A LANE KEEPING ASSIST SYSTEM FOR PASSENGER CARS

-DESIGN ASPECTS OF THE USER INTERFACE

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ABSTRACT

Many road departure accidents are caused by the drivers' lack of attention. This is in many cases due to distraction, drowsiness or intoxication. The Lane Keeping Aid System (LKAS) described in the paper intends to be used as an active safety system, thus aiming at decreasing the amount of unwanted lane departures. The challenge in the development of such kinds of functions lies in the determination of dangerous situations and the design of appropriate warning/ intervention strategies. The system is intended to go unnoticed with the driver and intervenes only in instances where the driver mismanages steering control. Unlike systems which issue an audible sound, the type of warning is a tactile feedback via the steering wheel. The torque is designed in a way that it communicates to the driver the appropriate steering wheel angle required in order to return in lane. In this paper, both the underlying ideas for such a lane departure warning system and test track measurements will be presented and discussed.

1. INTRODUCTION

Surprisingly many Single Vehicle Roadway Departures (SVRD) accidents take place in comparable uncritical traffic situations and good weather conditions, see ADAC (2001). Such accidents are often road departures due to drivers' lack of attention. SVRD accidents are often caused by the driver's distraction, drowsiness, intoxication or illness which leads to the relinquishment of lane keeping (LK) control.

The lane keeping assist system described here is intended to be an active safety system, thus aiming at decreasing the amount of unwanted lane departures and preventing a possible subsequent accident. In this manner, active safety functions collaborate with the driver-vehicle system in order to increase the overall system performance in critical driving situations. The principal system layout is shown in figure 1. Besides technical issues such as sensor and actuator performance, the challenge in the development is to find the "correct code of communication" between human and machine. Product ergonomists call this *scenaric transparency*, i.e. the understanding of an advice is an essential prerequisite of its following. An overall goal with the Human Machine Interface (HMI) is besides enhancing transparency, to increase system reliability. Here the behavioral science definition of reliability is more important than the engineering definition. The higher the driver's confidence in the system is, the more active safety issues can the car manufacturer associated with it. In these terms system transparency is a contributing factor for reliability, i.e. if the driver fully understands the systems function his/her confidence in the system increases thus increasing reliability.

Lane keeping assist systems have been in focus during the last years, leading to an abundance of different system layouts in terms of sensors, actuation and HMI. Before entering details about the system described here, a classification scheme is briefly discussed. According to Pilutti it is useful to distinguish between *warning, intervention and control* functions. *Warnings* do not directly alter the vehicle trajectory and require that the driver must choose to act on the warning in order for the warning to have any effect. Intervention and control have the ability to directly affect the vehicle trajectory. *Intervention* has limited authority and is meant to augment driver commands – not replace them. *Control* is defined here as automatic control having full authority to steer the vehicle, which effectively removes the driver from the loop. This definition gives rise to the question of the appropriate actuator for lane keeping. There are in principle two ways to intervene with the vehicle in terms of steering, namely to provide a torque signal in the steering wheel, or to provide a differential wheel angle (which could be accomplished on the front or rear axle). The size of the angle or torque determines whether such a system is classed as an intervention system or a control system, i.e. whether it is possible for the driver to override the system.

In terms of this definition the system presented here falls in the category of intervention systems, since the driver perceives a torque feeling in the steering wheel which mediates the correct lane position but still can be overridden by the driver. However, the type of intervention provided is of importance as well, i.e. how the torque is built up. In Pohl *et al* (2003) an intervention system for unintended roadway departure is discussed, where the principle of operation is a steering wheel torque which is related to the vehicle lateral position and speed in relation to the lane boundaries. This approach is extended here taking lateral vehicle dynamics into account, so that the torque signal guides the driver back in lane.

therefore an offset torque to the base assist torque. In contrast to the Lane Keeping Aid Systems presented by Naab *et al.*(1994) and by Renault, where an extra actuator on the steering column is used in order to produce the additional torque requested by the system, an Electric Power Assisted Steering (EPAS) gear is used.

An important issue is how the steering wheel torque relates to lane position and how this torque is perceived by the driver. The Lane Keeping Aid module shown in figure 1 consists of several sub modules, namely a vehicle state observer, steering angle calculation, torque calculation as well as an intervention module.

