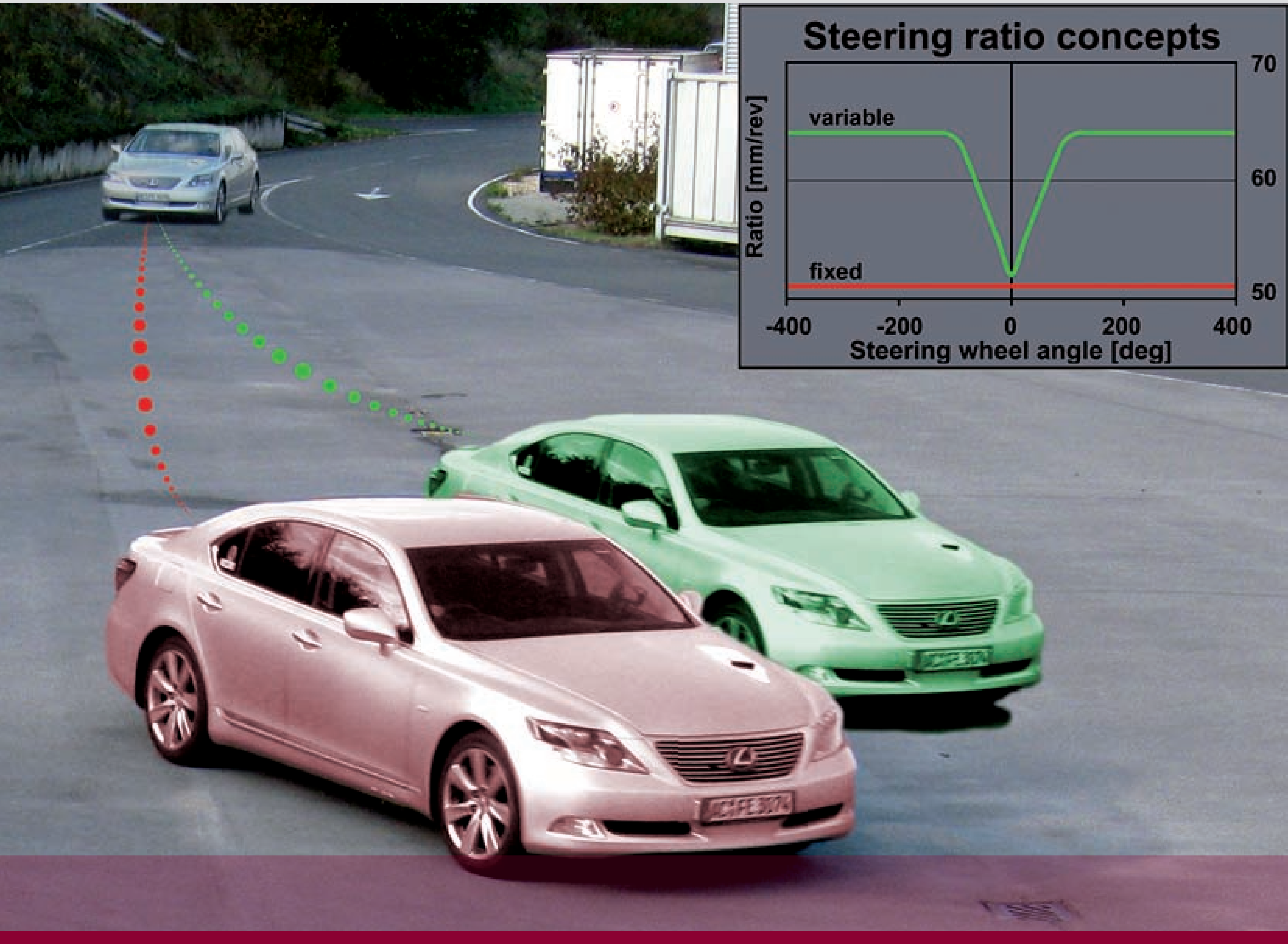

New Test Procedures for Handling of Vehicles with Variable Ratio Steering Systems

Vehicle handling tests have been standardised which makes it possible to compare vehicles for several items, such as understeer level. FEV uses some of these tests to establish scatter bands for all vehicle classes. The introduction of steering systems without a fixed ratio makes that the results of these tests are no longer valid for general vehicle comparison. Therefore a method was worked out which makes the procedures fit for future steering systems as well as the existing ones.

