Concepts of Improving the Dynamics of Passenger Cars through Cooperating Control Systems

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With today's vehicle dynamic control systems it is possible to improve the behaviour of passenger cars in different ways. Superimposed front steering, additional rear steering and individual brake intervention are compared in this article by use of simulation methods to point out in which sense they are similar and how they differ. Furthermore it is examined what level of additional improvement can be achieved if the systems are being used in cooperation, rather than on a stand-alone basis.

1 Introduction

Since the mid 70s various vehicle control systems have been developed which improve the longitudinal and/or lateral dynamics of passenger cars, **Fig. 1**. Depending on the concept of actuation one can categorize them in those using the steering system, the brakes or the power train. It turns out that all principles are capable of influencing the vehicle lateral dynamics. At this point, the question can be brought up how the systems differ and if a combination or integration could bring additional performance. To find answers to these questions was the objective of an investigation [1]. The findings of this research are summarised in this article.

2 Process of analysis

2.1 Simulation model

The investigations have been performed exclusively by the use of a mathematical model that simulates the vehicle dynamics. That way it was possible to compare the three systems in the very same vehicle being activated alternately, **Fig. 2**. The coloured elements in Fig. 2 show the extensions that are added to the basic vehicle. The elements of the superimposed front steering are coloured red, those of the additional rear steering green and the brake intervention system is coloured blue. On the one hand, the design of the individual systems is based on existing concepts. On the other hand, it was required to use comparable control laws. The demand of comparability is very important in order to be able to make fundamental statements about the systems.

The two additional steering systems on front or rear axle (red or green elements) include yaw rate ($\dot{\psi}$) feedback with a non-linear reference model. Additionally the control laws possess a feed forward term that differs between the two. In case of superimposed front steering it adds a steering angle that is proportional to the steering wheel velocity $\dot{\delta}_L$ (ref. [3]). Additional rear steering adds a steering angle that depends on the steering wheel angle δ_L and the vehicle velocity v via a look-up table (ref. [2]).
The brake intervention system combines several control loops. One is basic slip (S) control which encompasses the anti lock braking and traction control system ABS and

ASR/DSC/TCS (no special colouration of these elements) which is standard equipment in current passenger cars. Additionally there is the blue loop that is equivalent to the yaw rate ($\dot{\psi}$) control of the additional steering systems. With this function (individual brake intervention) the vehicle stability control systems ESP/DSC/VSC are represented which have been introduced in passenger cars in the mid 90s [5].

2.2 Simulated manoeuvres and analysis

In order to compare the different control systems nine individual situations were chosen from a collection of manoeuvres [4]:

- Steady state cornering,
- Step steer input,
- Lane change,
- Sinusoidal steer input,
- Power off in a turn,
- Acceleration in a turn,
- Braking in a turn,
- Braking on μ-split surface,
- Cross wind.

This combination of manoeuvres covers all relevant dynamics of the vehicle that can also be modelled and simulated with a given numerical tool, **Fig. 3**. Extracting "characteristic values" from the simulation results performs the analysis of the manoeuvres. In this way, one can compare the benefits of the different control systems in a quantitative way. The objective of the investigation is to give an over-all view on all kinds of driving situations. For this purpose, the characteristic values are related to the different categories of vehicle dynamics that are categorised as follows: "handling", "stability", "road holding" and "longitudinal dynamics". A dimensionless assessment that values the specific capabilities of the control systems finally enables a clear distinction between the advantages of each system.

3 Stand-alone systems

3.1 Description of the stand-alone systems

The control concept of the two single additional steering systems and the single brake intervention system are designed according to the approach explained above. In order to show their specific properties, the systems are first analysed independently, **Fig. 4**. The uncontrolled vehicle (which contains only black elements in Fig. 2) is equipped with only one of the three systems so that the influence of the single systems can be evaluated. The results of the stand-alone systems can then also be directly compared.

In order to take the state of the art of a passenger car as a basis for comparison, the basic brake and traction slip control functions (ABS, ASR/ASC/TCS) are included even when investigating additional steering as stand-alone systems. For instance, wheel lock is prevented even in manoeuvres that simulate strong deceleration. In this way, one can be sure that the effect of the steering systems is not distorted by any disturbances related to the loss of cornering potential due to high levels of longitudinal slip.

