Tyre dynamics, tyre as a vehicle component
Part 2.: Driver judgement of tyre handling characteristics

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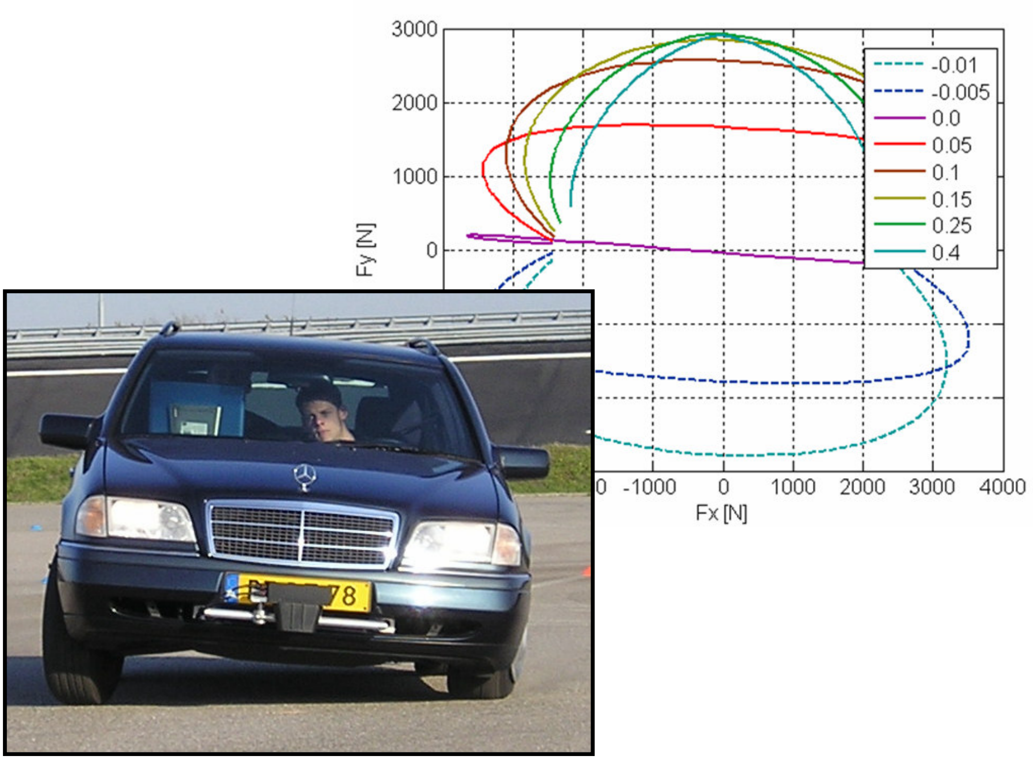

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1. Introduction.

There is no doubt that tyres have a strong impact on vehicle behaviour and on the driver assessment of vehicle performance. This relates to handling, perceived safety and controllability, the amount of effort required to react, course following and straight line stability, etc.

Several of these aspects are known to correlate to some extent with objective indicators such as gains, response times and alike, as obtained from open loop reference tests. But there is more, particularly in relation to the interface between steering system and the driver control and perceived feed-back, where these phenomena are still not well understood.

In this document, several studies from the past are discussed focusing on the influence of tyre design parameters on the driver assessment, where both open-loop and closed-loop results are considered. This results in an overview of the discriminating physical tyre parameters examined, the experimental approaches applied, and the output parameters (subjective and objective identifiers) describing the vehicle behaviour.

These studies start with variation in quantities such as tyre pressure, compound, age (effect of tyre wear), geometry whereas vehicle handling simulation studies deal with performance characteristics in terms of cornering stiffness, pneumatic trail, etc. Mathematical studies are suited for interpretation of vehicle handling performance in terms of tyre characteristics (e.g. Magic Formula model data). This means that, in order to use these studies for further investigating the impact of tyre characteristics on driver assessment, relationships between tyre design parameters and performance characteristics are required.

Using a simple simulation model, derived from and validated by realistic vehicle characteristic data, it appears that the complexity of such models (such as the single-track or two-track model) is not appropriate to study the sensitivity of the driver opinion on tyre performance in all its detail.

1.1. Driving task hierarchy

In order to understand the behaviour of a driver-vehicle system under normal or emergency conditions, the role of the tyre is of outmost importance. Tyres keep the vehicle on the road under extreme manoeuvring by the driver in response of unexpected situations, they assist the driver in predicting the performance of his vehicle under such conditions, they confirm him that he is still in control, they inform him about deviations from an intended path through the steering system, that means that they serve to preview and warn for danger ahead, etc. This means that tyres work out on the driver perception and response at different levels. These levels can be considered with reference to the categories of human behaviour and driving task hierarchy as distinguished by Donges [3] and depicted in fig. 1.

At the left of this figure, the classic hierarchy in behavioural categories is shown with distinction between **knowledge based behaviour** corresponding to the response to unfamiliar situations, **rule-based behaviour** corresponding to associative response based on selection of the most appropriate alternative according to earlier subjective experience, and **skill-based behaviour** which can be regarded as an automatic, unconscious reflex. Comparing this classification to the different driving task levels as shown in figure 1, tyres are mainly of relevance at the levels indicated as **guidance** and **stabilisation**. The dynamic status of the vehicle involves changes in the input data for the driver, a major part of which is effected by the tyres (steering feel, vibrations, noise, lateral motions, etc.). The driver responds partly at guidance level (such as corresponding to open loop control) and partly at stabilisation level (such as corresponding to closed loop control). The distinction between those two levels depends on the driver and his experience with similar traffic situations. At the lowest level, information is obtained through the dynamics of the vehicle, yielding a perceived friction level, road-wheel contact, road unevenness, resulting cornering and braking resistance on basis of which the driver has to decide, consciously or unconsciously, about safe versus unsafe conditions and the necessary measures to overcome the endangered circumstances. Anticipation of forthcoming situations will improve the driver's response, and his ability to avoid accidents.

