COLLISION AVOIDANCE SYSTEM PRORETA
Strategies Trajectory Control and Test Drives

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Abstract: Methods and experimental results of a collision avoidance driver assistance system are described with automatic object detection, trajectory prediction, and path following with controlled braking and steering. The objects are detected by a fusion of LIDAR scanning and video camera pictures resulting in the location, size and speed of objects in front of the car. A desired trajectory is calculated depending on the distance, the width of a swerving action and difference speed. For the trajectory control different control methods were designed and tested experimentally like velocity depend linear feedback and feedforward control, nonlinear asymptotic output tracking and nonlinear flatness based control using extended one-track models with vehicle state estimation for the sideslip angle and cornering stiffness. Automatic braking is realized with an electrohydraulic brake (EHB) and automatic steering with an active front steering (AFS). The various control systems are compared by simulations and real test drives showing the behaviour of a VW Golf with automatic braking or/and automatic swerving to a free track, such avoiding hitting a suddenly appearing obstacle. The research project PRORETA was a four-years-cooperation between Continental Automotive Systems and Darmstadt University of Technology.

1 INTRODUCTION

Driver Assistance Systems for Collision Avoidance have the goal to prevent accidents using braking or evasive maneuvers. An automatic collision avoidance system has to monitor its surroundings, detect an upcoming accident and intervene appropriately to avoid the accident. In case of the system developed by the research project PRORETA – Electronic Driver Assistance System for a Collision Avoiding Vehicle, a cooperation between Technische Universität Darmstadt and Continental AG, the driver is given the chance to avoid the accident himself as long as possible. Therefore, the interventions have to be conducted at the physical last possible moment or the driving dynamics stability boundary.

Using these predictions, a decision is made, whether an intervention is necessary or not and the intervention is planned. The intervention itself is then conducted fully automatically. An ergonomic study accompanied the development of the system. This study investigated how the driver reacts in critical situations and how he reacts on the interventions by PRORETA.
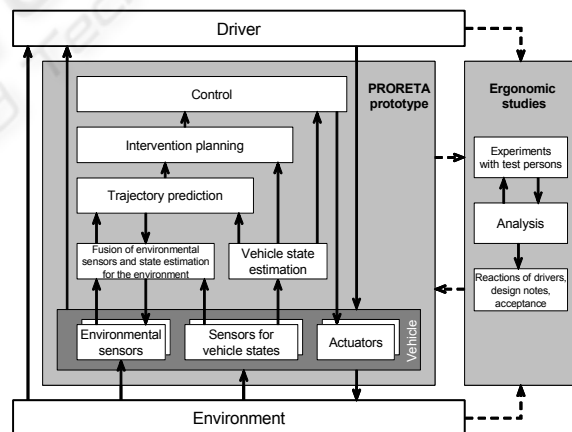

Figure 1: System overview prorate.

In this contribution, the intervention decision, the planning of the intervention and the conduction of the intervention are described. The environment perception is described in detail in (Darms and Winner, 2006). Results from the ergonomic study can be found in (Bender and Landau, K., 2006). The system was tested using a complex two track model followed by extensive driving tests with an experimental vehicle.

2 TEST VEHICLE

A VW Golf IV, which was only equipped with additional sensors and actuators required for the developed functions, served as experimental vehicle, see Figure 2.

Figure 2: Environmental Sensors of the test vehicle.

The driver assistance system uses an active front steering and an electro hydraulic braking system as actuators. For vehicle state estimation only ESP sensors and the sensors of the active front steering and braking system are necessary. For environment perception a laser scanner and a video sensor were used. The chosen design allows to scan the area in front of the vehicle. The detection area of the laser scanner covers an angular range of 22.5° with a resolution of 1.5° and is scanned in a 90 ms cycle. The distance to objects is determined by a time of flight measurement of emitted light impulses. The video sensor is based on a monochrome CMOS image sensor that provides data in a 40 ms cycle. The detection area is 44°, whereas the discretisation with approx. 0.07° is considerably finer than for the laser scanner. By means of image processing algorithms, vehicle rear views and lane markings can be detected in the image, however, a direct distance measurement is not possible, for details see (Darms and Winner, 2006).

