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THE IMPACT OF NONLINEAR STEERING SYSTEMS ON OBJECTIVE AND SUBJECTIVE STEERING EVALUATION

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ABSTRACT – Traditionally, vehicle steering systems had a linear relation between steering wheel rotation and road wheel angle. Nonlinear steering racks arrived in the last decades of the 20th century with the aim to achieve better parking characteristics. In the current century, the development of variable steering ratios has become more and more important and not only for parking. The aim of these steering systems is to combine a low speed agility increase with safe high speed behaviour. Both mechanical solutions (variable rack) and mechatronic solutions (active front steering) have been implemented in production cars.

FEV has investigated the impact of these two approaches on the experienced steering behaviour.

Actual production vehicles with both systems have been tested to confirm the targeted improvement of agility whilst maintaining safety at high speed, including the feeling of linearity and transitional behaviour.

Secondly, the effect on objective test results was predicted using simulation models in which the different concepts were implemented. Here the advantage is that in this virtual vehicle several concepts and settings can be directly compared. For the system with the highest subjective impact (BMW 3 series), a series of objective tests was performed to confirm the simulation and subjective results.

The impact on expected test results is shown in relation to FEV's scatter bands which show the current state of technology of traditional systems on the market. Here it becomes clear that the active mechatronic solutions deliver characteristics that are not possible with the current traditional steering systems. The mechanical solutions do reach the desired agility increase, but deliver characteristics that still fit into the scatter bands.

Finally, the impact of these results in relation to standardized test methods such as ISO 7401 is discussed. Here it is concluded that these test methods need some modification or extension to properly describe the behaviour of vehicles equipped with these nonlinear steering systems.

TECHNICAL PAPER –

INTRODUCTION

Humans are used to linearity. Many laws of physics show what was already subjectively assumed: there is a linear relation between the input and output of many systems. Passenger cars behave in a linear way concerning many aspects regarding steering and handling. This is based on the fact that the tyre, as the most important component for transferring steering angle and force into vehicle behaviour, has linear characteristics up to a certain level of lateral acceleration.

With the introduction of power steering systems, the relation between steering angle and steering force started to lose its linearity, because they limit the steering forces to give a better comfort feeling to the driver. Good steering systems, however, still have a linear relation for the steering force in the range of small to medium steering angles.

The relation between steering angle and vehicle turning behaviour lost its linearity with the introduction of variable steering racks that were developed to give the driver a better comfort feeling during parking. This comfort improvement can be achieved by a reduction of the force (change to less direct) or by a reduction of the rotation angle (change to more direct), both for large steering angles. Depending on the boundary conditions, both systems exist in current cars.

Recently, however, even the linearity in normal driving conditions no longer exists in all cars. In the 21st century, car makers started to introduce steering gears with a nonlinear steering ratio. The aim of these systems is to improve the agility in the low to medium speed range – so as to give a more direct feeling to the driver – but without threatening the high speed safety condition that is typical for very direct steering systems.

This paper shows the results of the investigation on the impact of nonlinear steering systems: What does the driver experience? Does he miss the linearity feeling? What is the impact on objective testing? Do existing test procedures still give reliable and consistent results?

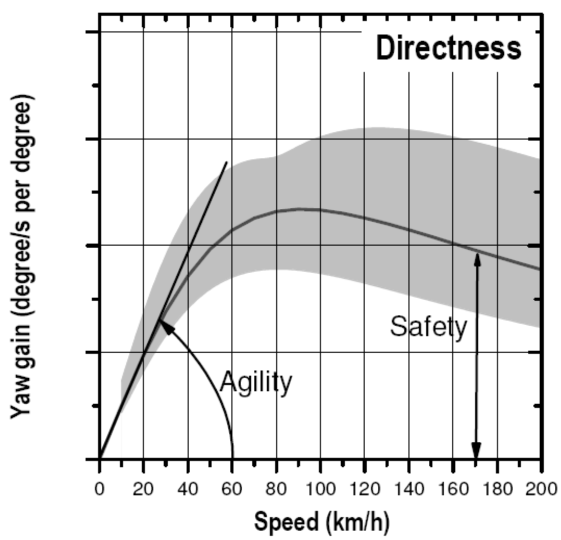

Figure 1: Traditional Relation Between Agility and High Speed Safety

STEERING SYSTEMS

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

Variable Rack Systems

Traditionally, steering systems consist of a steering gear with a fixed ratio. Although variable rack solutions have been in existence 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.
Relatively 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].