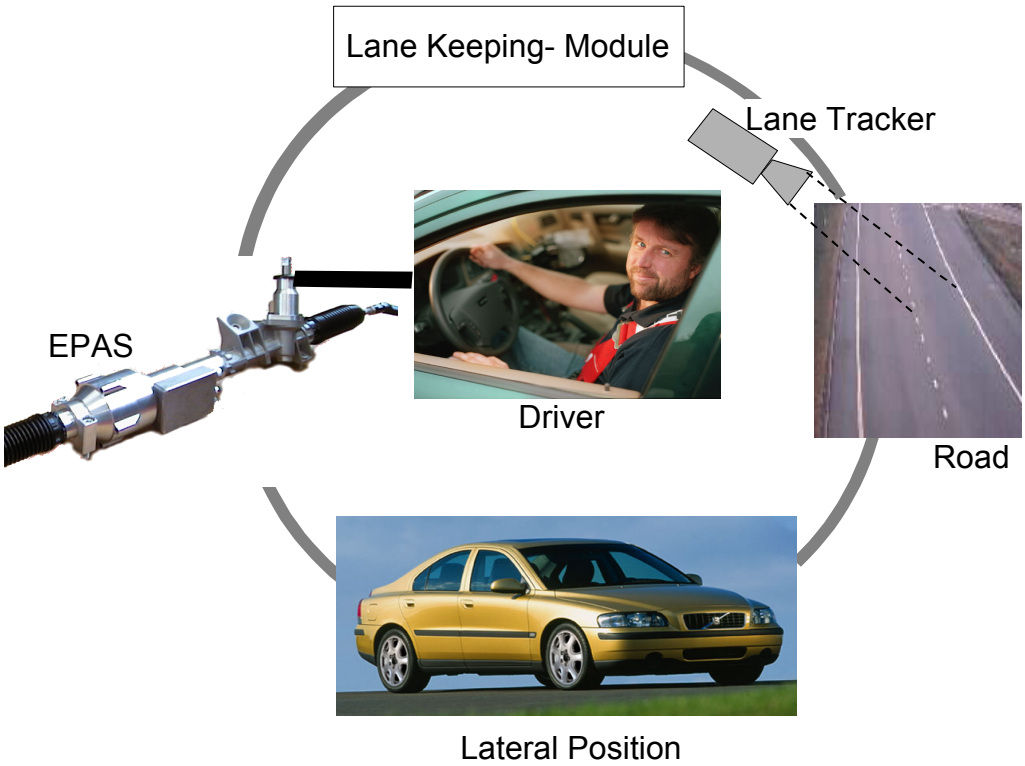

Figure 1. Principal System Layout for a Lane Keeping System

In this paper, both the underlying theory for such a lane keeping system as well as test track measurements with test participants will be presented and discussed.

2. Lane Keeping Module

Figure 2 shows the principle layout of the required hard and software modules as they have been implemented in the test vehicle. A CCD camera is used in order to detect the current lane position, while an Electric Power Assisted Steering (EPAS) actuator is used in order to generate the required offset torque in the steering column. As the EPAS is primarily used for power assisted steering, it provides an assist torque which is determined by the boost curve and the current driving conditions. The lane keeping torque is

The task of the vehicle state observer is to calculate the required vehicle states as well as road geometry data from camera and vehicle data. From these signals the optimal steering angle is computed, which is translated into a steering wheel offset torque by the torque calculation module. This torque is superposed on the basic power steering assist characteristic. The intervention module finally determines whether all required conditions for a steering intervention are fulfilled, as well as duration of this intervention. Intervention criteria are for instance the current lane position, indicator and brake pedal activity as well as whether the driver has his/her hands on the steering wheel or not. The individual modules are discussed in detail in the following sections.

