Control algorithm for hands-off lane centering on motorways

Chris **Van Dan Elzen** M.Sc., Dipl.-Ing. Axel **Nix,** Dr.-Ing. Karsten **Michels**
Magna Electronics, Inc.

Dipl.-Ing. Marc **Wimmershoff**, Dr.-Ing. Adrian **Zlocki**
ika - Institut für Kraftfahrzeuge – RWTH Aachen University, Aachen

Summary

The following paper deals with a lane centering system for motorways, which is implemented into a demonstrator vehicle in order to evaluate sensor performance and support the development process of assistance systems for lateral vehicle dynamics and lane detection sensors. The implemented system uses lane information acquired by a mono camera system, which is mounted behind the windshield of the demonstrator vehicle. At first, the motivation and an introduction to lateral dynamic assistance systems are given, which includes an overview of the systems which are currently available on the market. Furthermore, requirements on the developed lane centering system are presented, followed by the description of the lane centering system. The implemented controller is a predictive PID controller, which outputs a steering torque to the series production steering actuator. Finally, results of real-world test drives are shown to demonstrate the proper functioning of the system to test sensor performance with regards to lane detection.

1 Introduction

Since the mass introduction of automobiles, mobility is constantly increasing. Especially in the past few decades, individual traffic shows steady increases due to the availability of good road infrastructure and affordable vehicles. Based on the increasing complexity of the driving task, which is provided by the increased individual traffic, the number of accidents has also significantly increased in the past few decades. Passive safety measures were developed and made available. Therefore the number of killed humans is decreasing. Fig. 1 shows the development of individual traffic, the number of accidents and the number of killed occupants in Germany with the year 1975 as the basis. Furthermore the introduction of passive and active safety measures is provided. Active safety measures are available on the stability level and on guidance level of the driving task in form of advanced driver assistance systems (ADAS)

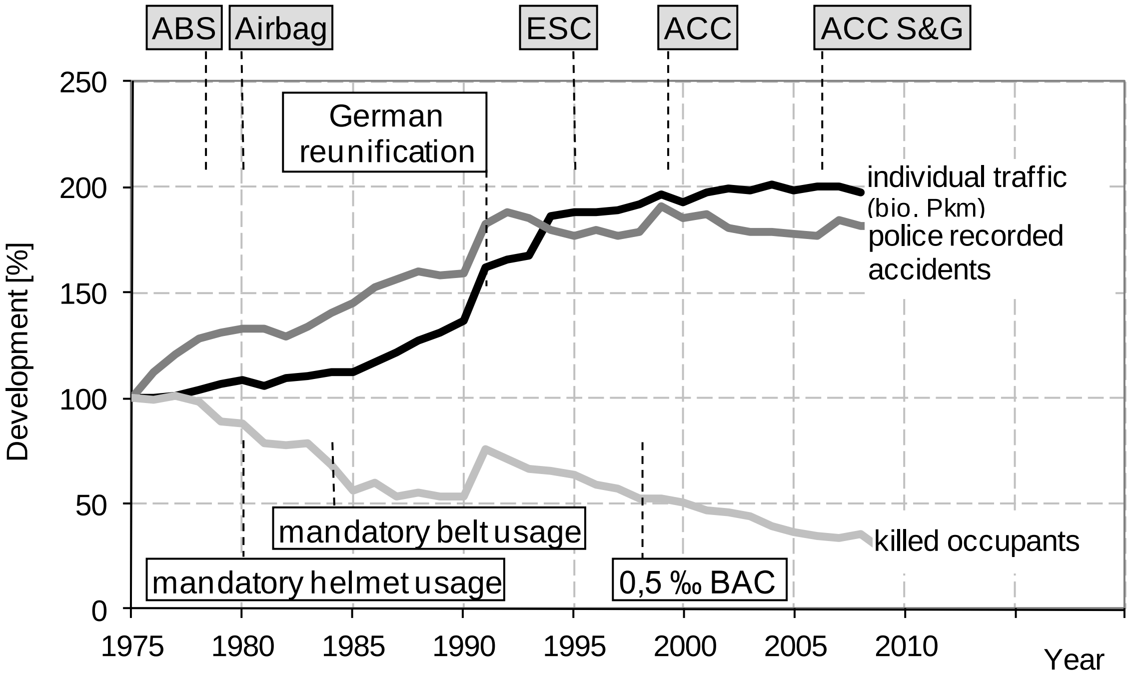


Fig. 1: Accident statistics of Germany [1]

ADAS help to release drivers from part of the driving tasks in monotonous driving situations, inform drivers with navigation advice or support them in critical driving situations by means of active safety measures. The production development of ADAS on vehicle guidance level with active intervention into the driving task started in Europe in the 1990s. Since then a variety of ADAS have been introduced into the market, see Fig. 2.