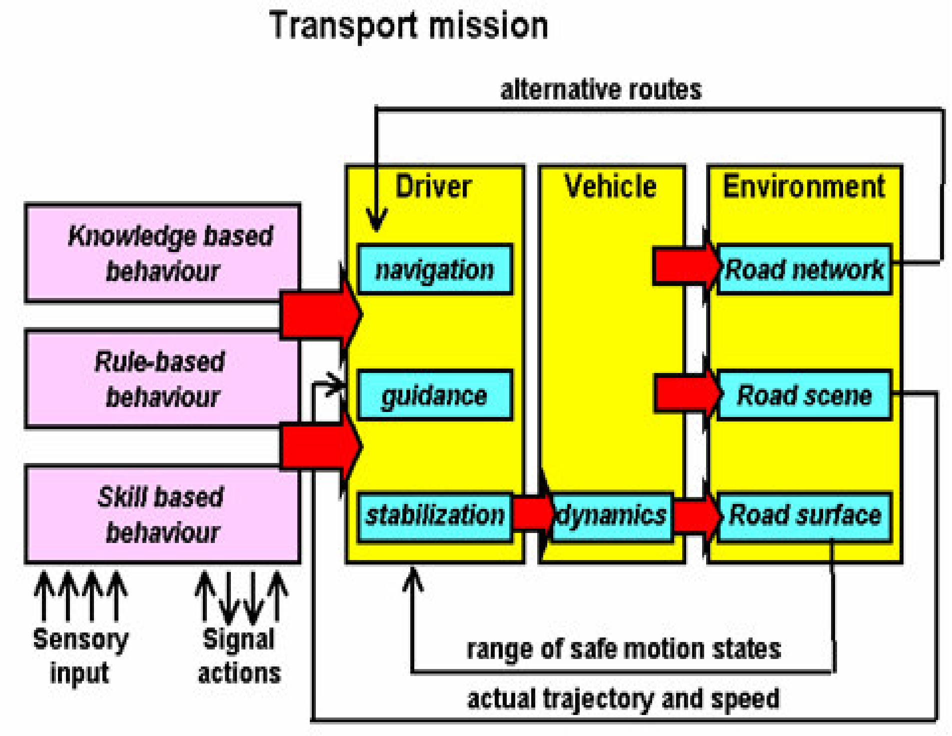

Figure 1.: Human behaviour and driving tasks [3]

1.2. Driver's action to emergency situations

Another schematic overview of the driver's actions to emergency situations has been given by Braun and Ihme and reported by Käppler and Godthelp in [6], see fig. 2. The

three “partners” in any arbitrary traffic situation indicated in the right part of figure 1, i.e. driver, vehicle and environment, are shown in figure 2 as contributors to an experienced level of risk. Such “latent risks” could be effected by poor driving behaviour (like excessive speed), a vehicle deficiency (e.g. low tyre pressure) or changes in the environment (slippery road, poor visibility, dense traffic,...). Reduced safety margins under typical adverse road- and weather conditions have been studied within the DRIVE project ROSES (ROad Safety Enhancement Systems), where not only single causes but also combinations of different hazards have been considered [13]. A sudden event may yield a sharp increase in risk level and, as a consequence, a reduced stabilising tolerance, that is a return to the original risk level. After some reaction time the driver may intervene correctly, he may intervene incorrectly (braking on an icy surface) or he may not respond or respond too late if the accident level has already been reached.
Again, it is clear that appropriate information that is based, to a large extent, on tyre performance would help the driver to anticipate risky situations (i.e. reduce the reaction time), whereas the driver-vehicle system performance is crucial to overcome emergency situations.

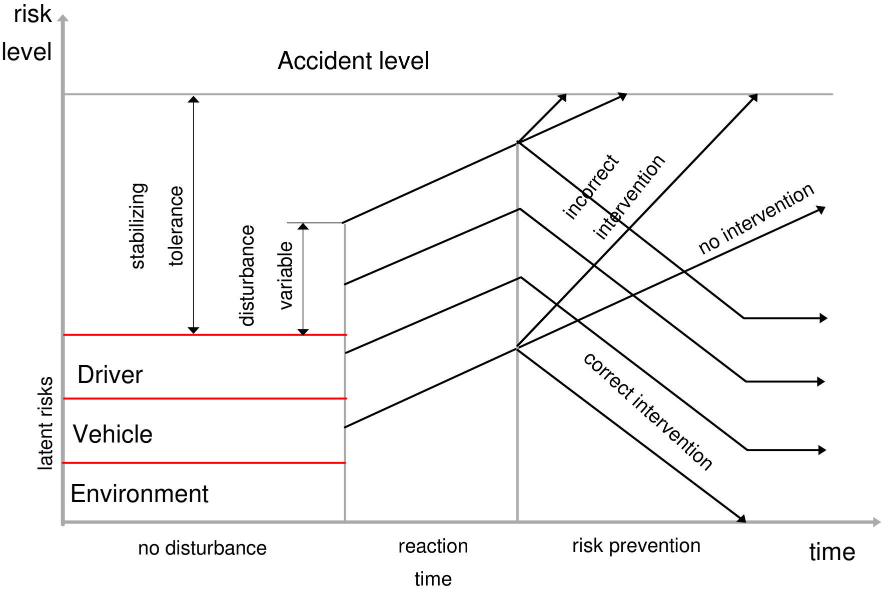

Figure 2.: Driver response to potentially dangerous situations [6]

1.3. Human judgement and automotive industry objectives

The approaches as outlined in the preceding subsections support the conclusions that the tyre-road interface characteristics affect vehicle handling qualities and constitute, through these, a critical factor in the risk reduction potential at critical situations. They contribute to the driver input and the driver’s ability to take appropriate corrective measure to avoid potential crash conditions. As an example one may think of the steering wheel torque feedback, which depends on the non-linear characteristics of tyres and suspension, and which may contribute to the subjective rating of the control behaviour. This example illustrates the interaction of tyre response with other vehicle subsystems, making it more difficult to obtain a clear understanding of the impact of tyre characteristics on driver judgement and control.

There is yet another more economic reason to look more closely into the driver assessment of tyre characteristics. In the automotive industry there is a strong desire for further improvement of the safety and handling qualities of vehicles, both under normal and extreme operational conditions. As a consequence of this development, vehicle manufacturers presently put increasing demands on the various parts of a vehicle (such as suspension and tyres) in order to guarantee the optimal vehicle handling and safety qualities as envisaged in the vehicle design. Since most of the verification of vehicle performance qualities is based on human judgement, a better understanding of the driver monitoring and assessment process will contribute to an improved vehicle-driver response and a more efficient and effective design process. In particular, this is true when the additional benefits of introducing advanced control concepts as part of new designs are considered, with the objective to improve or maintain the safety of the vehicle under a wide range of driving conditions. One may think of developments related to yaw moment control (ESP) and other slip-control systems to understand that the tyre road interface plays a dominant role here.

The success of critical automotive component design (either related to the tyre/suspension part, or to advanced vehicle control systems) is determined to a large extent by the integrated behaviour of the component-vehicle-driver system. When analysing these developments from an engineering, marketing or business point of view, considering the fact that basically, evaluations are subjective, business risks are implied for a manufacturer when investing in these developments. This situation may be relieved by expanding the knowledge about the human judgement of critical vehicle qualities. Research in the area of human assessment of vehicle performance may lead to a further understanding of the criteria of assessment of an experienced or inexperienced driver in his judgement of vehicle properties.