1 Introduction

Test procedures that describe objective tests for vehicle handling exist for more than 50 years. Many tests are developed by vehicle OEM's and several have been standardised by VDA, ISO and other organisations. The results from standardised tests generally provide no general rating or ranking but are used to quantify a certain behaviour and for comparison between vehicles. This is possible, because of the standardisation, the test conditions are the same for all tests performed according to this procedure. FEV, as a player on the market for engineering services in the field of chassis tuning, also uses a number of these standards to perform benchmark activities and for the establishment of scatter bands for vehicle handling.

With the introduction of variable steering systems there are several reasons why the test procedures and also the results obtained with them are no longer complete.

- Steering gears with mechanical variable ratio deliver different outcome for different steering angles
- Steering gears with speed dependant ratio deliver different outcome for different operation speeds.

The obtained results still give information about the perceived characteristic by the driver but no longer give information about the basic chassis characteristic of the vehicle.

In this investigation this is further analysed for two important characteristics: understeer gradient and directness, derived from the following ISO tests:

- ISO 4138 Steady state circular behaviour [1]
- ISO 7401 Lateral transient response test methods [2]
- ISO 8726 Pseudo Random steering response test [3]

Proposals for improvement, as used by FEV, are given.

2 Steering Systems

In this chapter two steering systems will be discussed, both for front axle steering. The fact that four-wheel steering also affects the investigated characteristics is recognised but these systems are not part of the investigation.

2.1 Variable rack systems

Traditionally steering systems consist of a steering gear with a fixed ratio. Although variable rack solutions exist for many years, until recently the variation took place for larger steering angles, influencing the parking characteristic. Both, less direct and more direct solutions for larger steering angles are known, the first for lowering the forces that have to be applied by the driver or the assist system and the second for lowering the amount of turning, which can only be used in systems that have sufficient assistance to overcome the higher forces that come with this application.

New are steering gears with a variable rack that provide more agility due to more direct steering ratio already after a few degrees of steering wheel rotation [Opel Corsa, Mercedes Direktlenkung], **Figure 1**.

These gears have in common that they influence the directness in the normal operation condition and therefore test results of the mentioned tests depending on the actual test conditions.

2.2 Active front steering (AFS)

This system basically decouples the steering wheel input of the driver from the turning of the wheels. Typically in normal driving conditions the system is used to create a speed dependant variable steering ratio where the directness is

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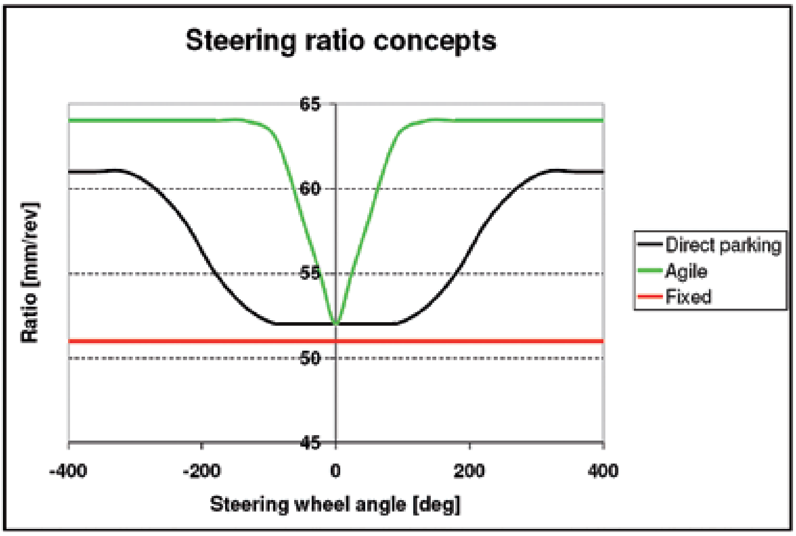

Figure 1: Variable rack concepts

increased for low speed and decreased for high speeds [Toyota, BMW]. In this study only this functionality has been investigated. With this functionality it is clear that test results related to steering wheel angle are influenced by the vehicle speed.