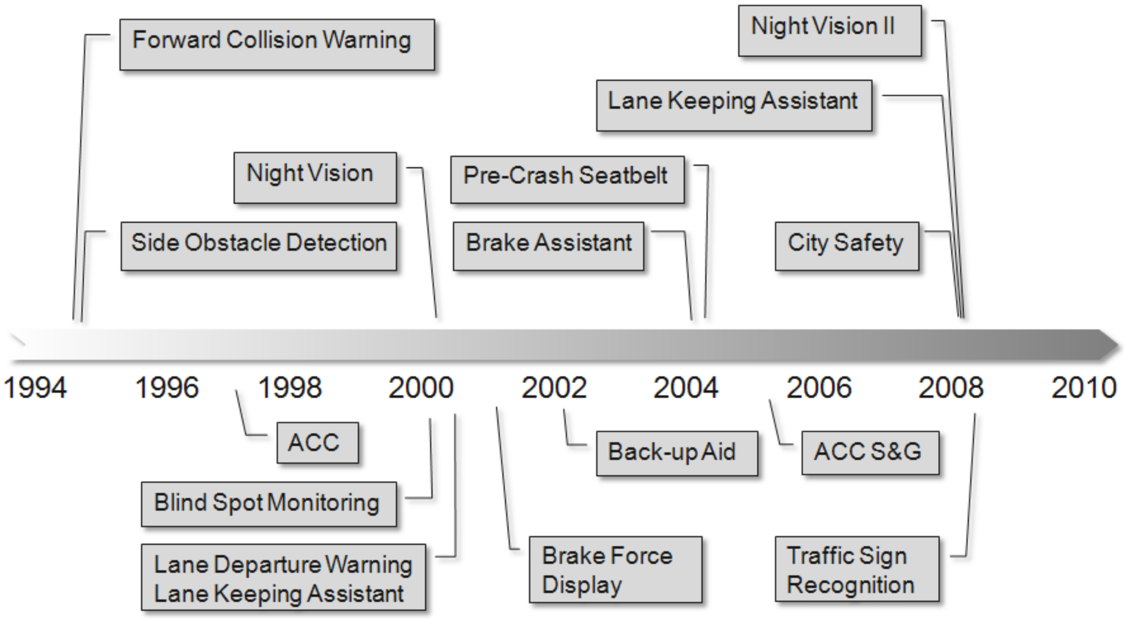


Fig. 2: Development of ADAS [2]

Next to ADAS for the longitudinal domain, such as ACC or forward collision warning systems, systems for the lateral domain, such as lane departure warning (LDW) and lane keeping assistant (LKA), were introduced. The first lateral support systems for series production were released in 2001 in Japan [2].
These lateral dynamic assistance systems are classified into the domains of lane change assistance and lane support systems (see Fig. 3). Lane change assistance systems are also subdivided into two groups; lane change assistance systems without intervention into the steering system (e.g. blind spot detection, see Fig. 3) and lane change assistance systems with intervention into the steering system (e.g. autonomous lane change, see Fig. 3) [3]. The main focus of lane support systems is to support the driver in keeping the vehicle in the current driving lane while lane change assistance systems support the driver in changing the lane. Lane support systems are subdivided into systems without intervention to the steering system (e.g. LDW see Fig. 3) and systems with intervention to the steering system (e.g. LKA or lane centering assistant (LCA), see Fig. 3). LKA systems will attempt to keep the vehicle within the path of travel and are thus orientated at the lane boarders while the lane centering system orientates at the lane centre and will centre the vehicle in the lane actively.

