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Collision avoidance with automatic braking and swerving

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Abstract: To avoid collisions in longitudinal direction emergency braking is suitable in many situations. However for higher velocites, an evasive maneuver is better because it can be applied later than the braking maneuver if there is enough free space. This contribution investigates methods for the decision-making of a collision avoidance system with regard to automatic braking and swerving. The resulting system tries to use the latest possible point for intervention if the driver does not react. This decision is based on certain time measures and distances. Further trajectory planning and control methods for swerving are described and some simulations are given.

Keywords: Collision Avoidance; Trajectory planning; Nonlinear Control; Interactive vehicle control; Vehicle dynamics.

1. INTRODUCTION

Collisions with other objects or vehicles on urban roads or highways in longitudinal direction can be avoided by automatic braking or swerving, if the driver does not react in an early stage and in the right way, Isermann et al. [2012]. This contribution extends former theoretical and experimental research for swerving at higher speeds and takes into account the available free space.

The assumed sensors are a suitable front radar system and a video camera and rear-left and rear-right radar systems. Some specialities of the investigations are the calculation of the last instants to brake and to steer, which depend on the relative velocitiy and are different. A decision making program will be developed which includes the estimation of available free space on the parallel lane considers several vehicles.

The methods are developed by simulations with the comprehensive IPG CarMaker simulation environment and include experimental results from earlier work.

2. CONSIDERED SCENARIO

As automotive collision avoidance systems have to consider several driving situations, the tested scenario has to be specified.

2.1 Sensor setup

The different sensors used as shown in Fig. 1. A camera is installed at the windshield, which delivers information about the lane-width, the position of the ego vehicle on the lane and the lateral position of the front vehicles.

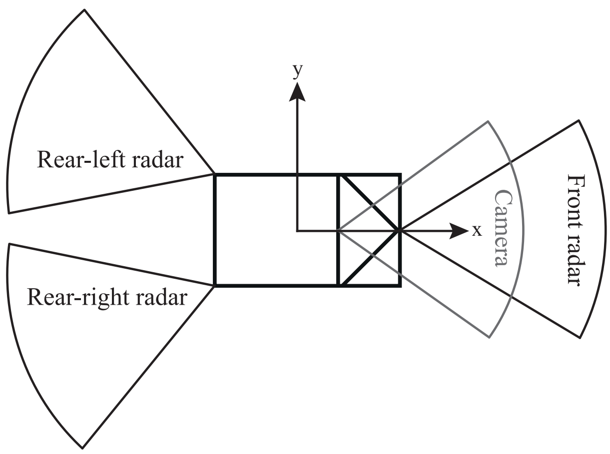


Fig. 1. Schematic sensor arrangement

Three radar sensor systems (e.g. 24 or 77 GHz) are assumed, the front system detects objects driving in front of the ego vehicle. The other two radar sensors are installed at the left and right backside of the car. All radar sensors supply object lists. For each object the position relatively to the ego vehicle and the difference velocity is provided relatively to the obstacles.

Because the rear radar sensors are turned, their information is transformed into the same coordinate system. Then

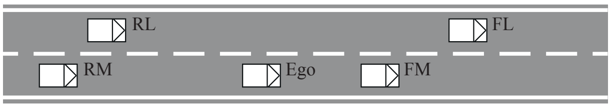


Fig. 2. Objects around the ego vehicle

the distance and difference velocity is provided in X- and Y-coordiantes relatively to the ego vehicle.

2.2 Objects

In the following the vehicles next to the ego vehicle are considered. Four vehicles as shown in Fig. 2 are assumed: Front-left, front-middle, rear-left, and rear-middle. The vehicles classified as "left" are the nearest objects on the left lane next to the ego-vehicle. The front-middle vehicle is the main object in front of the own car. For testing purposes in a first phase only the middle and the two left objects are considered in the CarMaker simulation environment.

Using the position of the ego vehicle and the object lists from the radar sensors and fusion with the camera Isermann et al. [2012], the relevant objects can be selected.

3. DECISION MAKING

3.1 Basic considerations

In the following it is assumed that the main object for collision avoidance is the car FM in front of the own (Ego) vehicle.

The goal is to avoid the collision in the last possible moment. This can be either the last point to steer (LPS), then swerving is the better maneuver, or the last point to brake (LPB), then braking is the better maneuver.

LPB after LPS At lower velocities the braking maneuver is the maneuver which can be performed later. This is illustrated in Fig. 3.

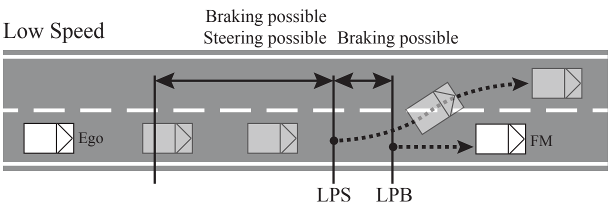


Fig. 3. Illustration of last point to brake and last point to steer at low velocities

This is the more easy case. When the last point to brake is reached, the system has to do a full braking automatically.

