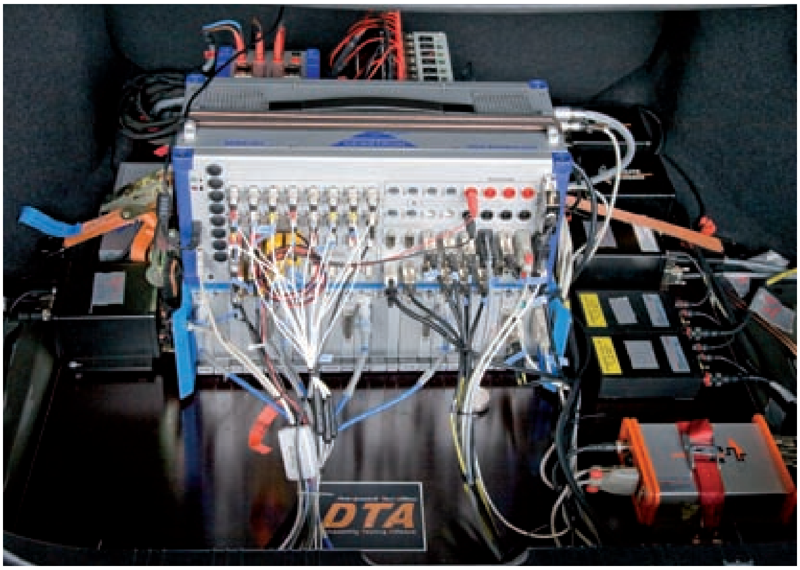

**Figure 3:** Data acquisition system with signal input connections (analog, digital, CAN, Ethernet, video)

**Table 1:** Excerpt from measuring positions list

| Zeichen | Messstelle | Kanal-Name | Messgerät | Signalart | Polarität | Einheit | Messbereich | Auflösung |
|---|---|---|---|---|---|---|---|---|
| δLenk | Lenkrad-winkel | aSter-MSW | Mess-lenkrad CDS | A oder CAN | Links-kurve | Grad | -1110/ 1110 | 0,05° |
| ay | Fzg.-Quer-beschl. | Accel_ Hor_Y | Kreisel-plattform GeneSys | CAN | Nach links | g | +/- 2,5 | |
| $F_{zVR}$ | Aufst.-kraft Rad VR | FZMRVR | Messrad P650 Kistler | | Kraft nach oben | kN | +/- 45 kN | |
| TVLa | VL_a | TAMRVL | $T^3M$ | A | | °C | -40 – 200°C | |

The positions of the sensors mounted to the exterior of the vehicle must be measured with exact geometric accuracy in order to (for example) consider the position of the sensors in relation to the vehicle's center of gravity (CG) in the correction calculations like the attitude angle with mathematical accuracy. **Figure 2** shows the configuration of the individual sensors on the vehicle. The position of the vehicle's center of gravity with completely installed measuring instrumentation was performed on a professional pendulum device, which, in addition to the CG position in x, y and z direction, determines the moments of inertia around the longitudinal, transverse and vertical (yaw) axis. Knowing the vehicle mass, moment of inertia and wheelbase, the agility factor of a vehicle can thus be calculated.

To determine the vehicle's attitude angle, the existing measuring equipment offers two options: For one, the attitude angle can be directly derived from the inertial system and for the other, the calculation can be performed from the signals of an optical biaxial speed sensor by including the yaw rate (turning angle around the vertical axis of the vehicle per unit of time) from the inertial measuring system.

The inertial measuring system firmly mounted in the vehicle's interior cannot be positioned precisely in the vehicle's center of gravity either; hence the position adjustments must be mathematically considered for a correct output of measurements.

Table 1 shows an excerpt from a measurements list with a total of 234 measuring channels, which considers the polarities according to DIN 70000.

Using the software implemented in the Dewe501 central data acquisition system, the measuring channels can be configured according to the established rules. This applies to the scaling of the various data and the selection of the measuring range. At the same time, required links between measuring channels can be performed with mathematical operations as needed. Other possible features are sensor support by the measuring amplifier and TEDS functionality of individual modules.

To evaluate the signal quality of the logged measurements, the synchronicity of all data is of particular importance. In daily, conventional measuring practice, the measurements made by different sensors and measuring systems can usually be correlated only with significant time tolerances, which requires considerable time.

In the data acquisition unit shown in **Figure 3**, a high-precision, quartz-stabilized system cycle with a frequency of 80 MHz and an edge accuracy of 2 nanoseconds (10-9 s) is generated, which is used to synchronize all measurement signals and to provide them with a real-time stamp. In the database that has been implemented, the DTA stores all information together with the corresponding time data. Due to the high precision of the time cycle and the synchronization via dedicated hardware lines, this is real-time data acquisition in this case.