3 Test procedures and important characteristics

3.1 Steady state circular behaviour (understeer gradient)

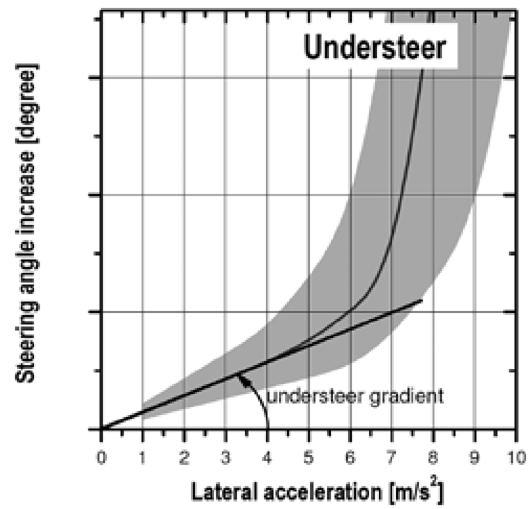

Figure 2: Understeer characteristic

The execution of this test is described in ISO 4138 and has the scope to describe handling properties during steady state cornering in the complete range of operation [1]. Basically the test is performed so that all combinations of vehicle speed, steering angle and cornering radius are covered. Since these are depending on each other, the test can be performed as constant radius test (which is commonly used), constant steering angle test or constant speed test, basically giving the same result.

From this test, several parameters and characteristics can be determined where the main focus is often on the understeer level of the vehicle. It is defined as the understeer gradient in degree/m/s² or degree/g. This gradient is positive for an understeering vehicle and negative for an oversteering vehicle. For a neutral vehicle it is zero and that means that for such a vehicle the circle can be driven with increasing speed without the need to increase the steering angle. It is also a parameter (or characteristic) that is often mentioned in publications (both scientific and popular magazines) since it gives information about the cornering power and the safety margin of a vehicle. The higher the understeer level, the lower the risk for over steer, which is considered dangerous for normal drivers.

Of course this is only an indication since the actual safety limit will be determined by the chassis tuning and tyre characteristics but it is generally considered to be a relevant parameter. At the same time a higher understeer level means a lower maximum cornering speed since the lateral tyre forces on front and rear axle become less balanced.

The driver will feel this understeer level on the steering wheel, when cornering forces increase, he has to put more steering angle. When reaching the limit he has to steer excessively and at the same time he will feel the front of car floating out of the corner.

Figure 2 shows the measured characteristic of a typical mid-size sedan it the scatter band that is obtained from measurements of a wide range of pas-