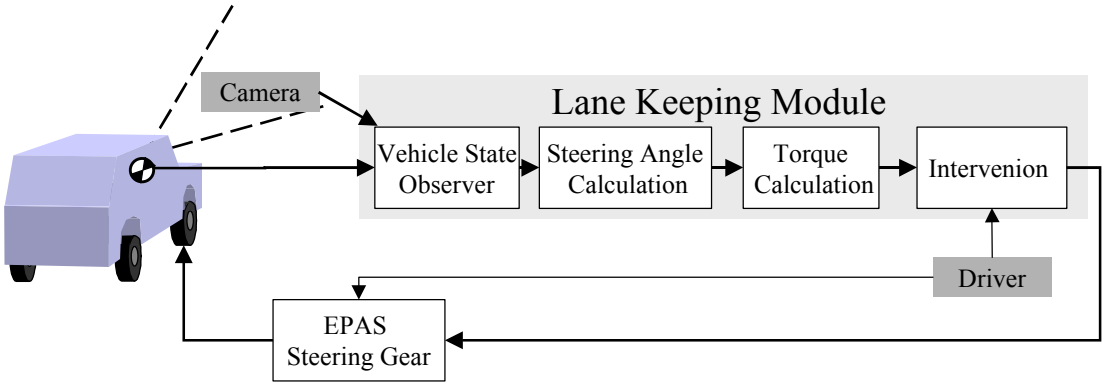

Figure 2. Components and Sub-functions of the Lane Keeping System

2.1 Vehicle State Observer

In order to establish the vehicle state observer, where even state variables of the road are included, several sets of equations describing vehicle motion, road geometry and the discrete state observer equations itself are required.

2.1.1 Vehicle Equations of Motion. The vehicle model used here is a so called bicycle or one-track model, where the vehicles roll motion (rotation round x-axis, see figure 3), pitch motion (rotation round y-axis) and bounce (z-axis) are neglected. These simplifications reduce the order of the model to four degrees, namely yaw rate, sideslip angle and side force on both front and rear axle.

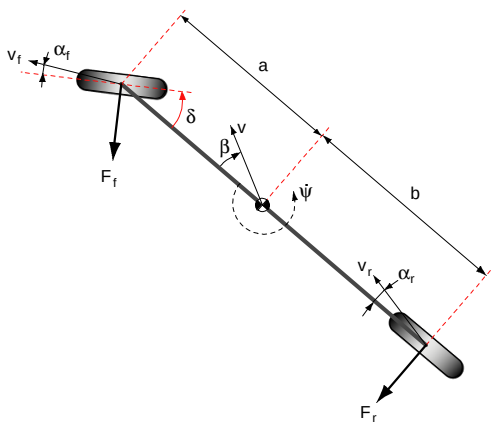

Figure 3. Bicycle Model

The vehicles front and rear axle track is thus set to zero and the front and rear tires are lumped to one single tire respectively. Both wheels on one axle thus share the same steering angles and each wheel produces the same side force. These simplifications are reasonable for driving scenarios with moderate side accelerations (< 0.4 g on normal dry asphalt roads, (Milliken and Milliken, 1995)) and constant vehicle speed. However, when it comes to test cases with higher side accelerations and/or acceleration and braking, a more complete vehicle model that even takes the vehicles roll and pitch characteristic into account, should be used. Figure 3 depicts the bicycle model with state variables yaw rate $\dot{\Psi}$, sideslip angle b and lateral force on both front F_f and rear axle F_r.

Using the equations of motion round the vehicles center of gravity yields:

$$F_f(a_f) + F_r(a_r) = ma_n \tag{1}$$

$$F_f(a_f)\cdot a - F_r(a_r)\cdot b = J\ddot{y} \tag{2}$$

The lateral acceleration a_L is related to yaw rate and sideslip angle time derivative by equation (3):

$$a_L = v_t \cdot \left(\dot{y} + \dot{b}\right) \tag{3}$$

The lateral forces F_f and F_r are functions of the sideslip angle

$$F_f = C_f \cdot a_f,\ F_r = C_r \cdot a_r \tag{4}$$

In equation (3) C_f and C_r are the cornering stiffnesses of front and rear tires respectively. The tire sideslip angel at front and rear can be calculated from yaw rate, vehicle sideslip angle and wheel angle:

$$a_f = d - b - \frac{\dot{y}\cdot a}{v},\quad a_r = -b + \frac{\dot{y}\cdot b}{v} \tag{5}$$

Equations (1) to (5) lead finally to the two state equations for sideslip angle and yaw rate:

$$\dot{b} = -\frac{1}{mv}(C_f + C_r)b - \frac{1}{mv}(m\cdot v^2 + C_f\cdot a + C_r\cdot b)\dot{y} - \frac{1}{mv}\cdot C_f\cdot d_H \tag{6}$$

$$\ddot{y} = \frac{1}{J}(C_f a - C_r b)b - \frac{1}{J}(C_f a^2 - C_r b^2)\dot{y} - \frac{1}{J}C_f\cdot a\cdot d_H \tag{7}$$

2.1.2 Lateral Vehicle Motion Relative Lane Boundaries. In the following required relations for lateral vehicle control are reviewed, see figure 4.