3 EVASIVE TRAJECTORY

An evasive trajectory is required between intervention planning and control For investigating several different intervention functions with different types of controllers, the type of intervention is selected using some flags. The flags

used in this article are braking, emergency braking and evasion. If braking is chosen, the desired deceleration has to be transmitted. If an emergency braking is chosen, the maximum possible deceleration at every point in time is achieved using braking controllers. For an evasion, the desired position and heading are given for one time step T_B, two time steps T_B and ten time steps T_B ahead in time, Figure 3. The coordinate system used is stationary for the duration of the evasion and is initialized at the beginning of the evasion to match the vehicle coordinate system at that point. The last position, which is supposed to be reached 10 time steps in the future, is used to make sure the controller can react predictively on deviations of the first 2 time steps. Figure 3 shows this interface. Every point $p(t)$ consists of the position (x, y) and the heading ψ of the vehicle. All three points are put together in one matrix transmitted to the controller:

$$\mathbf{P}_{\text{evasion}} = \begin{bmatrix} p(t+T_B) & p(t+2T_B) & p(t+10T_B) \end{bmatrix}$$
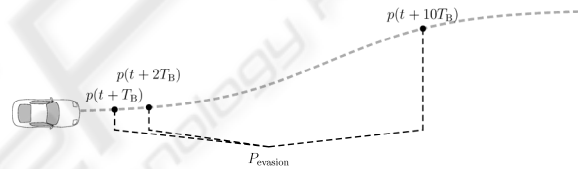

Figure 3: Evasive trajectory between planning and control.

4 PLANNING OF THE EVASIVE INTERVENTION

Primary goal of the evasive trajectory is to reach a predefined lateral offset with the shortest possible traveled path. The designed trajectory has to be feasible regarding the vehicle dynamics laws and after the maneuver the vehicle has to be in a safe and stable state.

Vehicle dynamics laws of the trajectory are taken into account to limit the maximum allowed lateral acceleration. This limit can be adapted to the actual traffic and driving situation, especially weather conditions. The steering actuator also limits the maximum possible jerk.

Since the trajectory is transmitted to the controller using positions, the general relations between the position on the trajectory and the driving dynamics are considered first. This relation is based on the simple equations of the one-track model and the Ackermann equations. The approach shown here uses a relation where the y-position on the trajectory is depended on the x-position:

$$y = f(x) \qquad (1)$$

Using geometric transformations, the yaw angle ψ can be expressed as (assuming no side slip)

$$\psi = \arctan\left(\frac{dy}{dx}\right) \qquad (2)$$

and therefore its derivative regarding time yields:

$$\dot{\psi} = \frac{d\psi}{dt} = \frac{1}{1+\left(\frac{dy}{dx}\right)^2}\frac{d^2y}{dx^2}v_x \qquad (3)$$

Based on this and using the Ackermann relations, the lateral acceleration is:

$$a_y = v\dot{\psi} = \frac{1}{1+\left(\frac{dy}{dx}\right)^2}\frac{d^2y}{dx^2}v_x v \qquad (4)$$

Further simplification can be accomplished assuming $v_x = v$.

Often, a sequence of klothoids is used for the evasive trajectory, see e.g. (Ameling, 2002). In general, trajectories for evasive maneuvers have the shape of a lying S. Functions describing such a shape are called sigmoidal functions or sigmoides. In the following a sigmoide of the form

$$y(x) = \frac{B}{1+e^{-a(x-c)}} \qquad (5)$$

is used. B is the maneuver width, describing the distance between minimum and maximum y-value. a defines the slope of the sigmoide, where high values for a are leading to a steeper curve. c defines the position of the inflection point and therefore the length of the evasive maneuver, which is $s=2c$. Looking at equation (5), the sigmoide has its maximum and minimum at infinity, meaning