LPS after LPB At higher velocities the braking distance is longer than the distance needed for the evasive maneuver, Bender et al. [2007]. This is outlined in Fig. 4.

This case is more difficult than the other one. Generally the evasive maneuver is the best way to avoid the collision. But an evasive maneuver is of course only possible, if there is enough space sidewards and backwards to swerve. So the assistance system has to ensure that the cars on the evasive lane are far enough so that they are not endangered.

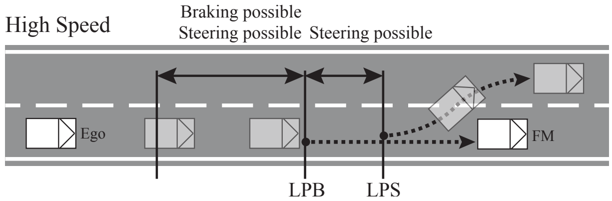


Fig. 4. Illustration of last point to brake and last point to steer at high velocities

If swerving is not possible because of missing free space, only the emergency braking helps to intervent or mitigate the collision. But this has to be started at earlier time. So the information if an evasive maneuver is possible at the last point to steer has to be available at the last point to brake.

3.2 Calculation of time intervals

For making a decision there are generally two possibilities. One is to consider the *distances* between all the objects. However the distance has to be interpreted dependent on the velocities.

The other possibility is to use *time intervals*. These time intervals indicate after which time a certain event occurs or how long a certain event takes. The advantage is, that only one value has to be considered. Furthermore human reaction times can be used as reference values.

Therefore the decisions are based on time intervals. They are calculated with the information from the environmental sensors and definitions made before.

Important time intervals are the time to collision (TTC), the braking time (T_{brake}) and the evasive time (T_{eva}). Based on these time intervals the time to steer (TTS) and the time to brake (TTB) can be calculated.

Time to Collision (TTC) Using the difference velocities and the distances it is possible to calculate the Time to Collision (TTC). The TTC represents the time after which a collision occurs if the two considered vehicles drive with the same velocity (Hayward [1972]):

$$\text{TTC} = \frac{s_{\text{dX}}}{v_{\text{dX}}}. \tag{1}$$

Braking Time If there is a negative difference velocity to the car in front ($v_{\text{dX,fr}} < 0$), then the own car moves towards the car in front. Under the assumption that this vehicle moves with constant velocity, and a constant maximum deceleration for dry asphalt is assumed with $a_{\text{brake}} = 9.81\frac{\text{m}}{\text{s}^2}$, for the braking time it holds (Ackermann et al. [2014]):

$$T_{\text{brake}}(v_{\text{dX}}, a_{\text{brake}}) = \frac{v_{\text{dX}}}{2a_{\text{brake}}}. \tag{2}$$

Evasive Time The evasive time depends on the width, i.e. the lateral displacement y_{eva}, from the evasive maneuver and the maximum lateral acceleration a_{eva} which depends on the road condition (Winner et al. [2009]):

$$T_{\text{eva}}(y_{\text{eva}}, a_{\text{eva}}) = \sqrt{\frac{2 \cdot y_{\text{eva}}}{a_{\text{eva}}}} + \tau_s. \tag{3}$$

τ_s is the steering loss time and can be assumed with 0.1s.

Time to Brake (TTB) The time to brake gives the time after which a braking maneuver has to be started to prevent the collision. If the TTB is smaller than 0, a collision can not be avoided by braking.

$$\mathrm{TTB} = \mathrm{TTC}_{\mathrm{fm}} - T_{\mathrm{brake}}. \tag{4}$$

Time to Steer (TTS) The time to steer gives the time after which an evasive maneuver has to be started to prevent the collision. If the TTC is smaller than 0, a collision can not be avoided by steering.

$$\mathrm{TTS} = \mathrm{TTC}_{\mathrm{fm}} - T_{\mathrm{eva}}. \tag{5}$$

3.3 Selection of free space

For making a decision the cars on the other lanes are considered. For simplification only the left lane is considered. Other lanes, if present, can be considered similarly.

The sensor based object detection observes the vehicles on the left lane in front and behind the ego vehicle. These two cars represent the highest potential risk.

In the following a forecast of free space selection is made for the last point to steer. Assuming that the cars are moving with constant velocity, it is checked, if the evasive maneuver will be possible at the last point to steer (LPS).

Some equations for the forecast calculate if the evasive maneuver will be possible when the last possible point to steer is reached ($\mathrm{TTS} = \mathrm{TTC}_{\mathrm{fm}} - T_{\mathrm{eva}} = 0$).