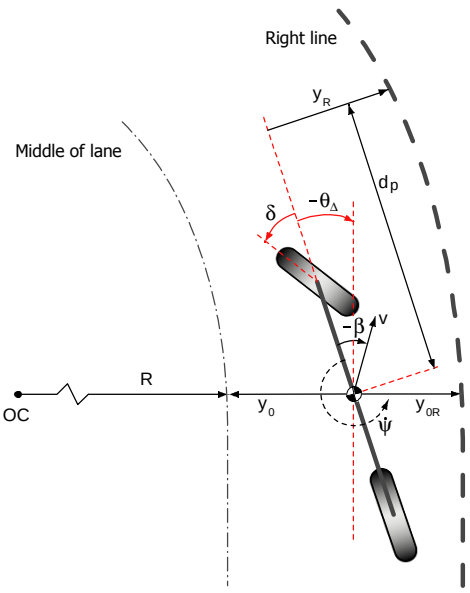

Figure 4. Lateral Vehicle Motion Relative Lane Boundaries

The motion of the vehicle relative to a given path, here prescribed by the road geometry, can be described by the vehicle heading angle Θ_Δ and the lateral distance to the lane markings at the vehicles center of gravity, here denoted as y_{0r} and y_{0r} for the right and left lane marking respectively.

$$\dot{q}_\Delta = -\dot{y} + \frac{v}{R} \tag{8}$$

$$\dot{y}_{0R} = \dot{y}_{0L} = v\sin(-\Theta_\Delta - (-b)) \tag{9}$$

$$\approx v(-\Theta_\Delta + b) = vb - v\Theta_\Delta$$

In order to determine the rate of the heading angle form equation (8), the road radius must be measured. This can be done directly by the camera system in case the video image is processed at several preview distances. However, this requires a camera with a comparably long look ahead distance. If the road radius or curvature (the inverse of the radius) cannot directly be obtained from the camera system, it can be calculated from the following equation, taking the vehicle motion into account.

$$y_L = Dp \cdot q_D + y_{0L} + \frac{Dp^2}{2R} \tag{10}$$

$$y_R = Dp \cdot q_D + y_{0R} + \frac{Dp^2}{2R} \tag{11}$$

Equations (6)-(11) describe the required relations for the estimation of vehicle and road state variables from lane position and vehicle yaw rate measurements.

2.1.3 State Observer. Kalman filtering is a well known estimation technique. When the system dynamics vary with time then the system matrices needs to be updated in every time step which requires a time dependant Kalmanfilter. A discrete state space can be described as:

$$\begin{aligned} x(t+1) &= Fx(t) + Gu(t) + v_1(t) \\ y(t) &= Hx(t) + v_2(t) \end{aligned} \tag{12}$$

where x are the system state variables (namely body sideslip angle, yaw rate, lateral distance to lane boundary, heading angle and road curvature), u the input signal and y is the output signal (here the state vector). The matrices F and G are obtained from the previous derived equations in a straightforward manner. These are time dependent due to the time dependency of the vehicle velocity. Here T is the sampling time.

The measurement update of the states is given by feedback of the innovation, i.e. the difference between the estimated and the measured signal.

$$\begin{aligned} &\hat{x}(t \mid t) = \\ &\hat{x}(t \mid t-1) + L(t)(y(t) - H\hat{x}(t \mid t-1)) \end{aligned} \tag{13}$$

The measurement update of the error covariance matrix P is given by:

$$\begin{aligned} &P(t \mid t+1) = P(t \mid t-1) - P(t \mid t-1)H^T \\ &(HP(t \mid t-1)H^T + R_2)^{-1} H \; P(t \mid t-1) \end{aligned} \tag{14}$$

The calculation of the Kalman gain L takes into account the uncertainty of the estimates and measurement noise R_2.

$$\begin{aligned} &L = P(t \mid t-1)H^T \\ &(HP(t \mid t-1)H^T + R_2)^{-1} \end{aligned} \tag{15}$$

The time update of the P-matrix is given by:

$$P(t+1 \mid t) = F \; P(t \mid t)F^T + R_2 \tag{16}$$

Finally, the time update of the state estimate, i.e. the new state vector, is given by:

$$\hat{x}(t+1 \mid t) = F\hat{x}(t \mid t) + Gu(t) \tag{17}$$

From the estimated state vector the optimal steering angle and steering wheel offset torque are calculated as explained in the following. A thorough treatment of Kalman filter techniques and applications can be found in Gustafsson et. al. (2001).