3.2 Results with the stand-alone systems

The stand-alone systems appear to offer very different possibilities for improving the vehicle dynamics, **Fig 5**. In the diagram the behaviour of the controlled vehicle is compared to that of the uncontrolled vehicle by combining the results of all manoeuvres as described in chapter

2.2. A positive value in the diagram indicates an improvement of the vehicle performance and a negative value stands for performance degradation.
The additional rear steering shows an outstanding potential to improve the vehicle handling. The reason for this is that the sideslip angle can be minimised. Furthermore, the additional steering angle that is applied for vehicle stabilisation does not affect the lateral acceleration in a negative way. On the other hand, the stabilising action of the superimposed front steering does have a negative effect on the lateral dynamics of the vehicle. However, front steering does enable improved handling whereas brake intervention does not show any effect in that category. This is mainly caused by the fact that this system is normally applied during critical phases of vehicle motions (e.g. stability problems). It is not often applied during subcritical cornering situation, denoted here as handling.
Brake intervention is best choice to improve vehicle stability. This is one of the reasons that these systems (ESP/DSC/VSC ref. [5]) have become standard equipment in passenger cars. Superimposed front steering can also improve vehicle stability, whereas additional rear steering does not such a large effect in this category. A stabilisation of the vehicle requires a decrease of the lateral force at the front axle. This can be achieved easily by a front steering system through counter steering. The lateral forces at the rear axle would have to be increased to generate a stabilising yaw moment that cannot always be achieved by a rear steering due to tire saturation.
With regard to the road holding abilities it appears that brake intervention does not achieve any improvement, mainly because in the examined manoeuvres (e.g. cross wind etc.) the system does not come into action at all. In contrast, the additional steering systems reach a considerable improvement of vehicle performance in this category. Their advantage is to act even when there is no critical situation at hand, even during straight line driving.
Regarding the longitudinal dynamics, brake intervention is once again the best choice. This system includes very effective brake slip and traction control that can be applied more or less individual to each wheel. All in all the additional rear steering neither achieves a positive nor a negative effect. In contrast, the superimposed front steering slightly worsens the longitudinal dynamics because of a lateral deviation of the vehicle while braking on μ-split that may lead to an increase of the stopping distance.

Summarising this step of investigations it can be stated that additional rear steering mainly improves vehicle handling, superimposed front steering improves both the road holding abilities and stability and finally brake intervention is most suited to the stability and longitudinal dynamics of the vehicle. The results also show that no system is able to optimally influence all categories of vehicle dynamics. When a further improvement is required, then a combination of systems is necessary.

4 Combined systems <u>without</u> functional connections

4.1 Description of the combined systems

A combination of systems is defined as the use of multiple systems that act without any functional connection, **Fig. 6**. This can imply that different systems can control the same vehicle motion independent of each other. In this research, one of the additional steering systems is combined with brake intervention. Doing this it should be possible to combine right the positive features of the stand-alone systems. A combination of the two additional steering systems does not seem to be practical. This would not lead to a better coverage of all regarded categories of vehicle dynamics. Furthermore, it would also require an additional investment from a hardware point of view.

4.2 Results with the combined systems

The results show that the two combinations achieve similar performances, especially in the categories of vehicle stability and road holding, **Fig. 7**. It is possible to reach the outstanding properties of the stand-alone systems. With regard to the vehicle stability one can observe that brake intervention is not affected by the additional steering systems.

The same holds for the combination of superimposed front steering and brake intervention in terms of road holding abilities. Also in this category the front steering is not affected by brake intervention. However, the performance can be improved if the additional rear steering and brake intervention are combined.

For the handling abilities this is no longer the case. The benefit of the additional rear steering suffers from the influence of brake intervention. This occurs for example during strong deceleration. In these situations the additional steer angles are too large and destabilize the vehicle because the rear steering does not take into account the inputs from the brake intervention system. The superimposed front steering is not as suitable to improve vehicle handling, even in combination with brake intervention. The reasons for this have been discussed previously in the results of the stand-alone systems.

The longitudinal dynamics can clearly be improved in the combined configuration. Once again here the superimposed front steering is not as useful as rear steering. However, the fact that both steering systems achieve an improvement of the longitudinal dynamics combined with brake intervention proves the clearer separation in lateral and longitudinal control tasks. The vehicle is mostly stabilized by the steering systems, so that the required brake intervention does not have such an effect on the vehicle velocity. In addition, brake and traction slip control can be applied to each wheel individually because the resulting disturbances on lateral dynamics are compensated by the steering systems. This is quite interesting as there is no interaction between the two systems in this stage of investigation.

In general it can be stated that it is possible to combine the advantages of different systems by using them in parallel. It is also clear that negative interferences can occur as well which can lead to a reduction of over-all performance. Because of this it is necessary to adapt the systems so that they influence each other in their control laws.

A closer investigation into the results show that superimposed front steering is not as useful in combination with brake intervention as additional rear steering is. The main reason for this is that the handling abilities cannot be improved as much as it is the case when using rear steer and brake intervention. The combination of rear steer with brake intervention therefore promises the highest increase of performance in the design of an integrated system.