These considerations lead to the following objectives for this part of module 11 of VERT:

- to contribute in understanding of the impact of tyre characteristics on driver judgement
- to explore the state of the art in the subjective assessment of tyre performance
- to explore potentially appropriate methodologies that could be successfully exploited for further research in this field

2. Human monitoring and tyre characteristics

Several papers have been published in the past on the impact of tyre characteristics on vehicle performance assessment and driver feedback information. These contributions have in common that the sensitivity of selected tyre parameters is investigated using objective or subjective assessment methods where, in some cases, correlations are identified between these open- and closed loop results. Hence, different tyre construction and performance parameters are distinguished (input tyre characteristics), different methodologies are explored related to certain vehicle handling tests, resulting into output

parameters that are either connected to open-loop vehicle performance or subjective driver ratings.
In this order, the previous research results will be treated in these lecture notes, including a discussion on the impact of the various input tyre characteristics on vehicle performance. We start with a concise characterisation of each of the papers.

Roland et al [14] investigated the sensitivity of tyre design (construction, dimensions) and, through that, tyre performance parameters on the vehicle dynamic response. Both manoeuvring and braking were considered. Several testprocedures were discussed where some of them were considered not to be appropriate. Correlation between tyre design and vehicle performance appeared to be not clear in many cases, and it was concluded to emphasise directly, in future studies, on tyre performance parameters. Fairlie and Pottinger [4] considered tyres that varied with respect to hardness and hysteresis with the objective to recommend best practice subjective methodologies in order to discriminate between these tyres in terms of suggested handling rating characteristics. They identified the different sources of error in judgement and proposed certain “rules” to minimise these errors. Brindle [1,2] examined the effects of tyre type (radial vs. cross-ply) and tyre dimension (standard vs. low-profile) on vehicle steering and handling and the perception of the driver on these characteristics. Whereas radials were favoured with respect to feelings about safety, security, control in case of emergencies, cross-ply tyres were rated better concerning the “feel” from the road. Brindle concluded that “steering feel” should be further studied from a broader perspective accounting for steering work, driver feedback from the steering, linearity in response, etc. Käppler and Godthelp [6] examined the effect of tyre pressure variations (resulting in different cornering stiffness at front and rear) through both open and closed loop test procedures, as well as subjective rating procedures to verify earlier findings. This work links objective and subjective assessment procedures that should form the basis for further research on the understanding of the impact of tyre characteristics on driver-vehicle performance. Xia and Willis [17] focused on the tyre cornering stiffness and compared different evaluation methods to rank the tyres with respect to vehicle handling performance. In addition to evaluation methods related to single performance parameters such as gain or response time, they considered four-parameter evaluation method attributed to Mimuro [9]. To some extent, this approach can be considered as an extension to the well known two-parameter evaluation method due to Weir and DiMarco [16].

2.1. Input tyre characteristics

The various input tyre characteristics as discussed in literature are summarised in table 1.
Distinction is made between construction parameters, geometrical characteristics (dimensions), service parameters such as inner pressure, performance parameters, and ageing of the tyre referring to the effect of age and wear-in procedures on tyre performance characteristics. The tyre construction and geometry imply certain performance characteristics, where the understanding and exploitation of these relationships is one of the main challenges for a tyre manufacturer. With our nowadays tyre models, one is pretty much capable of examining vehicle response as a result of modified tyre performance characteristics. However, by the end of the day, a tyre

manufacturer is faced with the task to manufacture a tyre satisfying such performance requirements. Some comments will be made on these issues later.

Tyre parameter	*Additional remarks*	*References*
Construction parameters:		
Compound	hardness	[4]
	hysteresis	[4]
Ply-type	cross-ply vs. radial	[1, 14]
Carcass material	nylon, rayon, polyester	[14]
Belt material	rayon, Fiberglas, steel	[14]
Dimensions:		
Size	-	[14]
Aspect ratio	standard vs. low profile tyre	[2, 14]
Service parameters:		
Inner pressure	incl. mixed conditions (front-rear)	[6]
Temperature	-	TIME
Wet vs. dry conditions		[2, 14]
Performance parameters:		
Cornering stiffness	incl. mixed conditions (front-rear)	[14,17]
Aligning torque	-	[17]
Pneumatic trail	-	[17]
Peak lateral force coefficient	$(F_y / F_z)_{peak}$	[14]
Braking force coefficient	$(F_x / F_z)_{peak}$	[14]
Ageing parameters:		
Wear after normal use	-	[6]
Wear-in	-	[14]

Table 1.: Input tyre characteristics

Finally, we do not pretend to give a full account of the impact of all possible tyre parameters on vehicle-driver performance. For example, the effect of tread design, tyre width, relaxation length etc. are not treated here and open for further investigations.

2.2. Methodologies

Methodologies on the assessment of vehicle performance can be structured as follows:

- **Subjective methodology strategies**
  - Performance tests
    Referring to a specific task as determining a maximum speed (lane change), minimum lateral deviations, steering motions (straight lane test), etc.,
  - Rating scales (based on a questionnaire) followed by data reduction (PCA: Principal Component Analysis, DFA: Discriminant Function Analysis).
  - Open questions, to be considered as additional to the previous two strategies.

- **Objective methodology strategies**
  - Reference Manoeuvres with instrumented vehicles

There doesn't seem to be a standard test procedure at hand, as illustrated from the tests as encountered in the literature and listed in tables 2 and 3, with some of the performance metrics indicated in the second column.

Subjective methodology strategies	*Some performance metrics*
Realistic driving conditions along mixed routes on public roads, including rural, suburban and motorway roads.	-
Closed loop straight lane driving test	lateral vehicle position, required steering inputs; both in amplitude and frequency.
Closed loop double lane change	

Table 2.: Subjective methodology strategies encountered in the literature

Objective methodology strategies	*Some performance metrics*
Random (or swept) steering input test, with frequency range between 0 and 2.5 Hz	phase lags, equivalent time lag, steady state gain; for yaw rate and lateral acceleration
Step steering input test	response times, overshoot values, TB-factor or "vehicle characteristic"
Pulse steer input(alternative to random steer test)	-
Trapezoidal steering input test	peak lateral acceleration, peak yaw and bodyslip angles, peak sideslip angular rate
Sinusoidal steering input test	similar to above
Steady state cornering test	understeer factor
Straight line braking	longitudinal average deceleration
Braking in a turn	deceleration, body slip angular rate and change in path curvature
Turning on a rough road	similar to above

Table 3.: Objective methodology strategies encountered in the literature

Subjective ratings consist of numerical values, provided by the testdrivers (subjects) for each characteristic from a predefined list, according to a scale of some magnitude. This could be a 5-point scale [1], a 10-point scale [4, 6].

One should be aware that not only the ratings itself are important but also the deviations among the ratings, allowing a distinction between **individual** assessments by the subjects and assessments with high level of **consistency**.

Usually, the set of original variables is reduced to a set of so-called Principal Components or factors which can be regarded as orthogonal (statistically independent) to each of the other components (PCA: Principal Component Analysis). Principal Components are weighted linear combinations of the original measured variables. A next step could then be to reduce this set to new linear combinations with maximum

discrimination between two or more clusters (e.g. related to tyres with high and low cornering stiffness). This second step is referred to as Discriminant Function Analysis (DFA). Some researchers skip the PCA-analysis and apply a direct reduction based on the criterium of maximum discrimination, followed by an interpretation towards more independent factors.
Carrying out such PCA-analysis on both open-loop test results and subjective ratings would allow for further correlation studies between the objective and subjective test procedures.