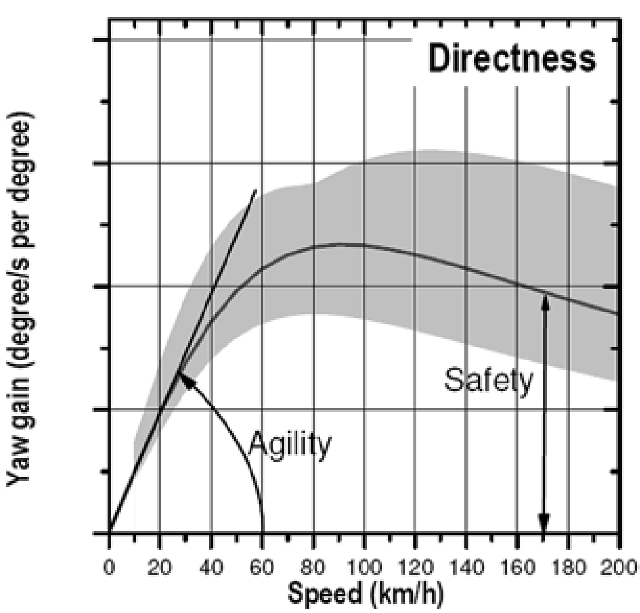

Figure 3: Typical yaw gain as function of speed

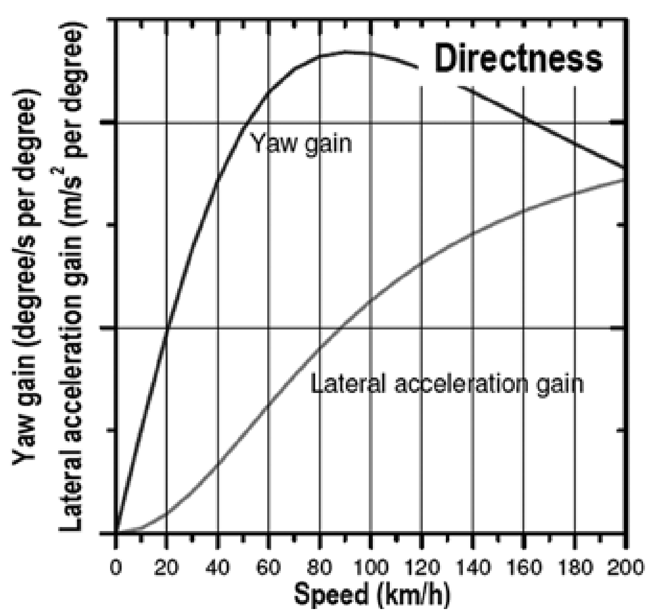

Figure 4: Yaw and lateral acceleration gain vs speed

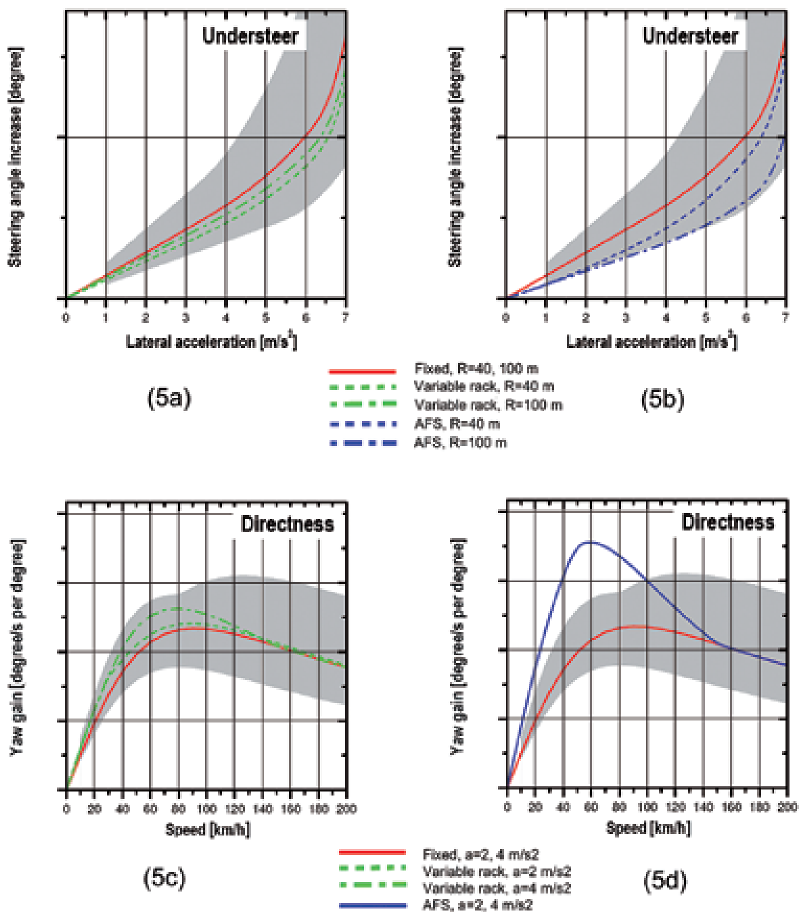

Figure 5: Effect of variable steering gears on understeer gradient

senger cars.

The tests have been performed as constant radius test. This means the vehicle is driven at low speed on a circle with constant radius and the speed is slowly increased. In typical –understeer- vehicles this means that when speed builds up and lateral acceleration increases, the steering angle has to be increased. The amount of steering is an indicator for the understeer level. Up to 4 m/s² there is a linear behaviour (understeer gradient), followed by a progressive understeer ending at the limit of adhesion.

The test procedure for constant radius tests gives a standard for the radius of 100 m but allows the usage of smaller radii, down to 30 m. The interesting thing is that the result as plotted in Figure 2 is independent of the curve radius and therefore test results from different radii can directly be compared to each other. Unfortunately this is no longer valid when steering ratios are not fixed, as will be shown in chapter 4.