5 Integrated systems (combined systems <u>with</u> functional connections)

5.1 Description of the integrated systems

The integration of rear steering and brake intervention can be derived directly from the previous analysis of the combination of the two systems. The two systems are integrated by linking the control laws with a weighting function. The concept is to apply brake intervention in dependency of the condition of the rear steer input, **Fig. 8**. The weighting function lies between zero (brake intervention switched off) and one (brake intervention switched on). A weighting value between these two extremes implies that brake intervention is applied only partially.

The value of the weighting function is designed to increase when the additional rear steer angle δ_{HA} clearly exceeds the value of the feed forward loop $\delta_{H\,Steuer}$ and approaches the limit of actuation $\delta_{H\,max}$, **Fig. 9**. Additional links are implemented between the two systems in order to improve the performance for specific situations.

5.2 Results with the integrated systems

With the proposed approach of integration one can avoid the negative interferences between the systems. The performance evaluation shows that the integrated concept achieves values that exceed those of all previous configurations, **Fig. 10**. One can observe the following:

This effect of integration comes out very clearly when regarding handling performance. It was clear that the additional rear steering is very useful to improve the vehicle handling, but in the combined case it was disturbed by brake intervention. The integration not only avoids this disadvantage but it also reaches a performance that exceeds that of the stand-alone rear steering concept. That is achieved by taking the longitudinal acceleration into account in the control law of the rear steering thereby avoiding unnecessarily large steer angles.

For stability and road holding performance no additional improvement can be achieved in comparison to the combined systems. In these situations the two systems act quite independently. Brake intervention ensures stability on its own, while the improvement of the road holding is determined mainly by the rear steering.

The category of longitudinal dynamics once again shows the advantage of the integrated systems in comparison to the combined and stand-alone systems. The connection of the two systems in their control laws provides a high level of cooperation between the additional rear steering and brake intervention. The brakes need not be applied as often because yaw control is performed mainly by steer intervention. As a result, the vehicle velocity is not affected as much as it is the case for the simple combination of the two systems.

So it can be concluded that system integration can combine the advantages of the various systems whilst avoiding negative interferences. An improvement of vehicle performance can be reached in a wide range of dynamic characteristics.

6 Summary

On a simulation level it was possible to quantify the influence of vehicle control systems when being used in a stand-alone, a combined or an integrated configuration. The superimposed front steering, additional rear steering and the brake intervention system have been investigated.

The stand-alone systems have very specific properties. Additional rear steering can mainly improve the handling qualities. The superimposed front steering has strong advantages for road holding and stability. The brake intervention system is most suitable to improve stability and the longitudinal dynamics. It could be summarised that it is necessary to combine various systems in order to achieve improvements in all categories of vehicle dynamics.

The combination of brake intervention with each of the additional steering systems showed that it is possible to combine the specific properties. The analysis also partially showed that the combined performance for specific properties had decreased in comparison to the stand-alone systems due to disturbances between the systems. It was therefore necessary to connect the systems in their control laws instead of using them in simple combination.

The proposed integration of additional rear steering and brake intervention is able to exploit the positive properties of the individual systems while avoiding negative interferences. This could be achieved by use of a weighting function so that the rear steer angle controls the brake intervention. The full system is able to improve the vehicle dynamics over a wide range of manoeuvres, thereby clearly exceeding the performance of the stand-alone systems.

Figures

	Lateral Dynamics	Long.- / Lateral Dynamics
Steering	Additional Rear Steering Superimpos. Front Steering	-
Brakes	Brake Intervention	Brake Slip Control
Power Train	Engine Intervention Active Differential	(Drive) Traction Control

Fig. 1: Possibilities to improve vehicle dynamics through different control systems