$$\lim_{x\to-\infty} y(x) = 0 \qquad (6)$$

and

$$\lim_{x\to\infty} y(x) = B \qquad (7)$$

respectively. Therefore, an additional parameter y_{Tol} is introduced. Using this parameter, the following counts:

$$y(0) = y_{Tol} \qquad (8)$$

and

$$y(2c) = B - y_{Tol} \qquad (9)$$

Figure 4 shows this sigmoide and the respective parameters. The parameters can be chosen according to the driving situation, such that the evasive path is minimal regarding the limitations for maximum lateral acceleration, maximal jerk and dynamics of the steering actuator. The derivation of the respective parameters can be found in (Stählin et al., 2006).
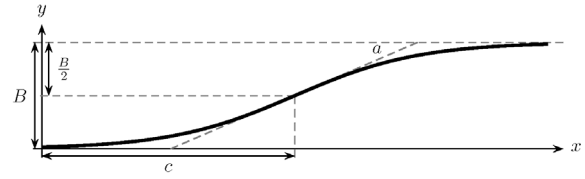

Figure 4: Evasive sigmoide and its parameters.

The most important value for taking a decision, whether the klothoide or the sigmoide should be chosen for the evasive trajectory is the length s of the path of the evasive maneuver, taking into account the limiting factors (maximum lateral acceleration, maximum jerk,…). Table 1 shows a comparison between klothoide and sigmoide for different limiting factors. It can be seen, that the sigmoide always leads to a shorter path for the evasive maneuver. This is due to the linear increase of the lateral acceleration for the klothoide in comparison to the faster and nonlinear increase in lateral acceleration for the sigmoide. Both trajectories can be realized by a controller trajectory.

Table 1: Comparison of the length of an evasion for klothoide and sigmoide with $y_A = y_m$.

B	v	lateral accel.	jerk	Klothoide	Sigmoide
2m	15m/s	5m/s2	30m/s3	26,83m	22,08m
3m	15m/s	5m/s2	30m/s3	32,85m	29,10m
2m	36m/s	5m/s2	30m/s3	64,30m	53,39m
3m	36m/s	5m/s2	30m/s3	78,85m	70,42m

5 INTERVENTION DECISION

Based on the fused environment data it is decided if a collision is likely to occur and if so, which maneuver has to be carried out to avoid the collision. The strategy is to avoid the collision at the physically last possible moment by an intervention in order to give the driver the possibility to defuse the critical situation by his own actions as long as possible.

In order to determine a threatening collision, predictions are first made for the own vehicle driving tube and the movement of the objects in the environment. By means of these predictions it can then be predicted whether a collision will occur. If this is the case, it is planned in a next step when and which intervention has to be carried out.

Basically, there are three strategies to avoid a collision:

- Braking
- Steering
- Combination of braking and steering

For the intervention decision it is calculated at what distance to the collision location the respective intervention has to be carried out, such that the collision can still be prevented. For a braking intervention the braking distance is calculated. In case of steering interventions the sigmoide is taken as the basis for the evasive trajectory.

In Figure 5 the quantities necessary for the calculation of the evasive trajectory are presented. By means of the vehicle's width b_v and the obstacle's width the necessary evasive width y_A is determined together with a safety distance y_S. Since the evasive width can be reached before the end of the maneuver, an associated maneuver width y_M arises.
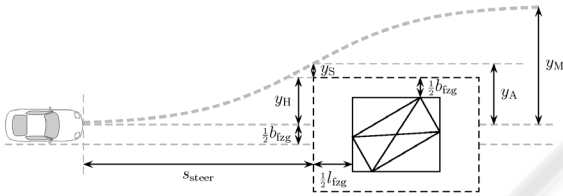

Figure 5: Evasive Quantities for calculating the evasive trajectory (see text for details).

However, the evasive trajectory is the trajectory until the evasive width y_A is reached. The maneuver width is chosen according to the strategy used. If the maneuver width y_M is chosen to be the same as the evasive width y_A, the evasive trajectory length s_{steer} reaches its maximum for given maximal lateral acceleration and maximal lateral jerk. These two last-named parameters also determine the optimal maneuver width which leads to the smallest possible evasive trajectory length s_{steer} and which makes use of the set limits ideally. However, it needs considerably more lateral offset for the same evasive width y_A.