2.2 Steering Angle and Torque Calculation Modules

The steering angle module calculates the optimal steering angle in order to guide the vehicle back into lane using the observed states from the observer.

$$d_{opt} = \left[\left(\frac{b}{C_f} - \frac{a}{C_r}\right)\frac{m}{(a+b)}v^2 + (a+b)\right]b_{steer} \cdot k \qquad (18)$$
$$+ K_{\Theta\Delta}(v) \cdot \Theta_\Delta + K_{y0}(v) \cdot y_0$$

The optimal steering angle d_{opt} is calculated using curvature, heading angle and vehicle lateral displacement at the center of gravity. The curvature can be seen as an outer disturbance thus being feed forward, while heading angle and lateral displacement are "feedback" signals. The gains for the latter are linearly dependent on the vehicle speed, and the curvature gain is obtained from the well known steady state cornering equation.

The torque calculation module consists of a feed forward and feedback path, with two vehicle speed dependent coefficients:

$$T = K_{ff}(v) \cdot d_{opt} + K(v) \cdot (d_{opt} - d) \qquad (19)$$

2.3 Intervention Module

The task of the intervention module is to make decision whether an intervention should occur and the duration of the same. The basic intervention strategy is illustrated in figure 5. Steering intervention should occur, when a set of conditions are fulfilled. These conditions can with advantage be arranged in different clusters, such as driver, vehicle and road/environment clusters.

The driver cluster contains information regarding the driver status in terms of drowsiness and distraction, as well as whether the driver has his/her hands on the steering wheel or not. A method for deriving this signal making use of the steering column torque provided by the EPAS system is discussed in the following section.

The vehicle cluster contains conditions about the vehicle states, such as vehicle speed, acceleration, braking, indicator operation, lateral acceleration and applied LK-torque. In the road environment cluster conditions regarding curvature, distance to lane marking and heading angle are included. If all conditions from the driver and vehicle cluster are fulfilled, intervention shall occur when the vehicle enters the intervention zone indicated in figure 4, and end when the heading angle is below a certain threshold. The time history of the applied torque is shown as well. This torque will guide the driver back in lane outside the control zone.

2.3.1 "Hands On" Detection. An integral component of lane keeping systems where the steering characteristics are changed due to lane position is a device which prevents the driver from misusing the system as an auto-pilot as stated by Balzer. The driver must always be kept “in the loop” and is thereby ultimately responsible for the control of the vehicle. Such a device could be a steering wheel which is sensitive to pressure on the steering wheel rim, in order to detect whether the driver has his/her hands on the steering wheel or not. Thereby an extra sensor is added to the system, which increases system costs.

Here the existing steering column torque sensor of the EPAS system is used in order to estimate the amount of torque which is applied on the steering wheel by the driver. The correct estimation of the driver’s torque is essential for the proper functioning of the “Hands on” detection. If the torque applied on the steering wheel is understood as an outer disturbance, a Kalman filter which includes a simple model of the column assembly can be used. Such a Kalman filter requires a set of observable measurements, here we use the pinion torque (as the torque sensor of the EPAS steering gear is used) and the steering wheel angle, see figure 3.

In figure 5, T_S represents the sensor torque, T_H represents the driver’s torque, $\hat{T}_H$ represents the estimated driver’s torque, L the Kalman gain (calculated from the covariance matrices from