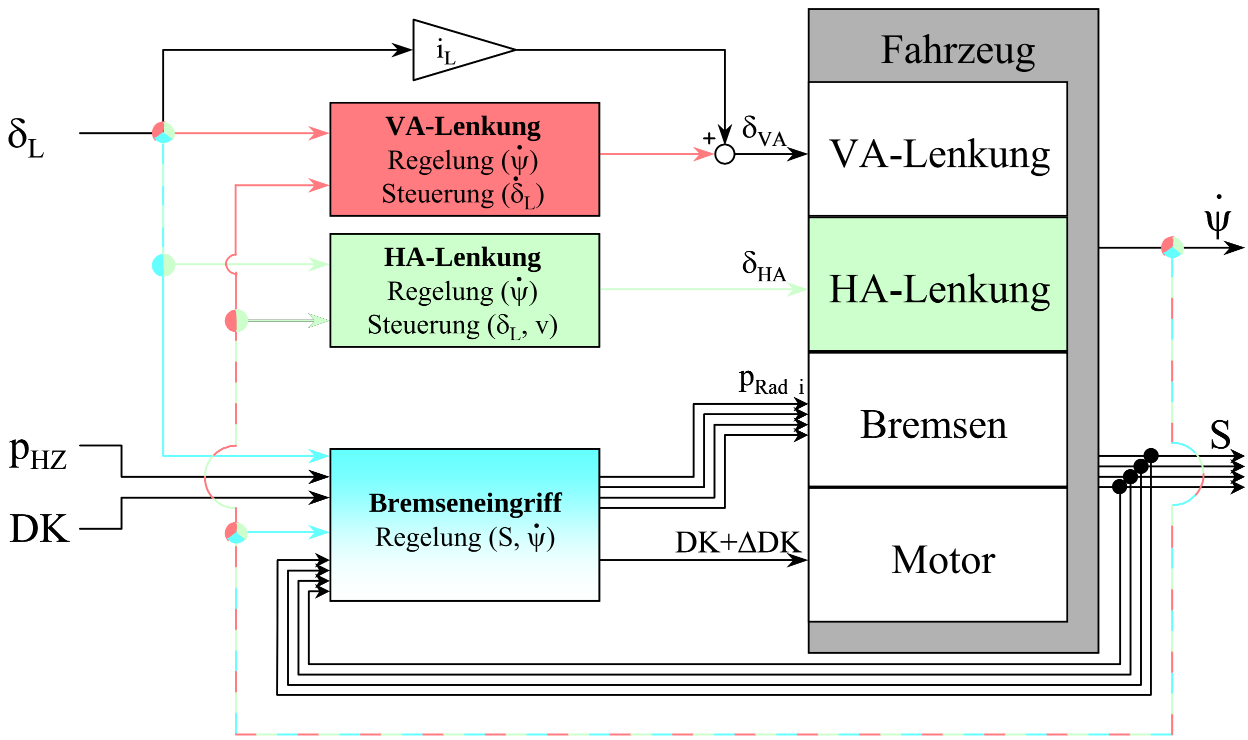


Fig. 2: Schematic depiction of the investigated systems

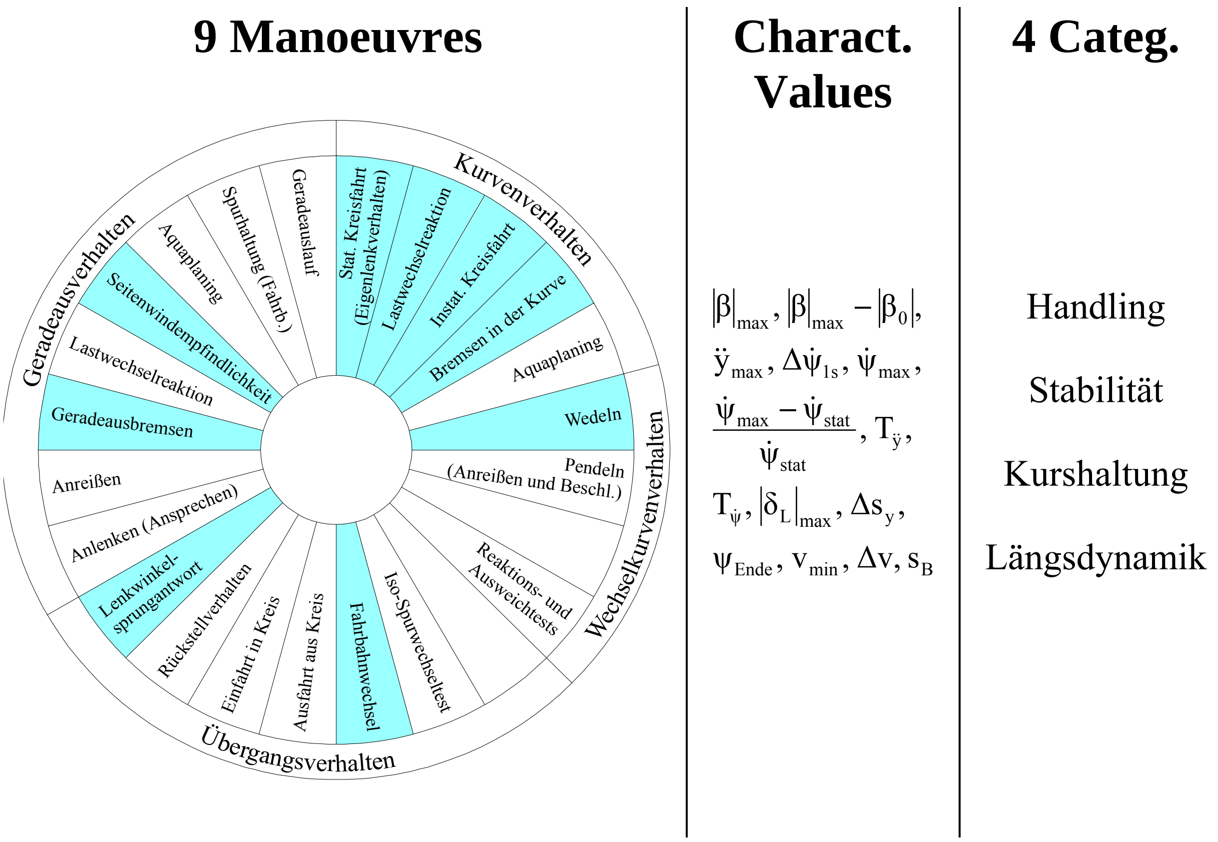