6 LATERAL VEHICLE GUIDANCE

If a collision with an obstacle is no longer avoidable by a reaction of the driver, then, according to the situation, the driver assistance system selects one of the intervention strategies described above. For the realization of the chosen intervention either the active steering and/or the electro hydraulic braking

system are used according to the maneuver. If a braking maneuver should be carried out, the vehicle is decelerated (Schorn et al., 2005) by utilization of the maximum force transmission available. The anti-lock braking system ABS supports in this case.

In case a collision can only be prevented by an evasive maneuver or by a combined evasive and braking maneuver the control block receives from intervention planning a trajectory, see Figure 1. The vehicle is driven on this trajectory automatically around the obstacle. Different linear and nonlinear feedback controllers for an evasive maneuver were developed, see e.g. (Schorn and Isermann, 2006), (Schorn et al., 2006). Each lateral guidance feedback control transfers an additional steering angle to the interface of the steering system. Vehicle variables, which cannot be measured directly by sensors the vehicle is equipped with, are estimated, see Figure 1, see also (Schorn and Isermann, 2006), (Isermann, 2006). For combined steering and braking maneuvers different feedback controllers were developed as well.

In the following only the lateral vehicle guidance is regarded. Exemplarily, two of the investigated approaches, a *nonlinear asymptotic output tracking feedback control* and a *speed-dependent local linear feedback control approach with feedforward control* are presented.

6.1 Nonlinear Asymptotic Output Tracking Feedback Control

For model based design of a feedback system, the system behavior is required. The path following feedback control is based on an extended one-track model:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} a_{11} \cdot x_1 + a_{12} \cdot x_2 \\ a_{21} \cdot x_1 + a_{22} \cdot x_2 \\ a_{31} \cdot \sin(x_1 + x_4) \\ x_2 \end{bmatrix} + \begin{bmatrix} b_{11} \\ b_{21} \\ 0 \\ 0 \end{bmatrix} \cdot u \quad (10)$$

$$y = y_E = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \cdot \mathbf{x} = x_3 \quad (11)$$

with

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} \beta(t) \\ \dot{\psi}(t) \\ y_E(t) \\ \psi(t) \end{bmatrix} \quad \text{and} \quad u = \delta(t) \quad (12)$$

β is the sideslip angle, ψ the yaw angle, y_E the lateral vehicle position and δ the steer angle. The speed dependent parameters follow from front and rear cornering stiffness $c_{\alpha F}$ and $c_{\alpha R}$, length from

front and rear axle to the center of gravity l_F and l_R, velocity v, mass m and moment of inertia J_Z, see e.g., (Isermann, 2006):

$$a_{11} = -\frac{c_{\alpha F} + c_{\alpha R}}{m \cdot v} \qquad a_{12} = \frac{l_R \cdot c_{\alpha R} - l_F \cdot c_{\alpha F}}{m \cdot v^2} - 1$$

$$a_{21} = \frac{l_R \cdot c_{\alpha R} - l_F \cdot c_{\alpha F}}{J_Z} \qquad a_{22} = -\frac{l_R^2 \cdot c_{\alpha R} + l_F^2 \cdot c_{\alpha F}}{J_Z \cdot v}$$

$$a_{31} = v \tag{13}$$

$$b_{11} = \frac{c_{\alpha F}}{m \cdot v} \qquad b_{21} = \frac{c_{\alpha F} \cdot l_F}{J_Z}$$

The model parameters were determined from construction data and identification experiments, (Schorn, 2007).

The lateral position $y_E(t)=f(x_E(t))$ of the vehicle in an earth-fixed coordinate system has to be controlled using the evasive trajectory described by equation (5). The reference input of the control system $y_R(t)$ is calculated by performing an interpolation.