2.3. Assessment of vehicle performance

There is a general understanding that for the evaluation of vehicle handling performance, the steady state gain between yaw rate and steering input, the response times after a step steer, and the equivalent time constant play an important role. Small values of phase lag in both yaw rate and lateral acceleration appear to correlate well with a positive driver judgement of vehicle controllability [17]. In addition, there is evidence that a small phase lag difference between the lateral acceleration and the yaw rate is appreciated by a driver as well. This indicator played an important role in the discussions on four-wheel steering, as well as the criterium of zero sideslip angle. In fact, it was found that, for example at a severe steering manoeuvre, a driver isn't able to distinguish properly between a nonzero sideslip angle and a delay in yawrate response. The highest correlation was found between subjective rating and the product of steady-state sideslip angle and yaw rate peak time as resulting from the step steer input test. This last combined parameter is usually referred to as the TB factor. Xia and Willis [17] refer to this parameter as the "vehicle characteristic".

According to the earlier discussion, all of these parameters as derived from some of the tests in table 3, may be further combined into statistically independent factors that may predict certain aspects of driver judgement of vehicle performance.
The equivalent time constant, denoted as T_{eq}, is defined by the frequency at which the phase shift between steering angle and yaw rate amounts 45 °. This means that the equivalent time constant T_{eq} describes the required driver phase lag compensation and the vehicle's effective steering bandwidth. It was demonstrated by Weir and DiMarco [16] that the steady state yaw rate gain G_r should not be too high (to avoid nervous behaviour) and not be too low (to avoid excessive steering input). They determined optimal boundaries in

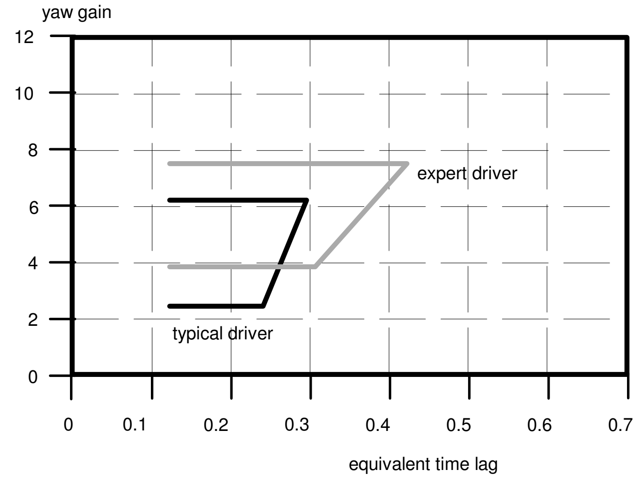

Figure 3.: Optimal handling boundaries [16]

the (T_{eq}, G_r) plane for expert and typical drivers, which were extended by Godthelp, Ruijs & v. Randwijk [5] for heavy vehicles. These boundaries, as indicated in figure 3, were derived based on a rating of 3.5 and higher on a 10-point scale.

Mimuro [9] extended the idea of multi-parameter evaluation to investigate vehicle handling qualities to a method including four parameters:

- G_r : steady state yaw rate gain
- ω_n : the yaw rate natural frequency
- ξ_r : the damping ratio for the yaw rate frequency response
- ϕ: phase lag of the lateral acceleration frequency response at 1 Hz

These four parameters together form a rhombus, as indicated in figure 4, where the area can be interpreted as a measure for linear vehicle handling potential. This approach has been applied by Xia et. al. [17] where the four parameters were obtained from fitting vehicle frequency response functions to the two degree of freedom "bicycle model", which appeared to work out very well. The most dominant factors turned out to be the natural frequency and the lateral acceleration phase lag, in discriminating between tyres with different cornering stiffness.

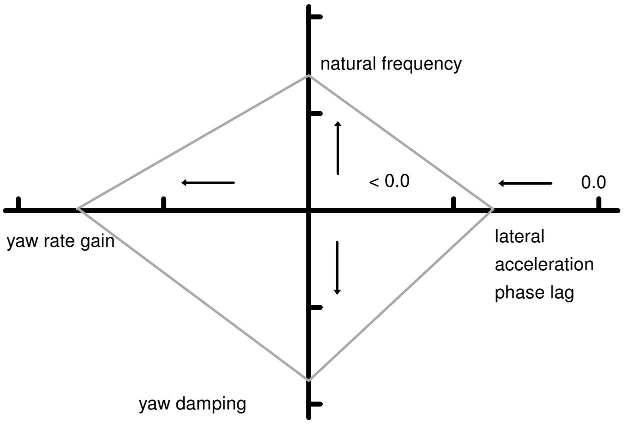

Figure 4.: Four parameter presentation [9]

2.4. Subjective characteristics

Let us return to the subjective ratings as mentioned in subsection 2.2. Some of the characteristics have been listed in table 4, with a clarification as far as available from literature. There is no strict order in this list. Again, one observes a lack of standardisation in the type of questions. The conclusion might be drawn that only a thorough analysis of the subjective findings including possibly a correlation with objective results would allow for a clear interpretation of these characteristics, in retrospective.

Clearly, the factors in table 4 are not independent. For example, "linearity in response" and "predictability" are related but formulated at different levels of perception. The same can be said about factors as "handling in general", "controllability" which are very general and qualitative concepts whereas "amount of effort of steering" or "reaction speed" are much more specific and closer to quantitative parameters as described earlier.

In addition, some factors are restricted to vehicle behaviour up to a moderate level of lateral acceleration (order 0.3 - 0.4 g) such as "linearity in response" whereas other factors are applicable up to the case of extreme manoeuvring such as "perceived safety and security".

Subjective characteristics (in random order)	
consequences of inattention	Predictability
Controllability	number of steering corrections
reaction accuracy	amount of steering angle
judgement about reaction speed	steering sensitivity
amount of steering force	steering reverse
reaction speed (to steering input)	handling in general
plowing (controllability vehicle front end)	swingout (controllability vehicle rear end)
tracking (maintain straight heading)	returnability (to original path)
perceived safety and security	perceived confidence (predictability)
sensitivity and lightness of steering	steering qualities in general
self-aligning strength of steering	vehicle stability
amount of effort while steering	linearity in response
amount of perceived feel through steering	amount of steering feel, thought ideal

Table 4.: Some subjective characteristics [1], [4], [6]

Based on maximum discrimination, various researchers have attempted to reduce the set of subjective characteristics to a more independent set of factors, with or without a preceding orthogonalisation step. In this way, Brindle and Wilson [1] concluded that the perceived feel of safety and security (including control in emergency), stability and course following, the effort required to steer the vehicle and the "feel" through the steering system were most appropriate to predict the ranking between different tyre types. Fairlie and Pottinger [4] arrived at steering sensitivity and linearity as most discriminating factors.