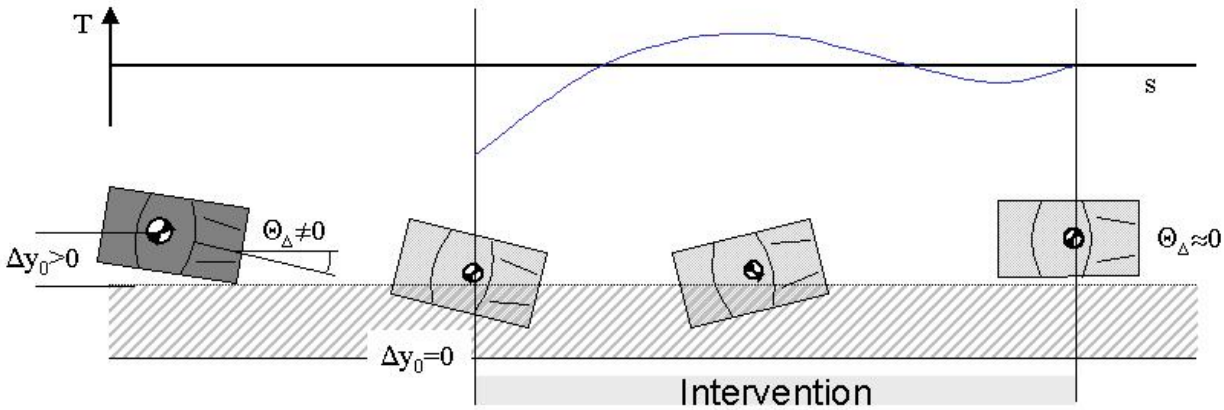

Figure 5. Intervention Strategy for the Road/Environment Cluster

process and measurement noise), B_V the viscous friction coefficient, α the steering wheel angle and J the steering wheel inertia. For real time applications the filter needs to be transformed into the discrete time domain which is straightforward using for instance the zero-order hold transform.

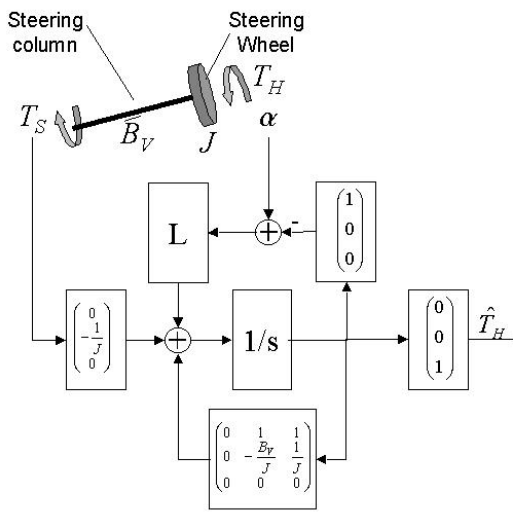

Figure 5. Disturbance Observer Kalman Filter

In instances where the driver does not apply any torque on the steering wheel, i.e. "Hands-off", the estimated driver torque $\hat{T}_H$ should be zero, if the model perfectly represents the dynamic characteristics of the steering column assembly. As for example frictional effects are only modeled by simple viscous friction and stick slip issues were neglected, the Kalman filter "confuses" these with a torque from the driver. The same counts for acceleration effects (as well as gravity effects) due to non-centric center of gravity (CG) where the lateral acceleration (or gravity) times the steering wheel mass and CG eccentricity acts as a torque on the wheel. Acceleration effects are easy to implement into the filter, but proved to have only minor influence on the estimated steering wheel torque in contrast to non-linear friction.

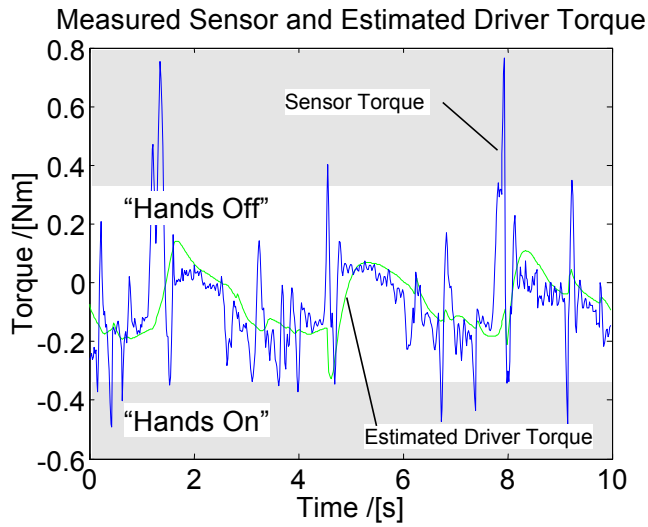

Figure 6. Torque Signals T_H and T_S of the Steering Column Assembly from Figure 5

However, thresholds can be used for deciding whether "Hands-On" or "Hands-Off" cures the problem in a practical manner. If the observed driver's torque is below a certain threshold over a certain time, the lane keeping torque is deactivated. This is interpreted as "Hands-off", meaning that the driver does not have the hands on the steering wheel. As soon as the driver applies a torque again the system will be activated.
In figure 6 the measured and Estimated Sensor torque signals are shown, as well as two zones for "Hands-On" and "Hands-Off" determination.