3.2 Lateral transient behaviour (Directness)

The execution of this test is described in ISO 7401 [2] and also in ISO/TR 8726 [3]. The pseudo random test [3] is often used since it can be performed very well without using a steering robot. The scope of this test is to describe the transient behaviour of a vehicle while steering from straight ahead driving. This test results in parameters describing the steering behaviour in the linear range of operation (up to ≈ 4 m/s²) in the time or frequency domain. Many parameters can be obtained but often the focus is on an aspect also described as directness. The definition of directness is the amount of rotation per steering angle input (yaw rate gain in degree/s per degree) for 0 Hz. This parameter can be determined for different speeds, resulting in a diagram where yaw gain is plotted as a function of speed. **Figure 3** shows an example of a typical passenger car and the scatter band from a wide range of vehicles.

In this graph the first gradient is a rating for the manoeuvrability and agility of the vehicle. If there would be no understeer in the vehicle, this gradient would remain constant, resulting in a very high yaw gain at high speed and this is not desired for normal passenger cars. The digression and decrease of the yaw rate gain over speed is a function of the understeer level and this means the steering ratio and wheel suspension need to be tuned to deliver a characteristic that fits to the vehicle both in low and high speed.

To better describe directness, a second characteristic is introduced, lateral acceleration gain. Normally this characteristic is not used or shown in publications since it is (was) completely based on the yaw gain (lateral acceleration$_{steady\text{-}state}$ = yawrate$_{steady\text{-}state}$*vehicle speed).

The two characteristics together describe what the driver feels when he is turning the steering wheel. At speeds up to 100 km/h the turning (yaw gain) will be mostly responsible for the response feeling where at high speeds the lateral acceleration gain becomes more important, **Figure 4**.

4 Effects of variable steering gears

4.1 Mechanical variable ratio

4.1.1 Understeer gradient

Typical steering angles for the circle test range from 20 degrees on 100 m radius to 100 degrees on 40 m radius. This means it is completely in the range where the ratio of variable rack systems is changing, Figure 1.

Figure 5a shows simulation results of a vehicle with standard and variable rack on 2 different radii.

In this graph, it is clear that the variable rack results in less understeer because of the more direct steering in this condition and that the effect becomes stronger for a smaller circle radius. Also the result is depending on the test condition (circle radius). Due to this fact, comparisons between vehicles with variable ratio measured on different radii are not valid.

4.1.2 Directness

For directness, tests are performed typically at a fixed steering angle that relates

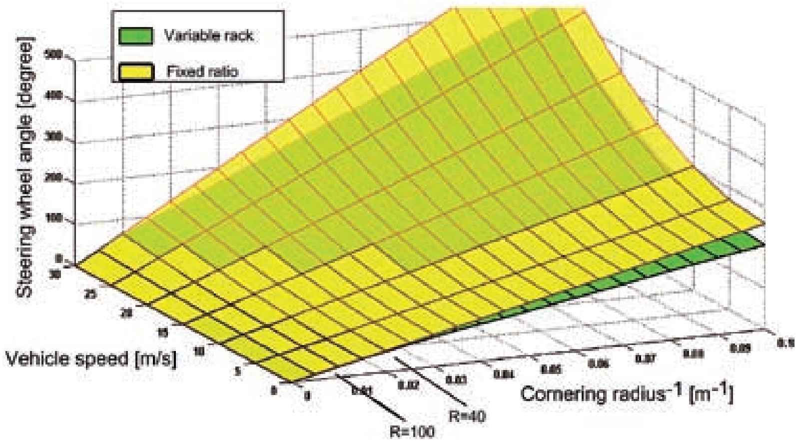

Figure 6: 3D surface for understeer behaviour

to a constant lateral acceleration. From Figure 4 (lateral acceleration gain) it can be derived that with increasing speed, a smaller steering angle relates to this constant acceleration level. Since the ratio is depending on actual steering angle, the ratio will become less direct for higher speeds.

Where normally the result is independent on the chosen lateral acceleration (between 1 and 4 m/s²), with these variable steering gears the result is depending on the amplitude. **Figure 5c** shows simulation results of the vehicle with fixed ratio and variable ratio but now for two different amplitude levels, related to 2 and 4 m/s². The first conclusion from this graph is that with the variable rack, the aim is achieved to increase the agility while maintaining the safety at high speed.

The second thing however is the fact that the result for the variable ratio in the mid-speed range is depending on the amplitude. From a driver's point of view this is a good solution since agility normally is required in a more sporty driving style with lateral accelerations above 3 m/s². From an objective measurement point of view however it means that different results can be obtained with the same test procedure.