Käppler and Godthelp [6] resulted at reaction accuracy and the amount of steering wheel angle needed as most consistent subjective characteristics. In contrast, they concluded that the number of steering corrections needed as well as the required steering moment show large variation in driver rating, and therefore should be regarded as more individual assessment.

Finally, Mimuro et. al. [9] gave an interpretation of the "rhombus-parameters" in figure 4:

G_r : handling easiness
ω_n : heading responsiveness
ξ_r : directional damping
ϕ : following controllability

2.5. Matching tyre characteristics to vehicle performance

In this subsection, the major conclusions are listed from the references mentioned earlier, based on the classification of table 1, section 2.1..

Differences in tread compound with respect to hardness and hysteresis are well discriminated by the vehicle steering response, indicating how quickly the tyre reacts to a steering input (including both time response and gain). Very low discrimination is found for tracking (how well does the vehicle maintain its course without driver input) and the controllability of the rear end or front end of the car. This result is supported by [6] where it was concluded that different tyre characteristics due to tyre pressure variations have hardly any effect on lateral deviation in straight lane driving.

Different choices for carcass material and belt material yield mixed effects with respect to cornering stiffness, with relative variation in the order of 30 % for the desired conditions. No clear relationship was found in [14]. Increased cornering stiffness is normally associated with a higher yawrate gain and shorter responsetimes, and therefore a better subjective evaluation. This is the reason why radial tyres are preferred above cross-ply tyres. It was shown in [14] that this difference between radial tyres and cross-ply tyres might be counteracted by severe (shoulder) wear-in. In addition, cross-ply tyres were reported to give more “feel” through the steering system [1], explained by the occurrence of a higher pneumatic trail. They show a more linear vehicle response in forward speed making extreme conditions better predictable.

These results do not seem to match with the conclusions by Schröder and Jung (reported in [17]) that the effect of the aligning torque on the handling performance is low. Apparantly, “feel” should be interpreted here as something different than handling performance. It might be more related to feedback to the driver through the required steering torque, not effecting gains and response times, and not well covered by objective testmethods presently in use.

There is evidence that cornering stiffness increases with tyre size and reducing aspect ratio. This last observation is consistent with the preference of drivers for low profile radial tyres with respect to steering feel, vehicle stability, road holding and handling. On the other hand, conventional radials are superior to low profile tyres with respect to steering return strength, rural comfort and rural steering performance. Moreover, conventional tyres tend to yield more “linear” behaviour in yawrate and lateral acceleration than low-profile tyres.

2.5.1. Impact of service parameters

Regarding service parameters, some observations are listed below with respect to wet surface conditions, the effect of tyre load and the effect of tyre pressure.

Different sources deal with tests on both dry and wet roads. It was specifically concluded in [14] that wet surface testing is a practical and useful approach for research on vehicle response characteristics. Without getting more specific about this conclusion, it seems to apply to braking tests exclusively. For steering tests, reduced ratings are obtained on wet roads making these wet conditions less suitable for judgement of handling performance.

Tyre loads increase the cornering stiffness. The cornering stiffness stabilises beyond a certain load and may even slightly reduce beyond this point. A similar non-linear effect is well-known regarding the inner pressure. A maximum (optimal) cornering stiffness is obtained for a certain pressure with lower values for smaller pressures (deflected tyre) as well as beyond this pressure value (changing contact patch).

The effect of tyre pressure on vehicle handling judgement has been extensively studied in [6] with mixed pressure conditions (different pressure for front and rear tyres) chosen such that three typical understeer-oversteer conditions resulted:

- standard understeer
- extreme understeer (low frontpressure)
- oversteer (low rearpressure)

It was concluded that these tyre pressure variations had hardly any effect on lateral deviation in straight lane driving. In contrast, the required steering activity (magnitude of steering angle as well as the required faster response time) increases with extreme understeer over the entire speed range. A more extreme result was observed in the oversteer situation, however only beyond a certain (critical) speed.

2.5.2. Impact of cornering stiffness

So far, we have considered the impact of changing conditions that refer to the tyre-physics or the service conditions. As mentioned earlier, such variation primarily affect tyre performance parameters and, through these, vehicle performance. Below we will focus directly to these last types of relationship.

As noticed before, a higher cornering stiffness correlates with a better handling evaluation by the driver. One should distinguish here between matched tyre conditions at front and rear, and with mixed tyre characteristics.

A higher cornering stiffness in general leads to lower phase lags, both in yaw rate and in lateral acceleration, as well as to a lower phase lag difference between lateral acceleration and yaw rate. In addition, it has been reported to correspond to a lower TB-factor (or "vehicle characteristic") and a higher yaw rate natural frequency.

For mixed conditions, we refer to the comments on [6] and the observation in [14] that mixed cornering stiffness conditions have impact on the peak lateral acceleration (with trapezoidal steer test, or sinus-steer) indicating a smaller stabilising tolerance (in the sense of figure 2).

2.5.3. Effect of tyre wear.

Finally, some comments are made on wear-in procedures and normal tyre wear.

It was observed in [14] that the peak lateral force coefficient is strongly effected by tyre shoulder wear, with opposite results for radials and cross-ply tyres. It illustrates that one should be careful about wear-in procedures.

The evaluation of the understeer-oversteer characteristics of certain mixed tyrepressure conditions as reported in [6] were repeated after one year of normal use. These characteristics appeared to have developed into a more pronounced direction, both for the pressure combination with original understeer performance and the pressure combination with original oversteer characteristics.

3. The variation of tyre characteristics, a model approach.

The previous section discussed variation in physical tyre parameters, their effect on tyre performance characteristics and their sensitivity with respect to assessment of vehicle performance. Both links, between tyre design and tyre performance as well as between tyre performance and vehicle performance, are still not well understood.

Tyre performance characteristics can be described using the well known Magic Formula tyremodel, the latest version of which for passenger car tyres is described in [12].

Its basic form is given by

$$(1) \qquad Y(x) = D.\{\sin\, or \cos\}[C \arctan(Bx - E(Bx - \arctan(Bx)))]$$

with $Y(x)$ equals either brake force (or driving force) or lateral force in case of the sine version, whereas $Y(x)$ is related to the pneumatic trail in case of the cosine version. The variable x denotes the longitudinal or lateral slip. The coefficients B, C, D and E are usually described as stiffness factor, shape factor, peak value and curvature factor, respectively.