3. Measurement Results

Figure 7 to 10 show a test case where the driver deliberately forces the lane marking without entirely leaving the lane. The vehicle lane position, steering wheel angle, lane keeping torque as well as estimated drivers torque have been recorded.

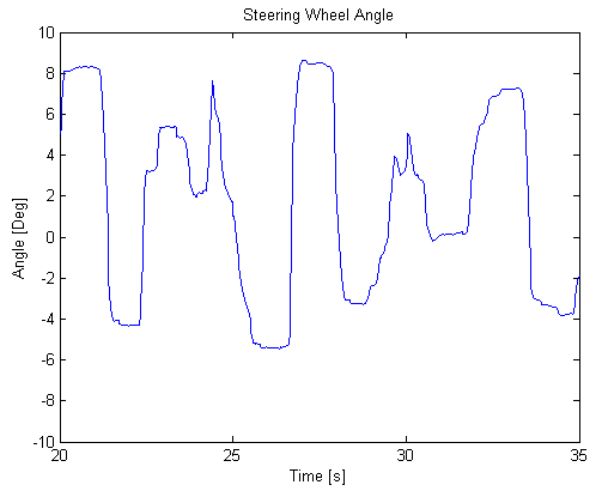

Figure 7. Measured Steering Wheel Angle

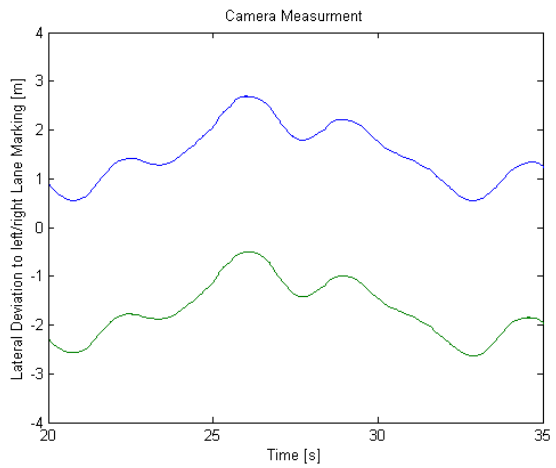

Figure 8. Measured Lane Position, i.e. Distance to Left and Right Lane Marking

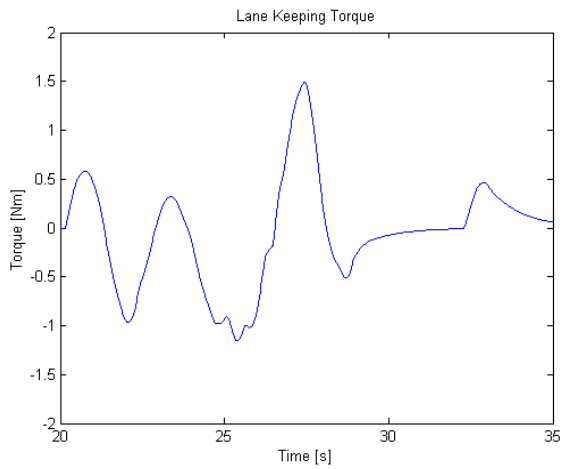

Figure 9. Applied Lane Keeping Torque

A close inspection of the lane position in figure 8 produces the impression of an oscillatory system behavior. However, it has to be kept in mind that the recorded sequence covers 15 seconds at a vehicle speed of 70km/h. The peak value of the lane keeping torque is 1.5 Nm and the main duration about 10 seconds. It has to be added that it is hard to assess the system performance from simulation or measurements only. Test and tuning has to be an integral part of the design procedure. However, the final judgement is to be made by the vehicle driver that the system is intended for. Concequently, human-machine aspects in terms of system transparency are of major importance. Tests with different drivers have been carried out in order to investigate these issues.

4. TEST DRIVE RESULTS

A decisive question in terms of customer acceptance, and whether a lane keeping system like the one described here truly reduces the amount of single vehicle accidents is if the driver intuitively understands the systems function, without knowing that a LKAS is active. Twelve participants have therefore been asked to drive the vehicle on a test track. The test participants have not been informed about the real intend of the experiment, they have rather been informed that their driving capability during distraction is measured. The experiment has been conducted on a closed track with only few other vehicles, and without oncoming traffic. In contrast to situation in real traffic, where severe distraction can result in dangerous situations, the drivers felt safe during the test, despite of larger lane deviations.