The vehicle model in (10) and (11) is a nonlinear single-input single-output model of type:

$$\dot{\mathbf{x}}(t) = \mathbf{a}(\mathbf{x}) + \mathbf{b}(\mathbf{x}) \cdot u(t)$$
$$\mathbf{y}(t) = \mathbf{c}(\mathbf{x}(t)) \qquad \text{with} \qquad \mathbf{x}_0 = \mathbf{x}(t_0) \tag{14}$$

Having the system's output $\mathbf{y}(t)$ converging asymptotically to a prescribed reference output $y_R(t)$, the system input $u(t)$ can be calculated as follows (Isidori, 1989), (Schwarz, 1999):

$$u(t) = \frac{1}{L_b L_a^{d-1} c(\mathbf{x})} \cdot$$
$$\left[-L_a^d c(\mathbf{x}) + y_R^{(d)}(t) - \sum_{i=1}^{d} \alpha_{i-1} \cdot \left[L_a^{i-1} c(\mathbf{x}) - y_R^{(i-1)}(t) \right] \right] \tag{15}$$

The relative degree d has to be determined according to (Isidori, 1989), (Schwarz, 1999). For the mentioned plant it yields $d = 2$ assuming $v > 0$ and $(x_1 + x_4) \neq \pm\frac{\tau}{2}, \pm\frac{3\tau}{2}, \dots$. With this information, the feedback control, equation (15), can be calculated. The elements are given by (Schorn et al., 2006):

$$c(\mathbf{x}) = x_3$$
$$L_a c(\mathbf{x}) = v \cdot \sin(x_1 + x_4)$$
$$L_a^2 c(\mathbf{x}) = -v \cdot \cos(x_1 + x_4) \cdot (a_{11}x_1 + a_{12}x_2 + x_2) \tag{16}$$
$$L_b L_a c(\mathbf{x}) = b_{11} \cdot v \cdot \cos(x_1 + x_4)$$

where L_a are so called Lie-functions (Isidori, 1989), (Schwarz, 1999). The structure of the resulting closed control loop is shown in Figure 6. The command variables, the reference output $y_R(t)$, $\dot{y}_R(t)$, $\ddot{y}_R(t)$ as described above, are calculated in the component "Calculation of command variables". The sideslip angle was estimated with a vehicle state estimator (Schorn and Isermann, 2006). The output of the controller is an additional steering angle $\delta_M(t) = \delta(t)$.

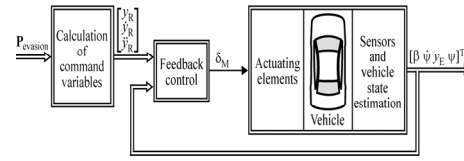Results from test drives with the experimental vehicle described above will be presented below.

Figure 6: Structure of nonlinear asymptotic output tracking feedback control.

6.2 Speed-dependent Local Linear Feedback Control with Feedforward Control

To guide a vehicle on a desired trajectory, a speed-dependent local linear feedback control approach with feedforward control was developed (Schorn and Isermann, 2006). A scheme of the control system is shown in Figure 7.
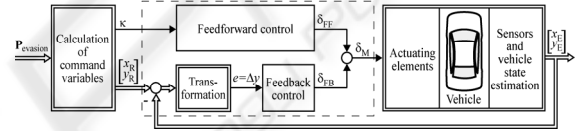

Figure 7: Structure of linear feedback control combined with feedforward action.

Based on the self steer gradient SG a steer angle δ_{FF} is calculated for the feedforward control by means of vehicle velocity v, wheelbase l and curvature $\kappa = \frac{1}{R}$ of the desired trajectory:

$$\delta_{FB} = (l + SG \cdot v^2) \cdot \kappa \tag{17}$$

A feedback control is added to compensate disturbances and deviations. The parameters of a proportional-derivative (PD) controller is tuned by two parameters only and provides the required dynamics by means of the differential component. Using the vehicle orientation ψ, the control deviation is transformed from an earth-fixed coordinate system into a vehicle-fixed coordinate system as control deviation $e=\Delta y$. The feedback of the vehicle's longitudinal position x_E is necessary for this purpose. The steering system is driven by the sum δ_M of the angles δ_{FF} and δ_{FB} of the feedforward and feedback control. For the implementation of the feedback control in the experimental vehicle the derivative, required for the calculation of the differential component of the control variable, was replaced by a high pass filter.