In order to study the effect of changing of these characteristics on vehicle handling, various User Scaling Factors have been included in the Magic Formula model. Some of these User Scaling Factors are listed below (restricted here to lateral pure slip):

λ_{Fz0} : nominal load
$\lambda_{\mu y}$: peak friction coefficient
λ_{Ky} : cornering stiffness
λ_{Cy} : shape factor
λ_{Ey} : curvature factor
$\lambda_{\gamma y}$: camber force stiffness
λ_{t} : pneumatic trail

For further clarification of these scaling factors, some of the Magic Formula expressions for pure lateral slip are included in this document below in (2) – (7). In (2), expressions of the lateral force and aligning torque are given in general terms, depending on wheel position (expressed by slip angle α, camber angle γ), load F_z, pneumatic trail t and residual torque M_{zr}.

$$(2) \qquad F_y = F_{y0}(\alpha, \gamma, F_z) \ , \qquad\qquad M_z = M_{z0}(\alpha, \gamma, F_z) = -t.F_{y0} + M_{zr}$$

The expression (1) is made more explicit in (3), with horizontal and vertical shifts included (absent in (1)) and with the coefficients and their relationship with the scalar factors further clarified (in terms of the tyre load F_z and nominal load F_{z0}). The scalar factor for the pneumatic trail is explained by (7).

(3) $$F_{y0} = D.\sin\left[\arctan\left\{B.\alpha_y - E.\left(B.\alpha_y - \arctan(B.\alpha_y)\right)\right\}\right] + S_V\,,\ \alpha_y = \alpha + S_H$$

(4) $$\gamma_y = \gamma.\lambda_{\gamma y}$$

(5) $$D = \mu_y.F_z\ ,\quad \mu_y = \mu\left(F_z,\gamma_y\right).\lambda_{\mu y}$$

(6) $$B = K_y\,/\,(C.D)\,,\qquad K_y = K\left(F_z, F_{z0}.\lambda_{Fz0},\gamma_y\right).F_{z0}.\lambda_{Fz0}.\lambda_{Ky}$$

(7) $$t(\alpha + S_{Ht}) = t_0\left(\alpha + S_{Ht}\right).\lambda_t$$

3.1. Tyre characteristics for varying scaling factors.

Plots for the side force and pneumatic trail are shown in figures 5 and 6 for varying scalar factors ($\lambda_{Ky},\lambda_{\mu y}$) (i.e. varying stiffness and friction) and ($\lambda_{Ky},\lambda_{\mu y},\lambda_t$) (i.e. varying stiffness, friction, trail) respectively.

Each scalar factor is chosen from two extreme values, high (indicated with **h**) and low (indicated with **l**).

The scalar factors for cornering stiffness and friction will be varied likewise in the next section in full vehicle simulation studies

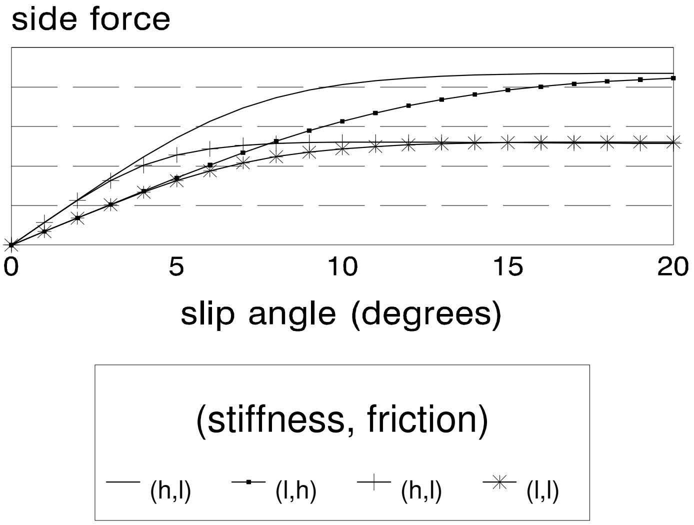

Figure 5.: Side force characteristics

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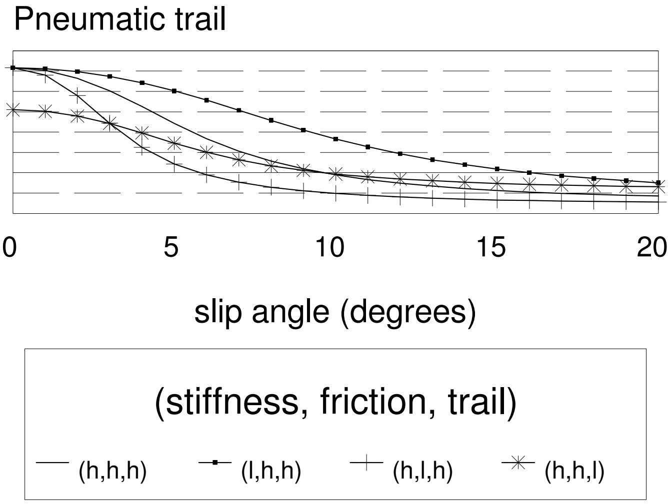

Figure 6.: Pneumatic trail characteristics

4. Tyre sensitivity, simulation studies.

In this section, the behaviour of a vehicle under various driving conditions is studied for different values of the cornering stiffness and friction. Two cases are distinguished here, the *"matched case"* with the same characteristics at front and rear tyres, and the *"mixed case"* with different characteristics.

4.1. Varied tyre characteristics

For tyres, some MF-data have been chosen related to a passenger car tyre on a dry road. The User Scalar Factors for cornering stiffness and friction are varied according to the following schedule:

λ_{Ky} : 0.5, 0.6,....,1.0
$\lambda_{\mu y}$: 0.1, 0.2,....,1.0

where the cases mentioned above can be expressed as:

matched case : $\lambda_{front} = \lambda_{rear}$
mixed case : $\lambda_{front} \neq \lambda_{rear}$

4.2. Modeldescription and selected reference manoeuvres

A non-linear vehicle multi-body model has been used in this study with the sprung mass modelled as one (6 dof) rigid body, connected to the unsprung mass with linear springs and dampers. Additional roll stiffness (stabiliser) was included. The tyres were described by the Magic Formula in lateral direction, whereas the vertical behaviour was described by linear springs. The model was validated in the time domain by comparison (and tuning) with data from reference handling manoeuvres from real vehicles (high performance passenger car). These manoeuvres included the double lane change, the step steer response and the random steer test.

The impact of varying tyre characteristics will be studied here on the basis of two types of steering input tests: the step steer input test (or J-Turn) to describe the response characteristics of the vehicle to a sudden steer input (response time, overshoot value,...) and the random steer test to generate frequency response data (gain, phase lag,..).

4.3. Results and interpretation

Simulations have been carried out for varying cornering stiffness for both the matched and mixed cases, as indicated above. First, the transferfunctions have been determined. The simulations in the time domain have been carried out for a ramp steer input (approximating the step steer input), growing from 0 to a maximum value within 0.4 sec's, such that a steady state lateral acceleration of 4 m/s^2 was obtained. With an initial speed of 20 m/s, this corresponds to a steady state bend with radius of 100 m.

Lowering the cornering stiffness simultaneously at front and rear tyres leads to lower gain and larger phase lag between steering angle and yaw rate, in contrast to the situation of a reduced lateral stiffness only at the rear tyres. In the latter case, understeer behaviour is reduced and possible oversteer behaviour may result which leads to increased gain at lower frequencies.