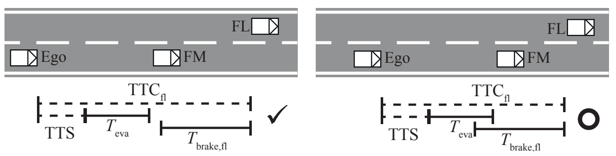


Fig. 5. Graphical illustration for front-left target

Front-left target Assuming constant velocities, $T_{\mathrm{brake,fl}}$ and T_{eva} stay constant and $\mathrm{TTC}_{\mathrm{fl}}$ decreases continously. Performing the evasive maneuver at $\mathrm{TTS} = 0$, $\mathrm{TTC}_{\mathrm{fl}}$ will decrease by TTS from the moment of calculation to $\mathrm{TTS} = 0$.

For the front-left target the TTC to the front-left object minus the braking and the evasive time has to be higher than the TTS, because first the swerving and then the braking is assumed:

$$\mathrm{TTC}_{\mathrm{fl}} - T_{\mathrm{brake,fl}} - T_{\mathrm{eva}} > \mathrm{TTS}. \tag{6}$$

With the relation $\mathrm{TTS} = \mathrm{TTC}_{\mathrm{fm}} - T_{\mathrm{eva}}$ this leads to:

$$\mathrm{TTC}_{\mathrm{fl}} - T_{\mathrm{brake,fl}} > \mathrm{TTC}_{\mathrm{fm}}. \tag{7}$$

Rear-left target The same is done for the rear-left target with the difference that now the braking time of the rear-left vehicle is considered, which leads to:

$$\mathrm{TTC}_{\mathrm{rl}} - T_{\mathrm{brake,rl}} > \mathrm{TTC}_{\mathrm{fm}}. \tag{8}$$

The question if the evasive maneuver will be possible at $\mathrm{TTS} = 0$ can now be answered by the following equation:

$$\mathrm{evaPossible} = \begin{cases} 1, & \text{if} \quad \mathrm{TTC}_{\mathrm{fl}} - T_{\mathrm{brake,fl}} > \mathrm{TTC}_{\mathrm{fm}} \\ & \quad \wedge\ \mathrm{TTC}_{\mathrm{rl}} - T_{\mathrm{brake,rl}} > \mathrm{TTC}_{\mathrm{fm}}, \\ 0, & \text{else.} \end{cases} \tag{9}$$

3.4 Decision rules

Now these calcuations are used for making a decision for the assistance system. This decision will then be given to the collision avoidance control.

For small difference velocities the braking distance is smaller than the evasive distance. For big difference velocities this is opposite. The intersection can be calculated very easily:

$$v_{\mathrm{dX;brake=eva}} = 2 \cdot a_{\mathrm{brake}} \cdot \sqrt{\frac{2 \cdot y_{\mathrm{eva}}}{a_{\mathrm{eva}}}}. \tag{10}$$

Because the system should intervent at the last possible point, for difference velocities smaller than $v_{\mathrm{dX;brake=eva}}$ braking is better than swerving, Stählin et al. [2007]. For higher difference velocities the swerving is the better maneuver but can only be performed when there is enough space on the evasive lane.

Example: Assuming $a_{\mathrm{brake}} = 9.81\frac{\mathrm{m}}{\mathrm{s}^2}$, $a_{\mathrm{eva}} = 7\frac{\mathrm{m}}{\mathrm{s}^2}$ and $y_{\mathrm{eva}} = 3.6\mathrm{m}$ the intersection velocity is $v_{\mathrm{dX;brake=eva}} = 19.9\frac{\mathrm{m}}{\mathrm{s}} = 71.6\frac{\mathrm{km}}{\mathrm{h}}$.

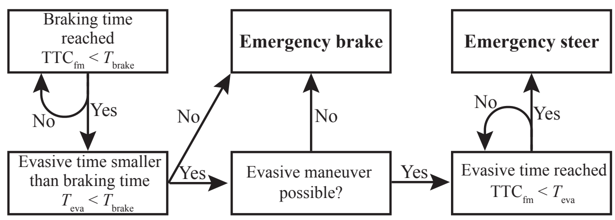


Fig. 6. Flowchart for decision making

Fig. 6 shows how the decision is made. When the braking time is reached, the system checks if the evasive time is smaller than the braking time. If not, braking is in every case the better maneuver and the system starts to brake. If not, it is considered if an evasive maneuver will be possible at the last point to steer. If this is not the case, the emergency braking is performed too. If an evasive maneuver will be possible, the system performs the evasive maneuver at the last point to steer.

4. DESIGN OF TRAJECTORY CONTROL

After the treatment of the decision-making this section deals with the control of the lateral and longitudinal dynamics of the vehicle. First, the controller for the braking maneuver is presented. Then a method for planning an evasive trajectory is introduced. Finally a controller for the steering system is presented to drive along the calculated trajectory.