Fig. 3: Overview of the investigated manoeuvres (blue segments in the circle) and its analysis

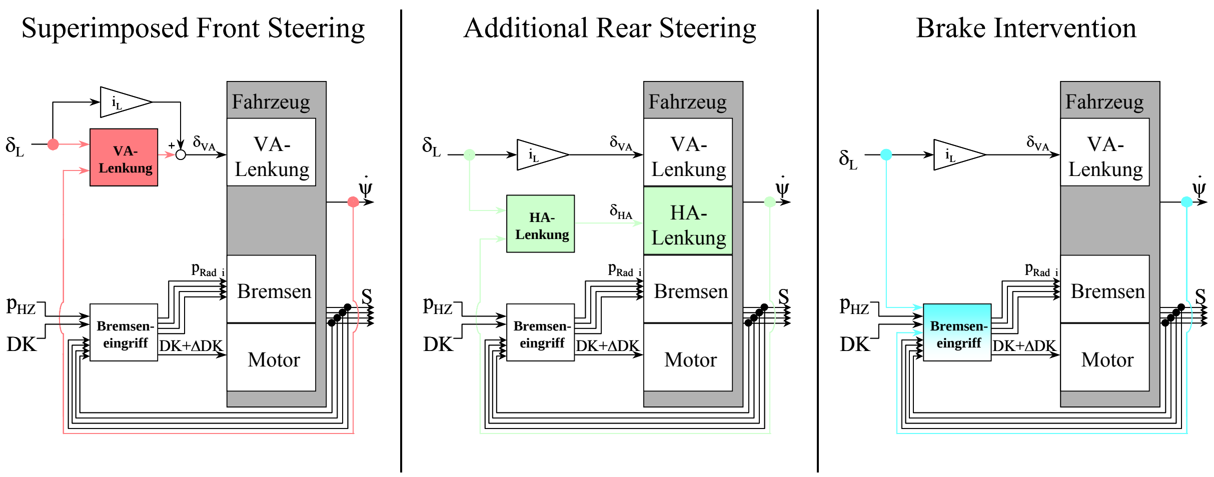
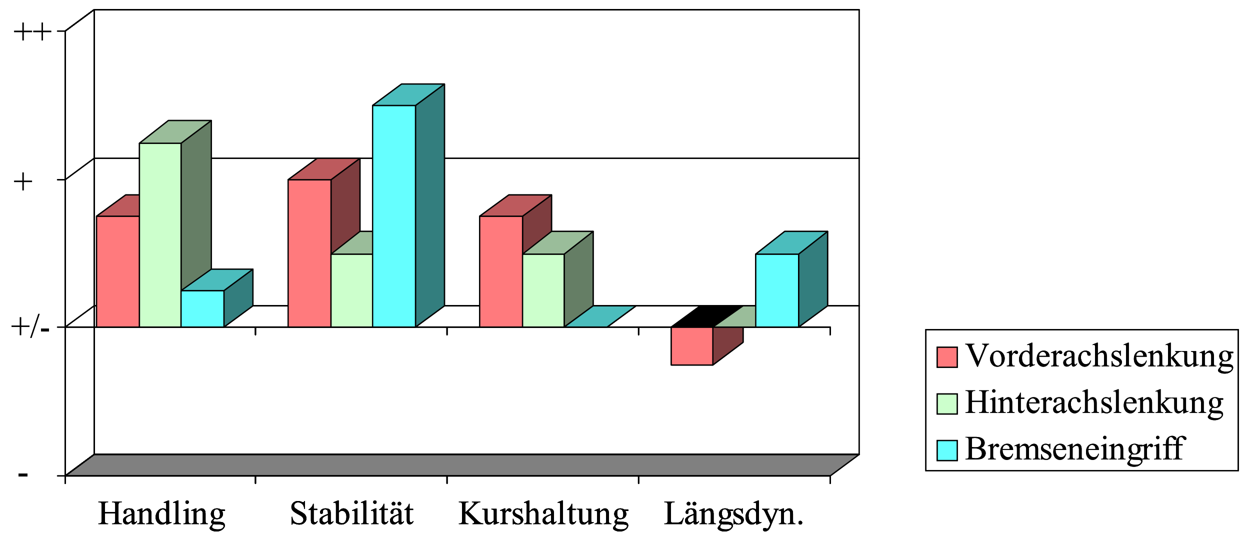