As the velocity v influences the vehicle's dynamics, because it changes continuously during a

driving cycle. The feedback controllers were designed for different operating points (velocities). Their outputs are weighted and superimposed based on Local Linear Models (LLM) (Schorn and Isermann, 2006), (Nelles, 2001).

7 EXPERIMENTAL RESULTS FROM TEST DRIVES

The developed components environment recognition, intervention decision and feedback control were implemented as a whole system in a test vehicle and tested by means of numerous experiments. This happened using an obstacle that represents the rear view of a car and can be moved laterally on the lane. Two test scenarios can be seen in Figure 8.

In the following sections the most important results from these tests are presented. It is required in each case that the lateral and back lane areas are monitored by additional sensors and thus permit driving maneuvers.
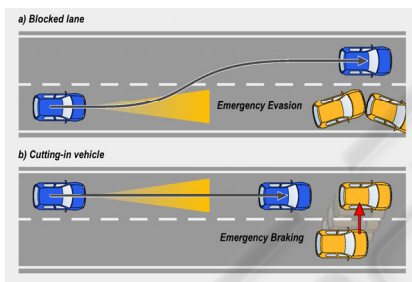

Figure 8: Scenarios for practice system testing.

7.1 Blocked Lane

In the scenario "Suddenly appearing obstacle / blocked lane" from Figure 8a) a lane is blocked unexpectedly. An example for this would be an end of a traffic jam in the case of bad visibility or after a curve. The emergency evasion is then conducted as an automatic intervention. The position of the used obstacle is determined by the environmental sensors and the necessary evasive trajectory is calculated based on the information about the vehicle's surroundings. The vehicle is then guided aside of the obstacle on the predefined evasive trajectory by the lateral guidance controller without the assistance of the driver.

Figure 9 shows results of a test drive with the test vehicle mentioned above, where the *asymptotic nonlinear output tracking feedback control* was used. A comparison of desired command variable and measured position shows that both values match very well. The evasive width y_M is 3m, the desired and the actual position correspond well, apart from a slight overshooting. The steering wheel angle indicates that the driver held the steering wheel in a straight position. The difference between total angle and steering wheel angle is provided only by the controller. The difference at the end of the intervention maneuver follows from the fact that the feedback control has been switched off at very low velocities.

Results from test drives for the *linear feedback control combined with feedforward* are presented in Figure 10.

Again, desired command variable and measured position match very well. The general conditions for this test drive have been the same as for the results shown in Figure 9 regarding evasive width y_M and velocity. The experiments show that the maximal lateral accelerations are $a_y \approx 7\,m/_{s^2}$ and the linear controller needs less maximal steering angle. Both control approaches presented above provide similar accuracies, but the speed dependent linear control system can be implemented and parameterized easier and with smaller computational expense.