These gears have in common that they influence the directness in the normal operation condition and therefore the steering behaviour is depending on the actual operating conditions.

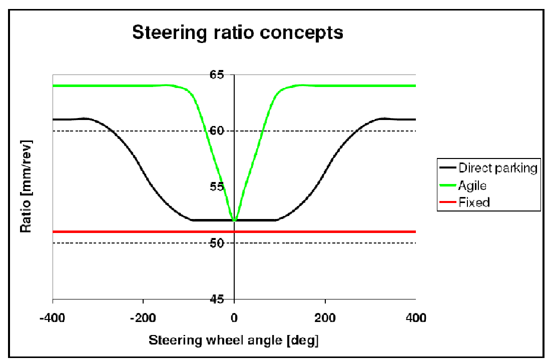

Figure 2: Variable Rack Concepts

Active Front Steering (AFS)

This system basically decouples the steering wheel input of the driver from the turning of the wheels by adding an electromotor to add or subtract a steering angle to the wheels based on the actual driving conditions. Typically, under normal driving conditions the system is used to create a speed dependent variable steering ratio where the directness is 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 steering behaviour is influenced by the vehicle speed.

SUBJECTIVE TESTING

Over the years, several cars with variable ratio steering systems have been tested at FEV (Toyota/Lexus, BMW, Mercedes and Opel). All cars were subjectively assessed by vehicle dynamics experts as well as 'normal' engineers, to gather feedback from typical drivers and experts on the experience with these systems.

Basically, the feedbacks were positive:

- The higher agility was appreciated by all drivers (although it was not recognised in all cars).
- The nonlinearity never appeared to be a problem or even a concern. All systems were judged as natural and linear.
- The speed dependency, even in case of large deviations from existing vehicles, is judged as natural and linear.
- The only negative comments came about the vehicles that have a very direct ratio during parking and manoeuvring: here some drivers were surprised when they had to make a quick turn at lower speeds; they actually put too much steering angle. This is not just related to the first time driving but even after more experience this seems to be a behaviour that is not easily learned.

SIMULATIONS

To investigate the influence of the two types of steering systems, simulations were performed with one vehicle and three types of steering systems: fixed ratio, variable rack and AFS. The vehicle model is that of a typical mid-size car which was modelled in Adams-car. The parameters for the steering gear are based on realistic proposals for this vehicle.

Several tests have been simulated, but in this paper only the steering response and understeer tests will be discussed. For the determination of the steering response, a frequency response test (with pseudo random input) is performed, whereas for the under steer gradient, the steady state cornering test was used.

Steering Response

The execution of this test is described in ISO 7401 (1) and also in ISO/TR 8726 (2). The pseudo random test (2) is often used, since it can be performed very well without using a steering robot. The objective 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/s^2) 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.

In Figure 3, the grey area shows the scatter band of typical speed dependent behaviour. The yaw gain is also depending on the virtual steering ratio during the test. The two steering concepts show very large differences, which can be best expressed in an analysis of directness vs. vehicle speed.