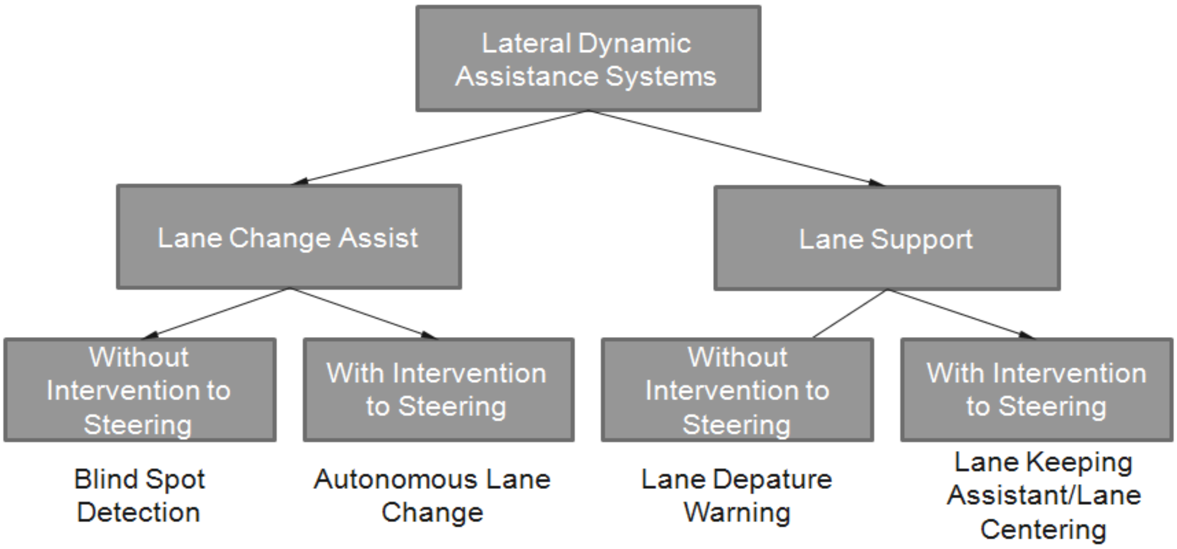
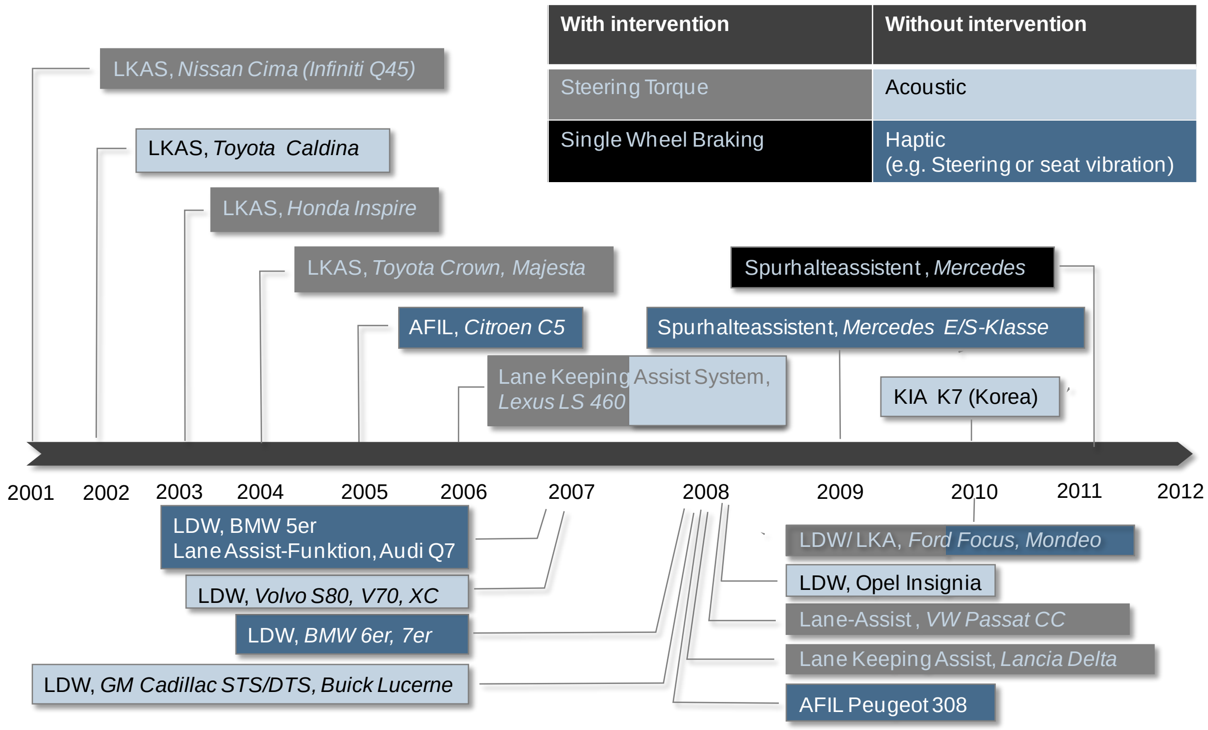


Fig. 3: Overview of lateral dynamic assistance systems [4]

Since the introduction of the first lane support system in 2001, a variety of systems are available in production vehicles. Next to systems with intervention and without intervention to the steering, the utilization of the single wheel brakes is also possible to provide vehicle yaw (see Fig. 4) and therefore keep the vehicle in the driving lane.
In this paper a hands-off lane centering system is presented. Focus of this system is the support of the development process for sensor systems in order to determine lane detection capability. Furthermore, the sensor performance while driving can be evaluated by such a system. If the developed lane centering system is active, the test driver will directly feel problems of the perception system and therefore mark the specific driving situation in the measurement data. Thus the necessary time for evaluation of test drives and the amount of recorded data can be decreased. Additionally the control algorithm for LCA can be evaluated in a closed loop system without the influence of a test driver. The introduction of a hands-off LCA algorithm for series

production of such a system is secondarily and not in focus of this paper.



With intervention	Without intervention
Steering Torque	Acoustic
Single Wheel Braking	Haptic (e.g. Steering or seat vibration)

Fig. 4: Market introduction of lane support systems

In a first step the requirements for such an LCA are derived. Based on the requirements the system is designed and the algorithm is implemented. The feasibility of the algorithm is analyzed and results from test drives are provided.