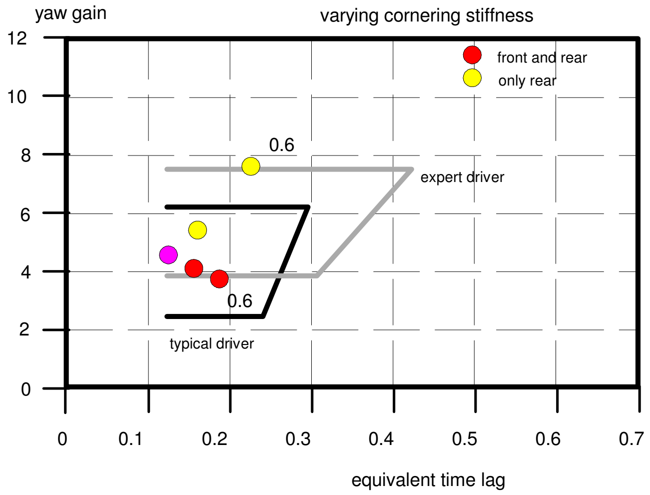

Figure 7.: Comparison with optimal handling boundaries cf. [16]

These results have been included in a “Weir and DiMarco plot, figure 7 similar to figure 3. Lowering cornering stiffness yields a tendency to “leave” the optimal area for both the matched and the mixed case. In the matched case however, this is due to a required larger steering angle whereas the car responds too violently in the mixed case. In both cases, the large equivalent time lag indicates a slower response to steering input.

A stronger steering input (matched case) results into a stronger overshoot. Clearly, the contrary is obtained in the mixed case where in both cases the larger response times are evident. Likewise, a similar effect is obtained for the body slipangle. The roll angle is very much associated to the lateral acceleration and doesn’t show a very significant difference between the matched and the mixed case.

4.3.1. Response times for varying cornering stiffness

The various performance indicators, relating to response time, are shown in figures 8 and 9 for different values of the cornering stiffness scaling factor λ_{Ky} for the matched case and mixed case, respectively. Distinction is made between the response time T_x and peak response time $T_{r.\max}$, corresponding to the time from the steering ramp until 90 % of the steady state value or until the maximum value of variable x is reached, respectively.

The variable x indicates yaw rate or lateral acceleration. These times differ in the sense that the stabilising capacity of the car and tyres effects the peak response time. In addition, the time lag between lateral acceleration and yaw rate is shown, as well as the TB factor (vehicle characteristic).

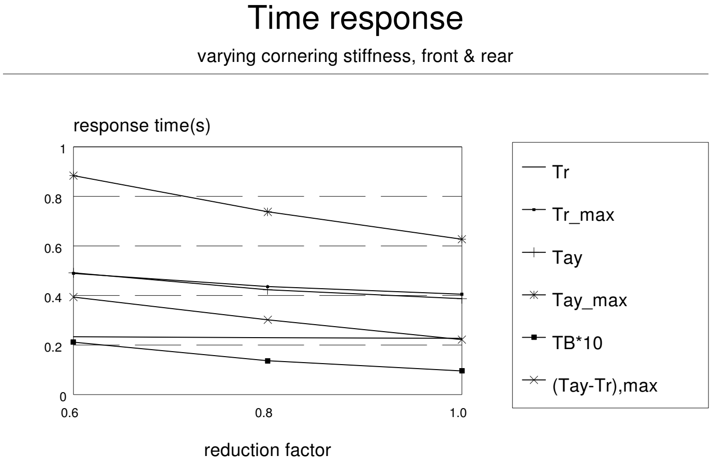

Figure 8.: Time response indicators, matched case

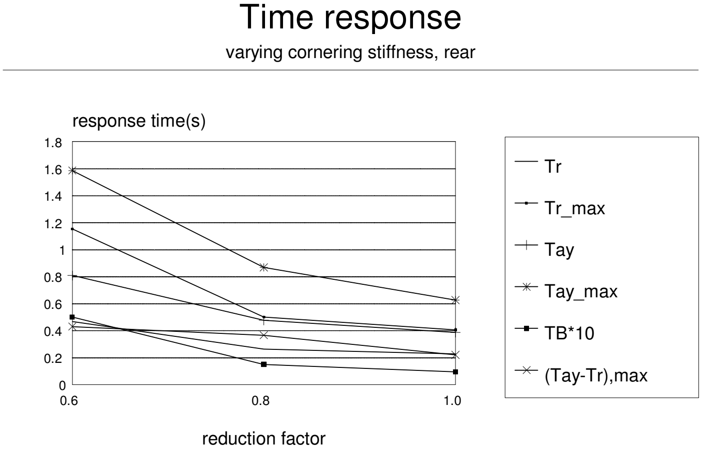

Figure 9.: Time response indicators, mixed case

It is interesting to examine the amount of distinction between the three values for the scalar factors, by each of the indicators. Each of the indicators is decreasing with higher cornering stiffness (both in the matched case and the mixed case), normally correlating with an improved driver judgement. This effect is more pronounced in the mixed case, demonstrating a higher sensitivity of cornering stiffness to the subjective assessment of vehicle performance.

However, the response time and peak response time for the lateral acceleration appear to discriminate better here than the corresponding variables for the yaw rate, if one compares the average relative variation per unit change in cornering stiffness. This confirms the results by Xia et al. [17]. Also, the TB-factor distinguishes well between the different values of cornering stiffness and especially the time lag between lateral acceleration and yaw rate shows a good discrimination in both cases.

4.3.2. Effect of friction coefficient on vehicle stability

Next, we have varied the friction levels at front and rear tyres independently. As a result, similar conclusions can be derived regarding the resulting response times, phase lags, gains, etc. A friction level at the rear tyres, exceeded by the friction at front tyres might yield unstable behaviour, that is, the vehicle shows strong oversteer behaviour and high absolute body slipangles are found.

For illustration, the combined effect of reduced cornering stiffness at the rear (λ_{Ky} =0.6) and mixed friction levels at front and rear is shown in figure 10, where dark squares indicate unstable behaviour. Restoring the cornering stiffness at the rear to the original value (λ_{Ky} =1.0) slightly improves the stability, but the road friction remains to be the dominant factor.