In order to produce lane deviation the test participants were severely distracted by several tasks they were asked to perform. These tasks started with changing radio channel, storing new channels in the radios memory, answering a cell phone and finally sending text messages from the same. A few test participants refused to execute certain tasks, as that might result in dangerous driving situations. This is important to have in mind when it comes to the evaluation of the questionnaire filled in by the test persons after the study. The fact that the usefulness of the system has been judged from proving ground driving only, influences surely the answers of the test participants on the test protocol.

It has to be mentioned that the test leader observed both the amount of LK torque and the test participant during the distraction tasks. It is interesting to note that the participants were highly occupied with the distraction tasks, that none commented on the steering intervention. Directly after the individual test programs were carried out the participants were asked if they liked the handling properties of the vehicle. Several drivers found the steering to behave strangely (see below), but could not relate this behavior to the driving situation.

After the driving test the drivers were asked to answer the following six questions, in a questionnaire: table 1.

1) How was your first impression of the system?

Since the test participants were not used to such kinds of systems, they ascribed the vehicle behavior to a number of different reasons, as for instance power steering malfunction or miss-aligned front wheels.

2) Was the functionality of the system easy to understand?

All test participants claimed that the system operation was far from being intuitive, and suggested an additional HMI in form of a designated lamp in the visual field.

3) Did the force given in the steering wheel bother you?

The majority of the test participants were not disturbed by the additional torque, however, two compared the function with lecturing the driver.

4) Did the system support you in your driving?

The drivers stated that the system lulls the driver in a sense of false security.
5) Did the system perform any incorrect maneuvers?
The test participants found the amount o torque applied on the steering wheel both to high and too low, which points out the need for a personalized setting of the LK-function.
6) Would you like to have a system like this in your car?

The questions were answered by ranking them on a scale from zero to ten, where ten is the perceived highest satisfaction. The mean value of the ranking, by question, is shown in table 1.

Table 1. Mean Values by Question

Question	Mean Value
1	5.1
2	7.1
3	6.3
4	5.7
5	7.2
6	6.6

The result indicates a promising satisfaction with the system. The majority of the test participants would like to have such a system installed in their own vehicle, if it is reasonably priced. However, it has to be remembered that the small size of the test group does not represent any statistical result.

5. Conclusions

In this paper design issues for a Lane Keeping Aid System are discussed, covering basic system requirements, algorithm modules and human machine interface aspects. The presented system has been tested on twelve drivers, who did not know the real intend of the test. In that manner, system transparency, i.e. whether the system function is intuitive or not, could be investigated.
The result of this investigation is twofold:

- The haptic interface as HMI in the steering wheel is in itself not sufficient. It is suggested that a multi-modal HMI is integrated to increase the driver's awareness about system operation. The HMI could incorporate a Head-up-Display or simply a standard symbol in an appropriate position together with the haptic steering wheel.
- In order to reduce the amount of nuisance warnings, the system needs additional information about the drivers' state in terms of distraction and drowsiness.

The next step towards a full-fledged Lane Keeping Aid System therefore includes detection of drivers' state, by e.g. integrating vision based driver monitors, which today unfortunately still lack the required robustness in terms of varying lightning conditions and varying drivers.

6. Nomenclature

b	sideslip angle	[rad]
k	road curvature	[1/m]
q_D	heading error	[rad]
a_f, a_r	front/ rear wheel angle	[rad]
d_H	wheel angle	[rad]
b_{steer}	gearing ratio	[-]
a, b	position of CG	[m]
a_L	lateral acceleration	[m/s^2]
Cf, Cr	cornering stiffness front, rear	[N/rad]
Dp	camera measurement distance	[m]
F	various forces	[N]
F, G, H	system, input, output matrix	
J	vehicle inertia aroiund z-axis	[Nm·rad/s^2]
K	various gains	
L	observer gain	
m	vehicle mass	[kg]
P	covariance matrix	
R	road radius	[m]
T	various torques	[Nm]
v	vehicle speed	[m/s]
v_1, v_2	noise vectors	
x, y, u	state, output, input vector	
y_0	lane position	[m]
$\dot{\Psi}$	yaw rate	[rad/s]

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