2 Requirements for the developed lane centering system

The system is designed for motorway use with a minimum speed of 60 kph for activation of the system. The upper speed limit is dependent on the sensor’s range towards the lane markings. In the proposed system the upper speed limit is set to 180 kph. The output of the LCA system is steering torque of the series production steering actuator. The maximum torque requested by the LCA is +/-3 Nm, which is also the limit of the series steering actuator for some manufacturer, e.g. VW Passat Lane Keeping Assistant. Nevertheless, this amount of torque is sufficient to drive on most motorway curves and can be easily overridden by the human driver in case of driver intervention [5].
In the following, requirements for the lane centering system are defined with regard to functionality, driver interface and failure reaction.

2.1 Functionality

The lane centering assist performs an automated control of the vehicle lateral dynamics. The responsibility for the safe operation of the vehicle remains with the driver. Thus the driver shall always be able to override the lane centering system at any time (see sub-chapter “Basic driver interface and intervention capability” for details). The system provides the states and transitions shown in Fig. 5.

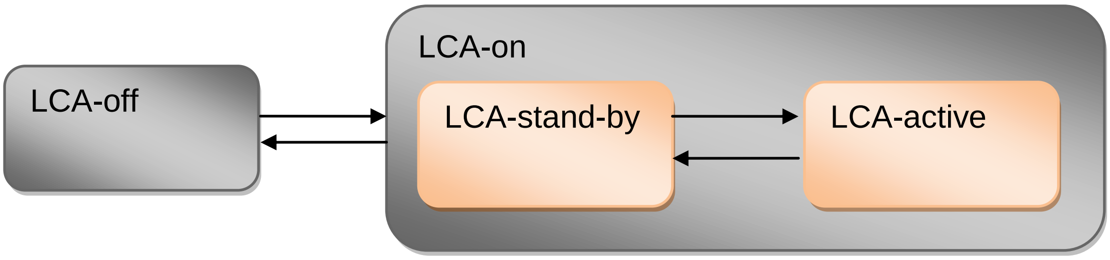


Fig. 5: LCA states and transitions

The transition from LCA-off to LCA-on (stand-by) shall be performed automatically. The criteria for transitioning shall be as follows (conjunction):

- Sensor system has detected both lanes properly (based on curve radii and lane visibility/quality).
- Current velocity is above v_{min}.
- Sensor system has not detected a construction area.
- Lane width is greater than test vehicle width.
- Turning indicator is not set.

The transition from LCA-on to LCA-off shall also be performed automatically. An automatic switch-off of the LCA should occur in the following situations (disjunction):

- Lane markings are not detected anymore by the sensor system.
- Lane width is smaller than the test vehicle width.
- Sensor system detects a contraction area.

The operational speed for LCA shall be between v_{min} = 60 kph and v_{max} = 180 kph as default for motorway driving.

In the stand-by state of the LCA, no intervention to the steering system should be executed. If all of the mentioned activation criteria are met and the driver presses the activation button, the system shall transition from LCA stand-by to LCA-active state. This transition shall not be done automatically, the confirmation of the driver by pressing the activation button is always necessary.

In LCA-active state the system shall evaluate the activation criteria. If any one of the selected activation criteria is not met anymore, the system shall transition from LCA-active to LCA-off state. If the test driver presses the LCA activation button in LCA-active state, intervenes into the steering wheel or activates the turning indicator, the system shall transition from LCA-active to LCA stand-by. In case of a transition from LCA-active state to LCA-stand-by/off state the lane centering action shall not end suddenly, but fade out smoothly.

In LCA-active state the system performs lane centering actions to influence the lateral movement of the subject vehicle with the intention of providing direct feedback on measurement mistakes by the sensor system to the driver.

In order to make the detected sensor data perceptible, the LCA sensor data shall not be filtered between the perception system and the LCA algorithm.

2.2 Basic driver interface and intervention capabilities

For safety reasons the system interface is designed comparable to ACC. As soon as the driver intervenes with the steering (presses the brake pedal for ACC), LCA is turned off and no steering torque is provided. A detection of external steering torque, which is provided by the driver, is necessary.

In the following, the requirements on driver interface and intervention capabilities are mentioned.

- Driver shall be able to override the lane centering action at any time by turning the steering wheel (+/- 3 Nm steering torque in the steering column can be easily overridden by humans [5]).
- The system shall provide a switch in order to switch from LCA-on to LCA-off manually (turning the system off at e.g. motorway exit ramps).
- The driver shall get continuous feedback, if LCA is available (feedback that all activation criteria are met).
- The driver shall get continuous feedback, if LCA is active.
- The driver shall get a warning, if LCA transitions from LCA-on into LCA-off. This warning shall be the same for all reasons of transition from LCA-on to LCA-off (e.g. no lane markings detected, system error, speed of the vehicle below 60 kph).
- The driver should be informed, if the LCA system is operating at the system limit of ±3 Nm of applied steering torque.

2.3 Failure reactions

If the messages of the sensor system are timed out, the lane centering system shall be switched off. Furthermore, the driver should be informed that the LCA is not receiving data of the sensor system anymore.