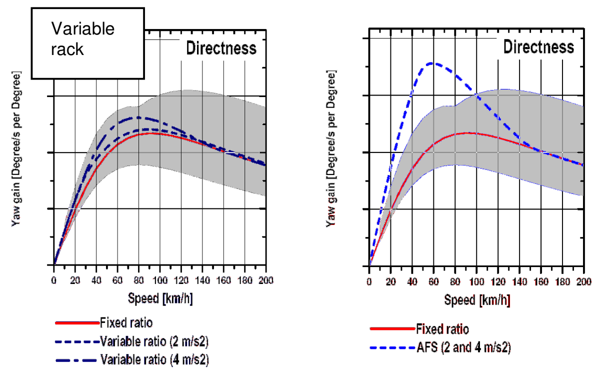

Figure 3: Influence of Variable Rack and AFS on Directness

The result of the analysis for the variable rack is shown in Figure 3 (left). While the yaw gain from 140 km/h remains on the original level (since the steering angles are small and the ratio is the same as the fixed rack), there is a clear increase in the low speed range. The increase depends, however, on the steering input level. The ISO test procedure allows a variation of the input level and both 2 and 4 m/s^2 lateral accelerations are possible but lead (contrarily to the fixed ratio rack) to different results.

The result of the analysis for the AFS is also shown in Figure 3 (right). While the yaw gain from 150 km/h remains on the original level (depending on the software parameters), there is a very strong increase in the low speed range. In this example, the result is independent of the steering amplitude. Again, this is a software tuning parameter. In actual vehicle applications, the result can be virtually anything, but an amplitude dependency seems a realistic solution.

Understeer Gradient

The execution of this test is described in ISO 4138. Its objective is 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, but the main focus is often on the understeer level of the vehicle. It is
defined as the understeer gradient in degree/m/s^2 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 4 shows the measured characteristic of a typical mid-size sedan it the scatter band that is obtained from measurements of a wide range of passenger cars.

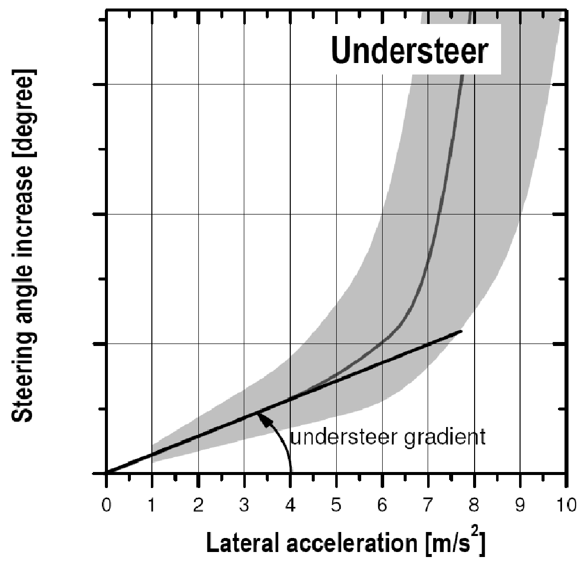

Figure 4: Typical under steer behaviour

The simulations 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/s^2 there is a linear behaviour (understeer gradient), followed by a progressive understeer ending at the limit of adhesion.

Figure 5 shows the results of the simulations. In both graphs, the red (solid) line shows the characteristic of the base vehicle, with a traditional steering gear with fixed ratio. What we see in the graph is that this result is valid for both 100m and 40m radius. This means that the result is independent of the radius on which was tested.

The left graph shows the effect of a variable rack solution. It is clear that the car seems less undertseering because the amount of steering increase is reduced by the more direct steering gear. The next thing is that there is a difference between the results for the 2 circle radii. The explanation for this is that for the 40m radius, higher steering wheel angles are required and this means a more direct steering ratio. Therefore the additional steering angle is further reduced, hence less understeer.

The right graph in figure 5 shows the effect of the mechatronic AFS solution. In this case we also see a more direct ratio and general less understeer. More interesting however is the influence of the circle radius. Here the explanation is that for the 40m radius, the speed will be lower to reach the same lateral acceleration. In this case this means a more direct steering ratio leading to smaller steering angles and a lower understeer gradient.

One must realise that although different levels of understeer are shown, the handling behaviour, related to the wheel angle, is the same in all cases. This means that the handling characteristic of the vehicle is not changed but to the driver it appears to be changed.