The internal system cycle can – additionally – be coupled in phase with an external cycle signal in order to (for example) make fully synchronous measurements via the pps signal of a GPS satellite. This is necessary in the case of simultaneous measurements of several vehicles.

With the technology created, all the parties involved in the project were able to reduce complex post-processing times of the measuring signals by up to 70% and to improve the quality of the measurements by a factor 5 to 10. A trusting collaboration between the development departments of the DTA partners was an essential prerequisite for this. The major benefit to potential users is the compatibility between all the measuring instruments used, starting with the hardware (including, among others things, plugs, cables, signal levels), the incorporation of all the different data protocols and the ability to synchronize all these elements.

## 4 Driving Dynamics Tests – Boxberg Proving Grounds

On the driving dynamics course of the Boxberg Proving Grounds, the DTA performed a number of standardized drive tests. These significant vehicle maneuvers provide information on a vehicle's handling characteristics and are indispensable for its development and set-up. Conclusive characteristics, among others, include the self-steering effect (steady-state circular test) or the transfer characteristics (step steering input and sinus test).

Specifically, the following vehicle maneuvers were performed:

- ISO Lane Change Test (ISO 3888-1)
- VDA Obstacle Avoidance Test (ISO 3888-2)
- Steady-state Circular Test (DIN ISO 4138)
- Power-off Reaction of a Vehicle in Turn (ISO 9816)
- Braking in a Turn (ISO 7975)
- Step Steering Input and Sinus Test with Steering Robot (ISO 7401 and ISO 13674).

In the interest of comparability, standards specify detailed test conditions – as well as the test procedures and test analyses. Only if the conditions specified by the standards are complied with can vehicles of different makes be compared with each other, or development stages evaluated internally.

**Figure 4:** Vehicle maneuvers: VDA obstacle avoidance test

### 4.1 VDA Obstacle Avoidance Test

In its original form, the VDA obstacle avoidance test – also known as moose or elk test – had been introduced in order to demonstrate the tipping stability of vehicles. However, the test conditions allowed the driver many degrees of freedom during the performance of the tests, which meant that due to the driver's influence the test did not produce any objective and reproducible results.

The VDA revised the obstacle avoidance test, and the course – measuring a total length of 61 m – is strictly specified. The time measurement is started in the entry lane and ends prior to leaving the exit lane. At the same time, the accelerator pedal is released in the entry lane so that the vehicle is moved through the course in power-off (deceleration) mode. This corresponds to the typical behavior of drivers. **Figure 4** shows the test vehicle upon leaving the entry lane before entering the obstacle avoidance lane.

During the test, no traffic cones may be hit. Otherwise the test is not valid. The entry speed is increased incrementally. The tests are driven with and without ESP (electronic stability program). In the case of the test vehicle, the maximum entry speed that could be driven was approx. 70 kph.

The relevant metrics for the VDA obstacle avoidance test are:

- Vehicle longitudinal and transversal speed
- Steering wheel angle and torque
- 3-axial wheel forces and moments
- Toe and camber angle as well as 3-axial wheel travel
- Vehicle attitude angle
- Slip angle
- Pitch, roll, yaw and attitude angle
- Longitudinal, transversal and yaw acceleration

The yaw angle in **Figure 5** that is present already when the vehicle enters the first lane can be explained by the special configuration of the pre-marked VDA obstacle avoidance test: the acceleration path has an angle of approx. 10° to the direction of the entry lane so that the steering correction, which naturally manifests itself as a roll angle, must be performed immediately before entering the lane. During the first directional change, the transversal acceleration is still almost in phase with the steering angle; later, a significant phase lag of transversal acceleration and roll angle occurs. Also, the delayed build-up of the vehicle's attitude angle is notable, which can be explained by the inertia of the vehicle mass.

According to [6], the VDA obstacle avoidance test can only produce limited conclusions about the tipping stability of vehicles. Typically, the so-called "fish-hook test" is performed, in which the criterion of tipping is met when two wheels have tipped up simultaneously by at least 50 mm.

### 4.2 Steady-state Circular Test

The steady-state circular test is an open-loop test, driven according to the methods of constant radius, constant steering wheel turning angle or constant speed. The tests are performed with constant transverse accelerations in standardized steps all the way up to the driving dynamics limits. During the steady-state test phase, the steering wheel turning angle and the accelerator pedal position must be kept constant over a period of time, which is specified as well. The signal courses (including, among others, the steering angle, attitude angle, roll angle, and toe and camber angle) are typically plotted via the transversal acceleration. In **Figure 6** the steering wheel angle requirement is presented over the transversal acceleration.