3 Lane centering system

In general, the developed lane centering system is divided into three parts:

- Human-Machine Interface (HMI)

- State machine
- Lane centering controller

Each part is described in detail in the following.

3.1 Human-Machine Interface

The human-machine interface (HMI) is the interface to the driver and determines, if the driver wants to change to LCA-on state by means of a switch. In addition, feedback to the driver is given by means of two status LEDs. One LED indicates, if the LCA is available/unavailable with regards to the sensor system (e.g. lane markings are detected). The second LED indicated, if the system is active or inactive.
If LCA has to shut down automatically (e.g. due to non-visible lane markings), the driver is informed by means of a warning tone and a message in the instrument cluster. This warning requests the driver to take over lateral control of the vehicle. In case of a requested torque of ≥|3 Nm| by the LCA, the driver is informed by a gong and a text message in the instrument cluster. Therefore the driver knows that the system is currently operating at the system boundary and a manual take over will be possible in the near future. In case the situation does not change towards the system specification, an acoustic warning and a text message in the instrument cluster are the second stage. In this case a manual take over is necessary.

3.2 State machine

The state machine defines the current status of the system. According to the requirements, three main statuses are used: LCA-off, LCA-stand-by and LCA-active, whereby LCA-active and LCA-stand-by are sub-status of LCA-on. Based on the sensor output for lane detection, current velocity and turning indicator signal, it is checked, if the current status could be switched from LCA-off to LCA-stand-by. LCA stand-by state is entered if both lanes are detected properly, the construction area flag is not set by the sensor system, the detected lane width is greater than vehicle width, the current velocity is greater than 60 kph and the turning indicator is not set.
The transition from LCA-stand-by to LCA-active occurs, if the test driver pressed the LCA activation button. If one of the conditions, which are necessary to switch to LCA-active, are not met anymore then the system is switched to LCA-off. In case that the driver presses the LCA activation button again, activates the turning indicator or the driver turns the steering wheel, while LCA is in LCA-active state, the system switches to LCA-stand-by state.

3.3 Lane centering controller

The lane centering controller calculates the desired steering torque to keep the vehicle in the lane centre. According to the paper “Automation in Road Traffic” [6] human lateral control is based on an aiming point which the driver wants to compensate. This control point is the intersection point in a predicted distance d_{xP} of the predicted vehicle movement and the lane path. This driver behavior is reproduced within the developed LCA controller.

The control circuit of the developed lane centering system is shown in Fig. 6. In general, this controller is a predictive PID controller with curvature compensation.

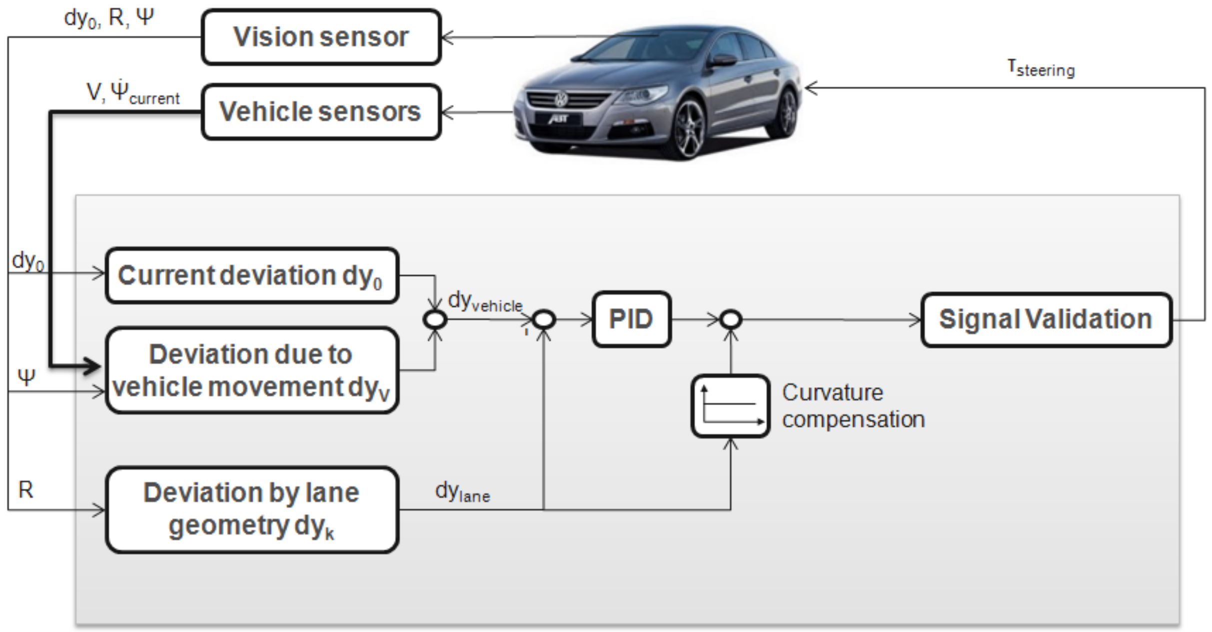


Fig. 6: Control circuit of Lane Centering Controller

In order to realize this controller design the following measured input values are necessary:

- Vehicle yaw rate $\dot{\psi}$
- Vehicle velocity v
- Lateral offset to lane centre dy_0
- Heading angle ψ
- Radius R or curvature c_0 of the lane markings
- HMI signals

Vehicle yaw rate and velocity are measured by the on-board sensors of the demonstrator vehicle while the lateral offset to the lane centre, heading angle and curvature are measured by means of a sensor system which should be evaluated. Within this development a mono camera system was used. The heading angle is the angle between vehicle’s longitudinal axis and tangent to the measured lane markings.
Having these values available, the position of the vehicle ($dy_{vehicle}$) and the position of the lane center (dy_{lane}) are predicted by means of a prediction distance to reproduce the driver behavior for lateral control [6]:

$$dx_p = v \cdot t_p \qquad (1)$$

The predicted vehicle position in the lane coordinate system is depending on the current lateral offset to the lane center dy_0, heading angle ψ and yaw rate $\dot{\psi}$ (see Fig. 8, left side). Thus, the predicted vehicle position is calculated by (2).

$$dy_{vehicle} = dy_0 + \sin(\psi + \beta) \cdot dx_p + \frac{\dot{\psi} \cdot dx_p^2}{2 \cdot v} \qquad (2)$$

β is the vehicle slip angle and is not measured or estimated in the demonstrator vehicle. Since this lane centering system is developed for motorway usage, the slip angle is neglectable in this case.
For the road geometry an approximation of a clothoid model is used according to [7]. Thus, the predicted position of the lane in the lane coordinate system is calculated by (3). It is better to calculate with a curvature signal, which is the inverse of the radius, because in case of a straight road the radius becomes infinite, while the curvature signal will be zero.

$$\begin{aligned} c_0 &= \frac{1}{R} \\ c_1 &= \frac{1}{A^2} \\ dy_{lane} &\approx \frac{c_0}{2} dx_p^2 + \frac{c_1}{6} dx_p^3 \end{aligned} \qquad (3)$$

c_1 in (3) is piecewise constant and A is the so-called “clothoid parameter”. In other words, c_1 describes the change of the curvature signal c_0. Since the measured signal for c_1 is estimated by the used camera system based on a clothoid model, this signal is noisy. In addition, tests on highways showed better performance of the lane centering system if c_1 is neglected. Hence, c1 is left out for the calculation of the predicted lane centre and equation (3) is simplified to (4) (see also Fig. 7 on the right side):

$$dy_{lane} \approx \frac{c_0}{2} dx_p^2 \qquad (4)$$

In order to steer the vehicle to the lane center, the desired predicted position, which is the predicted position of the lane center (dy_{lane}), is compared to the predicted position of the vehicle ($dy_{vehicle}$).

$$\Delta dy = dy_{lane} - dy_{vehicle} \qquad (5)$$

Δdy is the control deviation and is input into the PID controller. Since dy_{lane} and $dy_{vehicle}$ are dependent on the preview time t_p the preview time has a high influence on the controller behavior. If t_p is chosen too small, the controller will start oscillating and turn too late into a curve. If t_p is chosen too high, the controller will turn too early into a curve and the preview distance will move outside the camera viewing range in higher velocities.

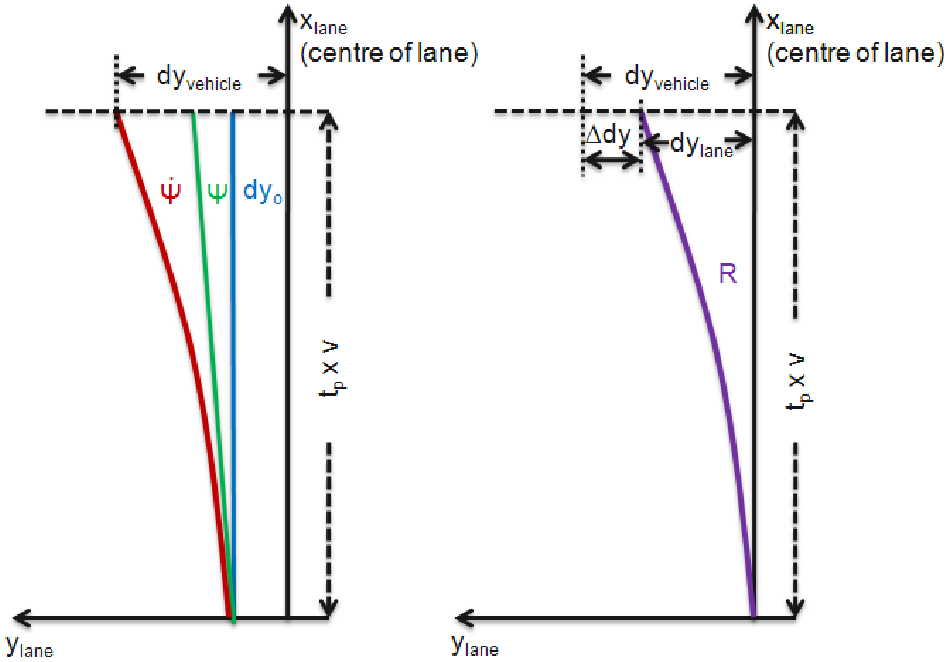


Fig. 7: Prediction of vehicle position and lane centre position in lane coordinate system