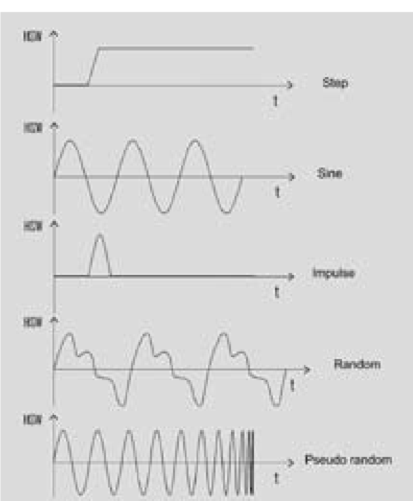

Figure 7: Input signals for determining directness

4.2 AFS speed dependant ratio

4.2.1 Understeer gradient

In the circle test the results are influenced based on the fact that on circles with larger radii the speed range is higher and therefore the ratio is less direct. This means that even for a neutral vehicle the steering angle should be increased and the larger the radius, the more increase. This increase feels like an understeer tendency and this is also what the measurement looks like. In **Figure 5b** a plot of simulation results shows how the steering angle increase is depending on the circle radius.

4.2.2 Directness

Assuming only speed dependant ratio, no influence of amplitude is expected. The directness measured in the traditional way will give good results, both for 2 and 4 m/s². But due to the high degree of freedom of this steering system tuning, the results will no longer fit in the existing scatter band based on fixed ratio steering gears, **Figure 5d**.

5 Implication for the discussed test procedures

5.1 Circle test

The weak point in the circle test is the fact that the circle radius is not fixed. One solution could be to agree to always use the recommended 100 m but this has two disadvantages:

- Not all test tracks allow this radius
- It only describes the behaviour for one radius.

A second solution would be to use another method, for instance the constant speed test. This however suffers from the same problem with speed dependant ratio.

The solution proposed and introduced by FEV is to perform the test for a number of radii.

To make a complete characterisation of the steering during steady state cornering, the complete area of possible (or normally used) speeds, lateral accelerations and circle radii should be measured and shown as a 3D surface as shown in **Figure 6**. The effort for this procedure however is very high.

A good compromise between cost and benefit offers the circular-course driving for two radii (40 and 100 m). An additional proposal is to decouple the actual understeer gradient at the steering wheel from that of the vehicle handling behaviour.

The decoupling can be achieved by measuring both the steering wheel and road wheel angle. Measuring road wheel angle however is not easy and also it is taking into account the kinematic and elastokinematic effects that in the end determine part of the understeer level. Therefore it was chosen to measure the displacement of the steering rack as second parameter beside the steering wheel angle.

With the known relation between rack displacement and wheel rotation, we derive a real understeer characteristic of the vehicle as if it had a fixed steering ratio.

For comparison, measurements from fixed ratio steering gears can be reworked if the ratio is known. Results from other radii should be valid also for 40 and 100 m.

5.2 Lateral transient behaviour

The weak points in these procedures are the assumption that the behaviour is linear in the range where the tyre characteristic is linear (up to ≈ 4 m/s^2). A solution would be to perform the test for the complete range of steering wheel angles but this again leads to an enormous amount of testing.

A compromise is to pick 2 important levels, corresponding to a steady state lateral acceleration of 2 and 4 m/s^2. For the determination of the directness characteristic, several steering inputs are allowed, **Figure 7**.

For each test the new approach is given:
- Step steer: both 2 and 4 m/s^2 should be measured
- Sine input: both 2 and 4 m/s^2 should be measured
- Pulse input: less suitable for non-linear systems
- Random input: less suitable for non-linear systems
- Pseudo random input: both 2 and 4 m/s^2 should be measured.

6 Conclusions and outlook

The examples of understeer gradient and directness show that current test methods do not allow a good comparison for vehicles with variable steering ratio. With the described changes to the test procedures these vehicles can be completely described and also be compared with other vehicles.

References

[1] ISO 4138:2004 Passenger cars – Steady-state circular driving behaviour – Open-loop test methods
[2] ISO 7401:2003 Road vehicles – Lateral transient response test methods – Open-loop test methods
[3] ISO/TR 8726:1988 Road vehicles – Transient open-loop response test method with pseudo-random steering input