The course of the steering wheel turning angle over the increasing transversal acceleration is an important evaluation criterion for the self-steering behavior of the vehicle. Its increase is an indication of understeer. For reasons of vehicle sta-

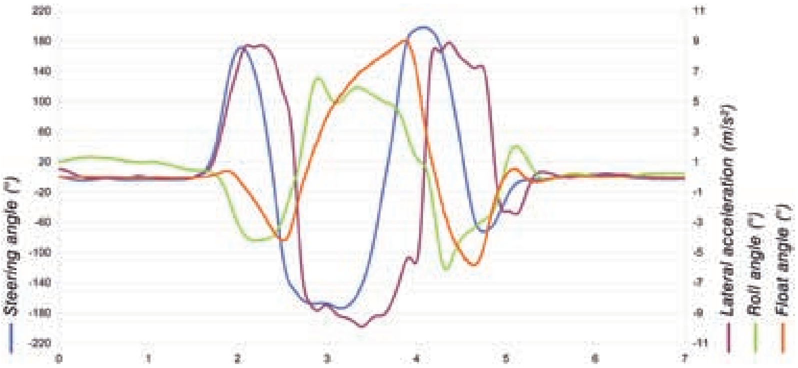

**Figure 5:** Significant signal courses as a function over time

bility and the subjective perception of safety of the vehicle occupants, developers normally strive to achieve an understeering to neutral self-steering behavior. When the limit range of driving dynamics is reached, this is indicated by a heavily increasing steering angle requirement. This is typically accompanied by a heavy decrease of steering wheel torque.

According to [7], the self-steering gradient > 0 characterizes understeering behavior = 0 a neutral behavior of the vehicle. Oversteering behavior is practically non-existent any more in modern vehicle development. However, it is certainly a question of vehicle set-up philosophy to what extent the gradient of yaw speed and steering angle approaches the critical speed, and the vehicle responds most sensitively to steering inputs in the process. In this context, descriptive terms like “driving pleasure” or “good-natured handling” can be encountered.

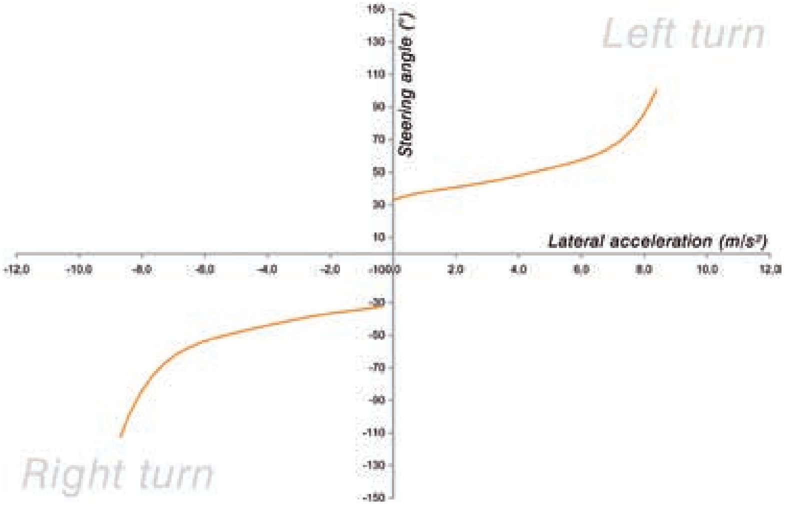

**Figure 6:** Steering wheel turning angle $\delta_H = f(a_{quer})$

## 5 Outlook

With its basic objective of simplifying complex measuring set-ups with highly varied measuring systems by different manufacturers, the Driveability Testing Alliance, DTA, is pursuing an ambitious goal, which can be expected to find wide approval in vehicle and component development. The required compatibility is an indispensable prerequisite for future cost reductions in the area of testing. Feasibility was basically demonstrated in a series of standardized tests of driving dynamics investigations performed on vehicles as well as by the data acquisition of a load population for the Nürburgring Nordschleife for two core areas of vehicle development. The test results presented in this text represent only a selection of the existing data pool, which could not be completely analyzed and presented within the short time frame available.

For the time being, the DTA will be the central point of contact for customer inquiries regarding vehicle dynamics measuring systems. In case of a respective intensity of such inquiries, a business structure independent of the alliance companies may be considered.

In particular, the pending complete presentation of the results of the measurements and their comparison with the contents of classic textbooks of vehicle dynamics is therefore an exciting prospect. Training events, customer consulting support and services thus reach a completely new dimension, delivered as comprehensively as this for the first time by the DTA.

## References

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