Fig. 4: Illustration of the stand-alone systems



Legende: ++ = sehr gute Eignung   +/- = kein Zusatznutzen
+ = gute Eignung   - = nachteiliger Effekt

Fig. 5: Results of the stand-alone systems

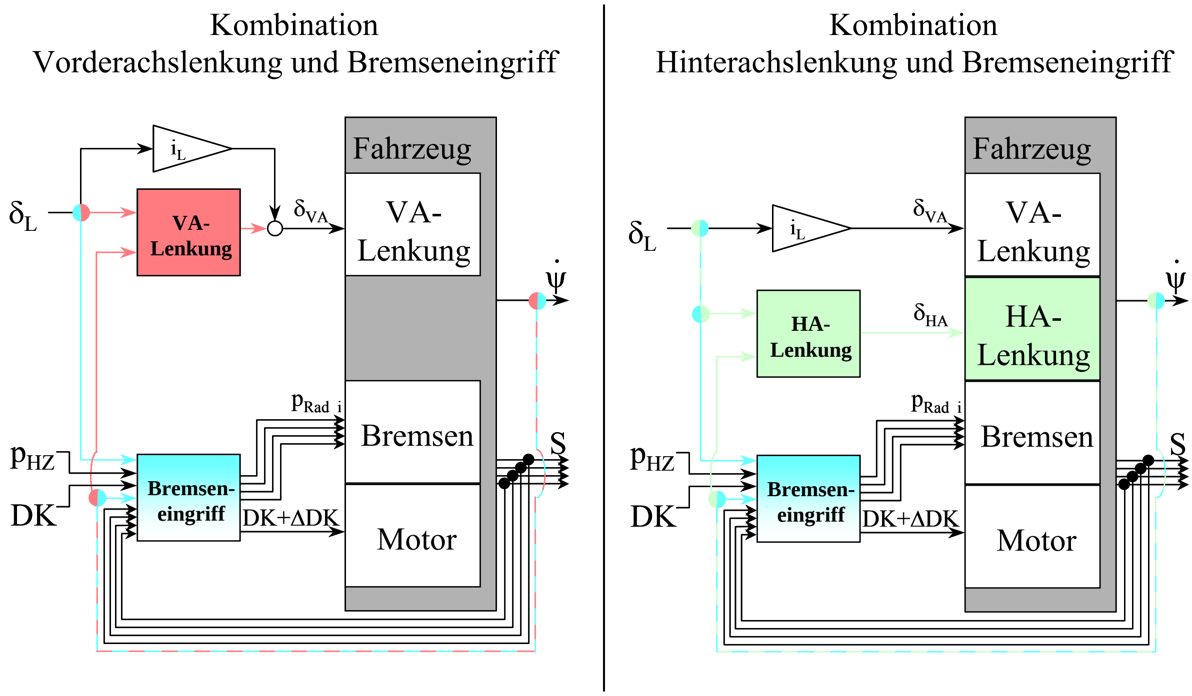


Fig. 6: Illustration of the combined systems

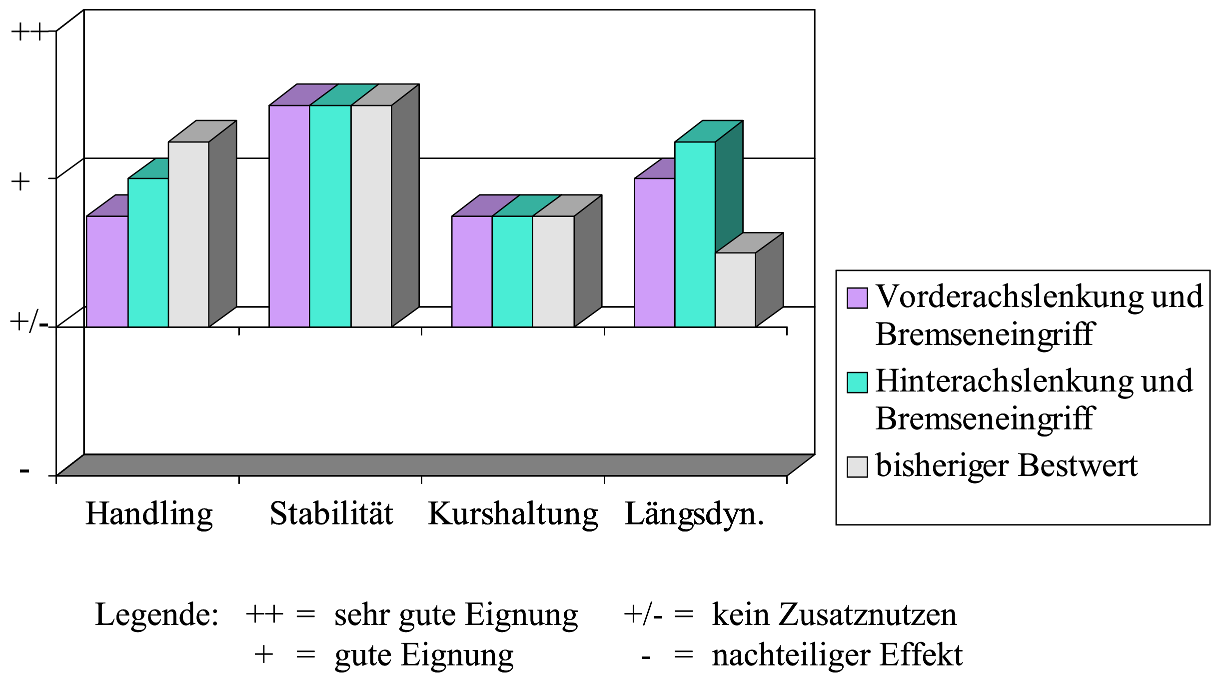


Fig. 7: Results of the combined systems