7.2 Cutting-in Vehicle

As a second scenario a suddenly cutting-in vehicle is reproduced by moving the dummy obstacle just in front of the vehicle from the right to the left lane (Figure 8b). Evasion is not possible since further obstacles block the right. The necessary maneuver is thus an emergency braking maneuver. By means of the environmental sensors it is recognized that both lanes of the road are blocked and it is calculated at which last possible moment the emergency braking maneuver must be started in order to come to a stop just before the obstacle. Assuming a maximum braking acceleration which is dependent on the road state (dry-wet), the required braking distance of the vehicle is calculated depending on the current speed. The driver assistance system triggers a braking intervention only if this minimal braking distance is reached in order to give the driver the chance to prevent the collision as long as possible by himself. The electro hydraulic braking system then decelerates the vehicle maximally with support by the anti-lock braking system ABS, on dry roads with a deceleration of $a_x \approx 10\,m/_{s^2}$.
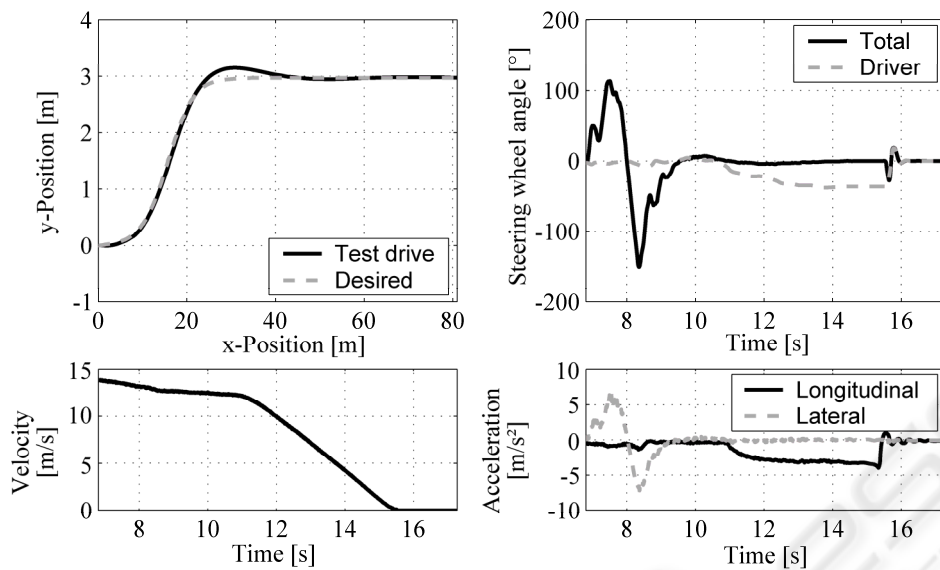
Figure 9: Results for asymptotic nonlinear output tracking feedback (test drive).
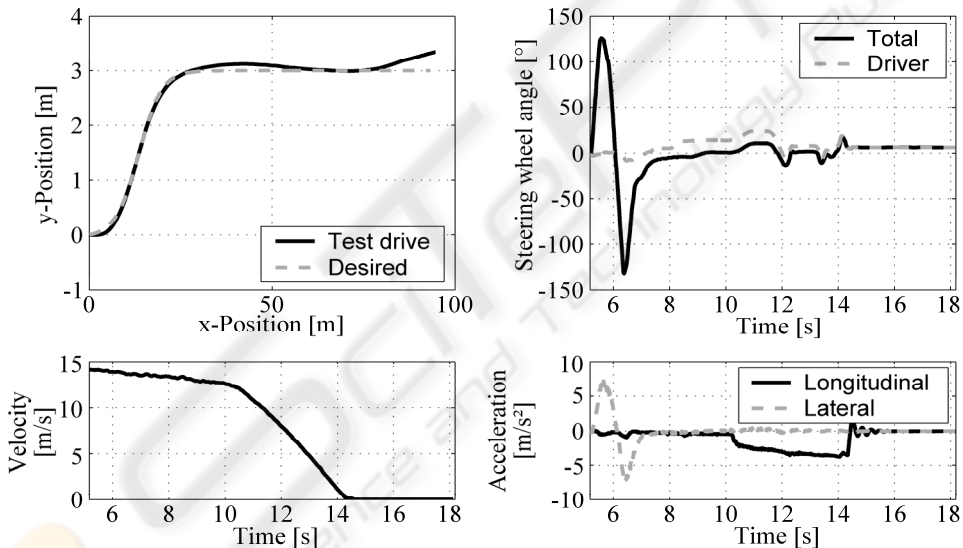

Figure 10: Results for linear feedback control combined with feedforward (test drive).

8   CONCLUSIONS

The described system for accident avoidance which was developed within the scope of the project PRORETA was presented to an audience selected by Continental Teves and TU Darmstadt. The guests had the possibility of experiencing the system within the scope of driving experiments. Every guest drove, amongst others, the scenarios presented in Figure 8. The system worked robustly and faultlessly. However, until such a system is available on the market, some tasks have still to be solved. An important one is the analysis of the oncoming traffic which is examined in a subsequent PRORETA project.

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