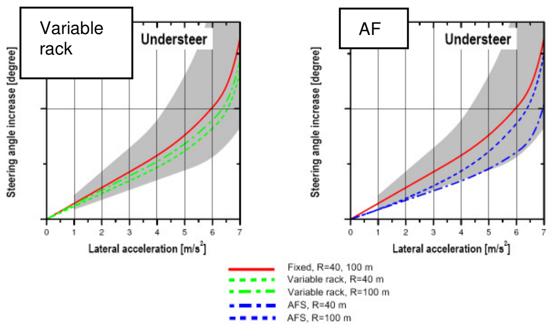

Figure 5: Influence of Variable Rack and AFS on Understeer Gradient

OBJECTIVE TESTS

In the subjective tests, the BMW system proved to have the most outspoken variable ratio. Therefore, this car was chosen for a series of objective tests. The tests were performed on the new ATC test track near Aachen. Many different tests have been performed, first of all for a better understanding of the system, but also to validate some of the simulation results. The most interesting result is that of the directness measurements. The yaw gain has been determined from several tests, including the ones mentioned above. In fact, the determined yaw gain was not consistent between all tests, but Figure 6 gives a presentation of the general result. Here the same trend as in the simulations is visible and, moreover, it is clear that the results obtained with this steering system are far beyond the possibilities that can be found in vehicles with traditional steering gears (the grey scatter band shows the results of many state-of-the-art vehicles measured at FEV in the last decade).
The results of the analysis regarding the understeer gradient are less impressive but also here, the tendency for different circle radii was recognised.

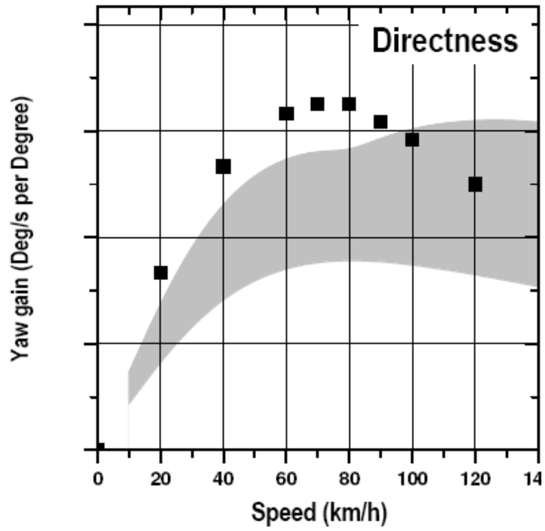

Figure 6: Directness of BMW 3-Series with AFS

Figure 7: BMW on ATC test track in Scatter Band

IMPACT ON TEST PROCEDURES

To fully perform a steady state circle test according to (1), all possible combinations of vehicle speed, cornering radius and lateral acceleration should be covered. To do this, an enormous effort is needed and also very large test areas are required. Therefore, typically a constant radius test will be performed. ISO recommends 100 m radius but others are allowed. In reality, different companies use different circle radii, mostly based on historical reasons. The understeer gradient that is measured on the different circles can be compared, if the steering system (and the rest of the vehicle) is linear. With nonlinear steering systems, this will no longer be the case. FEV recommends the use of 100 m as standard but to add a second radius for better comparison. 40 m radius is chosen, since it is possible on a wide range of test tracks and gives significant results compared to 100 m, both for mechanical (variable rack) and mechatronical (AFS) systems.

Most lateral response tests (2), (3), allow a band of lateral acceleration, as long as it is in the linear vehicle behaviour. Usually, this means between 2 and 4 m/s^2. This investigation shows that there can be a significant difference between these two values for nonlinear steering systems. Therefore, FEV proposes to perform all tests for both 2 and 4 m/s^2. Although this means more effort, it is necessary for a complete description of the steering behaviour and a solid comparison between vehicles.

SUMMARY

Nonlinear steering systems improve the sportiness, driving easiness and comfort for low speed manoeuvring. Although drivers are used to and like linearity, these steering systems are very well accepted.

The objective analysis of steering behaviour becomes more complicated with these systems, since commonly used procedures are no longer sufficient. FEV will extend their test procedures that are used for the establishment of scatter bands of state-of-the-art vehicles in such a way that even vehicles with nonlinear steering systems can be properly compared with other vehicles in their class.

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