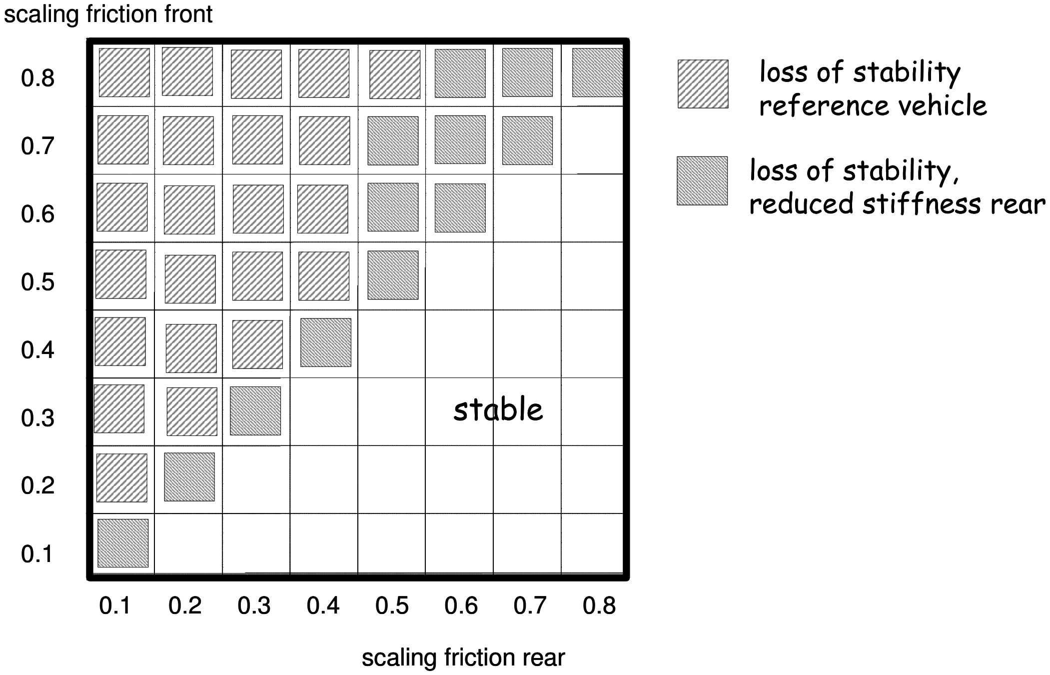

Figure 10.: Stability under the combined effect of reduced friction and modified cornering stiffness at the rear.

5. Discussion

Various studies on the assessment of vehicle performance have been reviewed, especially related to tyre characteristics. In most cases, this assessment is related to indicators that can be well defined by reference manoeuvres such as J-turn, random steer etc. Parameters such as gains, response times and phase lags are able to distinguish well between certain different tyre performance characteristics. Other tyre characteristics such as pneumatic trail do not result in such clear distinction whereas it was discussed in section 2.5 that a higher pneumatic trail might contribute to a better "feel" through the steering wheel to the driver. Moreover, there is some evidence that the ranking over tyres according to this

"feel" does not match the ranking according to the conventional objective indicators such as response times, gains, etc. Another intriguing indicator in this respect is linearity.
We concluded that there might be more impact of tyre performance to the driver assessment and performance then what can be described by the present reference manoeuvres. These observations are confirmed by other sources from which it is known that relatively minor changes in tyre design and tyre characteristics may result in significant dissimilarities in subjective driver assessment. Within the limits of human assessment, to a large extent these driver assessments appear to be reproducible. Dominating tyre properties and, additionally, the highly sensitive vehicle suspension/steering system contribute significantly to this assessment-reproducibility. However, it is presently insufficiently clear how such driver judgements are related to vehicle design characteristics.
Many of the studies reviewed above have been carried out on the correlation between driver ratings and objective assessments for dominant vehicle behaviour. However, the situation may be more involved than situations considered in previous studies. It means that relatively small parameter deviations yet have significant influence. Methods to objectively quantify the performance deterioration due to these small parameter deviations are virtually lacking. Further, it is not understood how results of such newly developed objective assessment methods could assist in improving the vehicle design. This demands to develop an understanding of information available to and criteria used by the driver in his judgement process, and of their relation with key variables and parameters of the vehicle. Identifying these key variables and parameters in connection with the information transferred through these variables to the driver constitutes a main research issue, yet to be undertaken.

References

[1] L.R. Brindle, L.R., W.T. Wilson.: *The Effects of Tyre Type on Driver Perception and Risk-Taking*. International Conference of Vehicle Handling. Institute of Mechanical Engineers C134/83, London (1983)

[2] L.R. Brindle: *The Influence of Tyre Characteristics on Driver Opinion.* Applied Psychology Executive Report. Cranfield Institute of Technology (1984).

[3] E. Donges: *Supporting Drivers by Chassis Control Systems*. In.: J.P. Pauwelussen, H.B. Pacejka: Smart Vehicles. Swets & Zeitlinger Publishers (1995).

[4] A.M. Fairlie, A.G. Pottinger: *Statistics of Double Lane Change Handling Tests Conducted on Tires Differing in Tread Compound Physical Properties.* SAE Technical Paper Series 880583 (1983)

[5] M.J. van Randwijk, J. Godthelp,W.D. Käppler, P.A.J. Ruijs: *Correlation of Driver Judgement and Vehicle Directional Data to Evaluate and Predict Truck Handling.* Third EAEC Conference, Strassbourg, France (1991)

[6] W.D. Käppler, J. Godthelp: *The Effects of Tire Pressure Variations on Vehicle Handling Properties and Driving Strategy.* Forschung für Anthropotechnik, Bericht Nr. 72 (1986)

[7] W.D. Käppler, J. Godthelp, M.J. van Randwijk, P.A.J. Ruijs: *Methodology for Predicting Car and Truck Handling Assessments.* Institute of Mechanical Engineers C389/379 (1992)

[8] R.J.A. Kleuskens: *The TNO Vehicle Dynamics Database (VDD).* A Tool for Comparison of Vehicles Dynamics Behaviour. Autotest '96, IDIADA Spain (1996)

[9] T. Mimuro et. Al. : *Four Parameter Evaluation Method of Lateral Transient Response*. SAE Paper 901734 (1990)

[10] J.J.M. van Oosten, E. Bakker: *Determination of Magic Formula Tyre Model Parameters*. Proceedings 1st International Colloquium on Tyre Models for Vehicle Dynamic Analysis. Swets & Zeitlinger B.V., Amsterdam/Lisse (1993).

[11] H.B. Pacejka: *The Role of Tyre Dynamic Properties.* In.: J.P. Pauwelussen, H.B. Pacejka: Smart Vehicles. Swets & Zeitlinger Publishers (1995).

[12] H.B. Pacejka: *The Tyre as a Vehicle Component.* XXVI FISITA Congress Prague (1996)

[13] J.P. Pauwelussen: *Assessment of Traffic Safety Margin in Adverse Weather Conditions*. In.: J.L. Kroes, J.A. de Stoop: First World Congress on Transport Safety, Delft (1992)

[14] R.D. Roland, R.S. Rize, F. Dell'Amico: *The Influence of Tire Properties on Passenger Vehicle Handling*. Calspan Corporation Report (1975)

[15] 'left blank '

[16] D.H. Weir, R.J. Dimarco: *Correlation and Evaluation of Driver/Vehicle Directional Handling Data*. SAE Paper 780010 (1978)

[17] X. Xia, J.N. Willis: *The Effects of Tire Cornering Stiffness on Vehicle Linear Handling Performance.* SAE Technical Paper Series 950313 (1995)