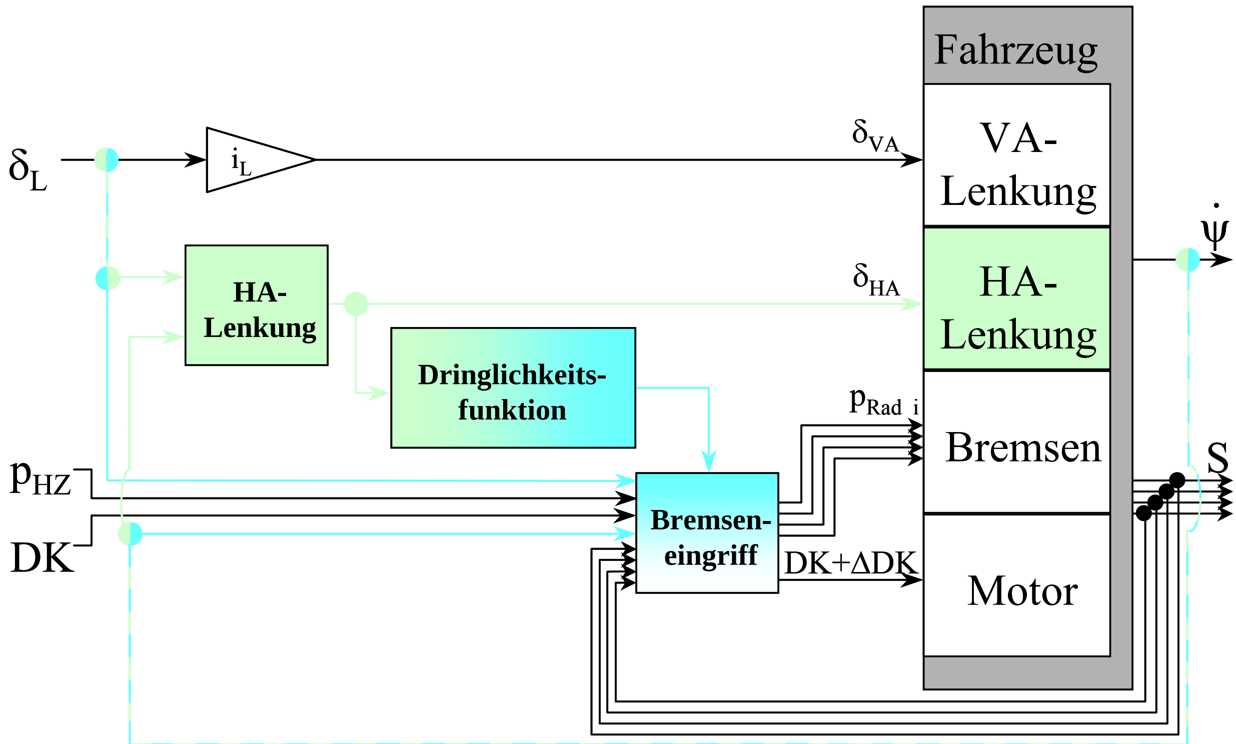


Fig. 8: Illustration of the integrated rear steering with brake intervention

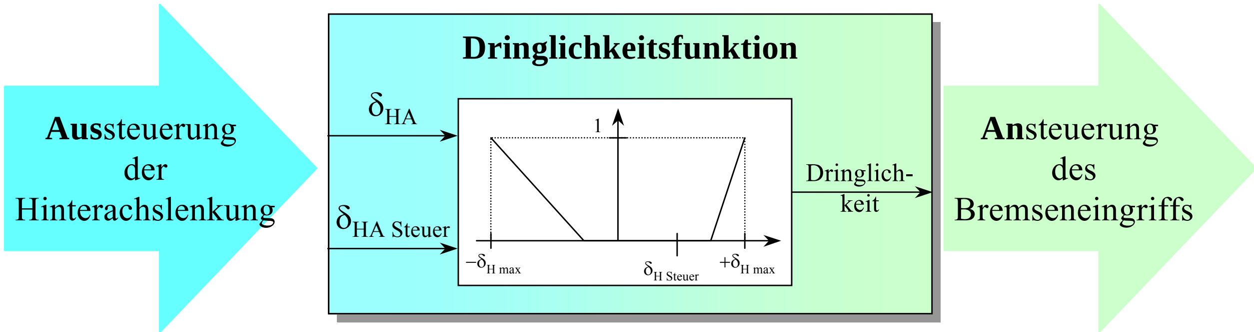


Fig. 9: Illustration of the weighting function for brake intervention

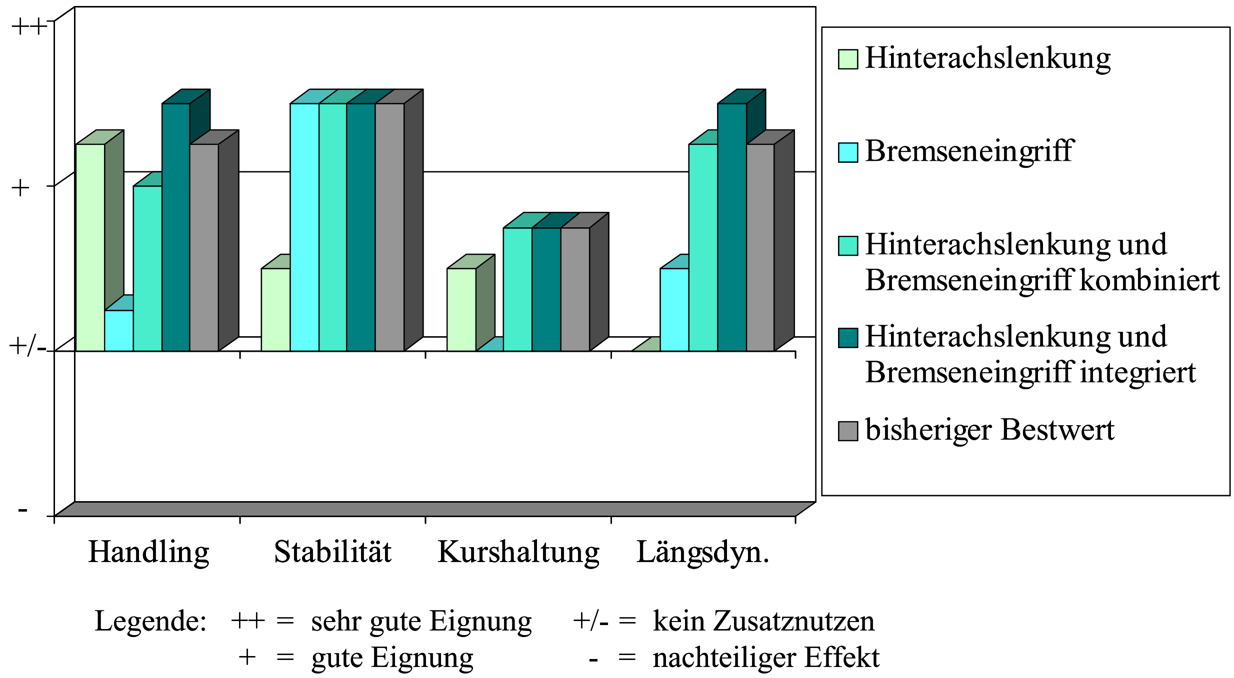


Fig. 10: Results of the integrated systems

Used Symbols

DK Throttle
i_L Steering ratio
p_{HZ} Brake pressure at master cylinder
p_{Rad} Brake pressure at wheel cylinder
S Slip
s_B Braking distance
s_y Lateral deviation
T Response time
v Vehicle velocity
$\ddot{y}$ Lateral acceleration

β Sideslip angle
δ_L Steering wheel angle
δ_{HA} Steer angle at rear wheels
δ_{VA} Steering angle at front wheels
$\dot{\psi}$ Yaw velocity

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