The factor t_p and the PID coefficients are tuned within test drives. The output of the PID controller is the steering torque, which is necessary to steer the vehicle back to the lane center, even on a curved road. In order drive along the curved road, curve compensation has to be regarded in the controller design. The curve compensation will result in an additional steering torque, which is calculated by (6).

$$M_{curve\_comp} = K_{curve\_comp} \cdot dy_{lane} \qquad (6)$$

Both calculated torques (output of PID controller and output of curve compensation) are summed up and are validated in a next step in terms of the absolute maximum/minimum value of +/-3 Nm and gradient of the steering torque.

4 Results

The lane centering controller is integrated into a VW Passat CC test vehicle built in Aachen. The lane centering system was modeled in MATLAB/Simulink and is operating on an MPC 565 microcontroller. As environmental sensor a camera system was installed behind the windscreen, which delivers measurement data to the MPC 565. The microcontroller provides a gateway between the camera, the vehicle and the control algorithm. The actuator as well as the status LED of the series production lane keeping assistant were utilized in order to provide the necessary steering torque and driver feedback. Furthermore, a switch with a background LED to switch the developed lane centering system on/off was installed in the test vehicle. The prototype vehicle was capable to allow test drives on public motorways.

As a first step the controller parameters were tuned within more than 5,000 km of test drives with focus on driving comfort. As mentioned in chapter 3.3, the preview time is a key value, which had to be tuned carefully in order to provide comfortable vehicle behavior. Based on the executed test drives, the prediction time t_p was determined for the used sensor to be a velocity dependant value. The current implementation operates with a value around 1 s whereby t_p slightly decreases with higher velocities.

The evaluation of the developed lane centering system consists of two steps. On the one hand, the system has to be evaluated with regards to the system's capability to keep the vehicle centered in the lane. On the other hand it has to be investigated how well this system makes lane detection sensor measurement errors sensible to the test driver. In order to evaluate the lane centering capability of the system, curved and straight motorway scenarios were tested.

Fig. 8 shows exemplarily a plot of dy_{lane} and $dy_{vehicle}$ over time. Furthermore, the status of LCA (0 means LCA-stand-by and 2 means LCA-active) and the steering torque output to the steering actuator is shown. It could be seen that the controller eliminates the error between dy_{lane} and $dy_{vehicle}$ and keeps the vehicle centred in the lane.

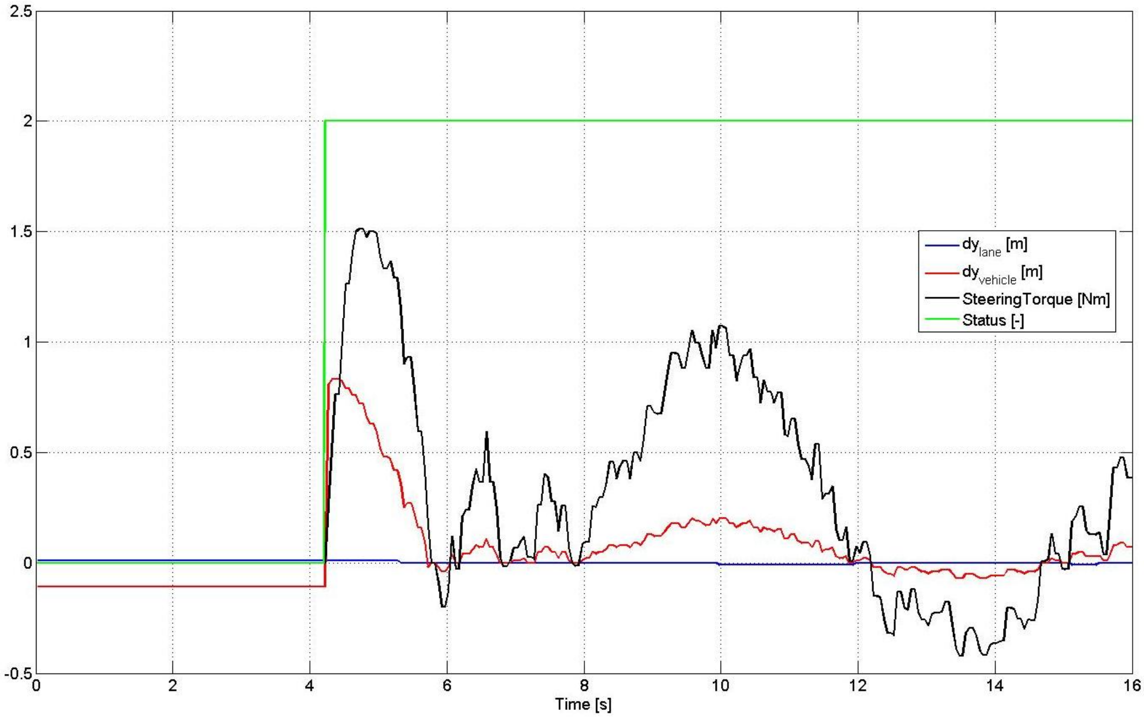


Fig. 8: LCA system eliminates error between dy_{lane} and $dy_{vehicle}$ to center test vehicle

Fig. 9 shows the measured data of the lane detection camera as well as the lateral acceleration over time. The LCA system is active during that measurement. At measurement time 69 s the curvature and heading angle signal of the right lane show a strange behavior. This behavior can be found in the lateral acceleration signal which is also shown in Fig. 9. The peaks of the lateral acceleration are felt by the test driver and subsequently he could set a marker in the measurement data.

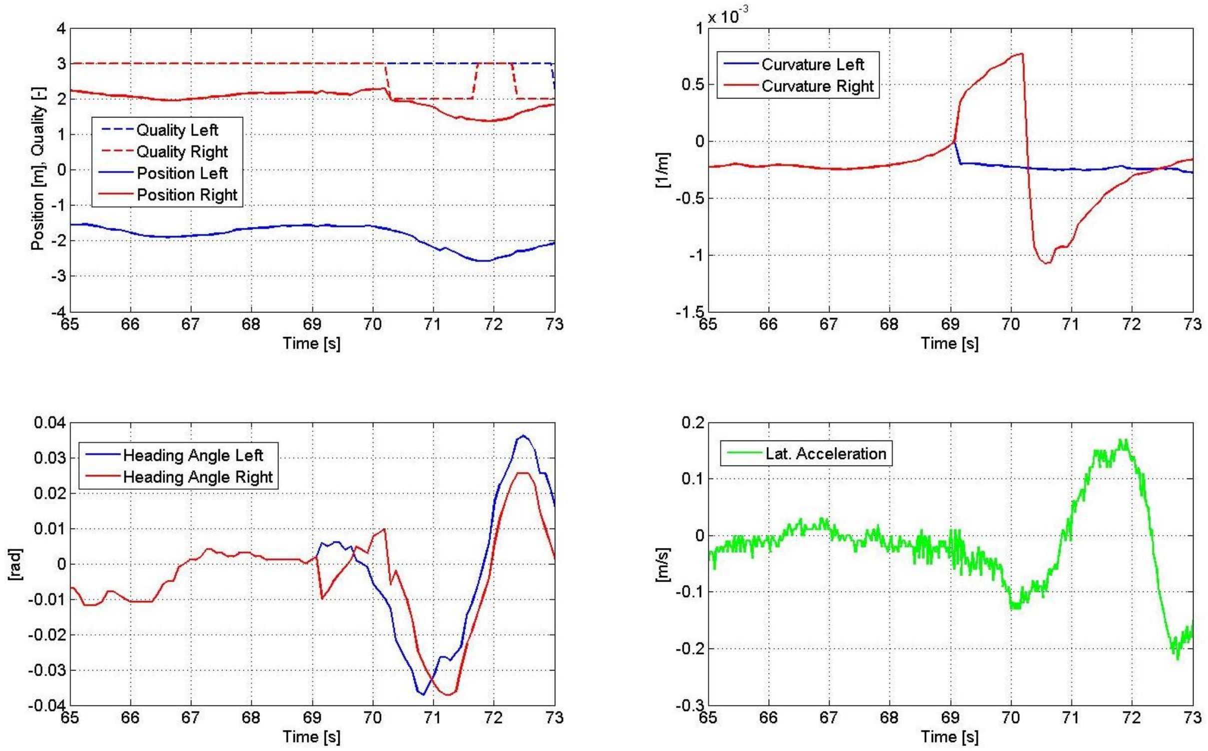


Fig. 9: Detection of a lane detection sensor measurement error by means of the developed lane centering system

In sum more than 10,000 km of test drives were driven in order to successfully find and measure difficult situations for the used lane detecting sensor. The recorded measurement data is subsequently forwarded to the sensor specialists so that they can evaluate the specific situation, which was marked by the test driver based on the lane centering system.

5 Conclusion

Within this paper the motivation, the requirements as well as the development of a lane centering algorithm for highways was described in order to evaluate sensor performance and support the development process of lane detecting sensors. The developed algorithm used exemplarily a mono camera system, which measures the lane offset, heading angle and curvature of the lane markings in front of the vehicle. By means of camera and vehicle motion data, the position of the vehicle and lane is predicted. Based on the prediction, a steering offset torque is calculated and output to the steering actuator. The hands-off LCA provides comfortable vehicle behavior in case sufficient detection quality of the lane markings is provided.

In order to provide assistance to an average vehicle driver, a hands-on solution can be realized using the proposed control strategy.

6 References

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