4.1 Brake control

Because only a fullbraking is needed it is sufficient to apply maximum braking to the vehicle. The assumed maximal possible deceleration is $a_{\mathrm{break}} = 9.81 \frac{\mathrm{m}}{\mathrm{s}^2}$ for dry roads.

4.2 Trajectory planning

For the evasive maneuver the required trajectory is subject to the steering controller. The manipulated variable is the steering angle.

There are different possibilities for planning an evasive trajectory. In every case it is important to limit the lateral acceleration. Otherwise the physical limits can be exceeded.

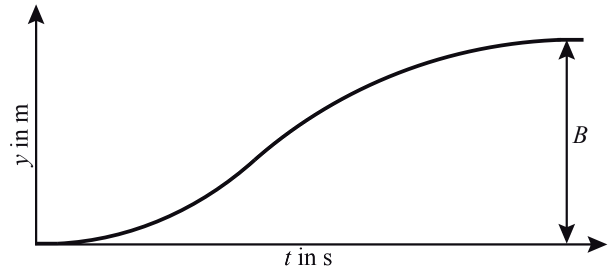


Fig. 7. Transfer function

A simple way is to create the trajectory as a step response. In Schmitt [2012] a fourth order transfer function was used to predict the lane-change-trajectory for the PRORETA 2 project. This can be also used for an evasive maneuver. The following transfer function is considered:

$$G(s) = \frac{1}{(1+Ts)^4}. \tag{11}$$

This function is obtained from the transfer function

$$G(s) = \frac{K}{(1+T_1 s)(1+T_2 s)...(1+T_n s)} \tag{12}$$

and the assumption that all time constants match, Isermann and Münchhof [2011].

The fourth order transfer function can also be written as a state space system:

$$\begin{bmatrix} \dot{y} \\ \dot{v}_{\mathrm{Y}} \\ \dot{a}_{\mathrm{Y}} \\ \dot{j}_{\mathrm{Y}} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{1}{T^4} & -\frac{4}{T^3} & -\frac{6}{T^2} & -\frac{4}{T} \end{bmatrix} \begin{bmatrix} y \\ v_{\mathrm{Y}} \\ a_{\mathrm{Y}} \\ j_{\mathrm{Y}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{T^4} \end{bmatrix} y_{\mathrm{ref}}. \tag{13}$$

When the evasive maneuver is started, y_{ref} is set to a step function of size B. Then an evasive trajectory in time-domain $y(t)$ follows as a step-response. T affects the shape of the trajectory and has to be determined in a way that the maximum jerk and the maximum lateral acceleration are respected.

Determination of parameter T

For determination of the time constant T the maximum lateral acceleration is considered, because it is included in the state vector. The maximum lateral acceleration occurs at

$$t_{a_{\mathrm{Y,max}}} = T(3-\sqrt{3}). \tag{14}$$

which is obtained by the solution in the time-domain of the step-response from Eq. (13). For $a_{\mathrm{Y,max}}$ then holds

$$\begin{aligned} a_{\mathrm{Y,max}} &= \frac{B}{T^2} e^{-(3-\sqrt{3})} \left(\frac{(3-\sqrt{3})^2}{2} - \frac{(3-\sqrt{3})^3}{6} \right) \\ &\approx 0.13 \frac{B}{T^2}. \end{aligned} \tag{15}$$

Now the time constant T can be determined in dependence of B and $a_{\mathrm{Y,max}}$:

$$T = \sqrt{0.13 \frac{B}{a_{\mathrm{Y,max}}}}. \tag{16}$$

4.3 Steering control

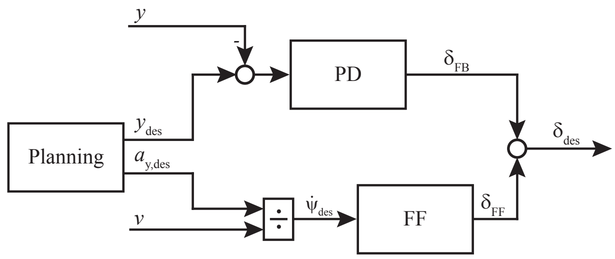


Fig. 8. Structure of steering controller

For steering control a two-degree-of-freedom structure is used, consisting of a feedforward and a feedback controller.

Feedforward control The trajectory planning leads to the following state space system is given:

$$\begin{bmatrix} \dot{y}_{\mathrm{ref}} \\ \dot{v}_{\mathrm{Y,ref}} \\ \dot{a}_{\mathrm{Y,ref}} \\ \dot{j}_{\mathrm{Y,ref}} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{1}{T^4} & -\frac{4}{T^3} & -\frac{6}{T^2} & -\frac{4}{T} \end{bmatrix} \begin{bmatrix} y_{\mathrm{ref}} \\ v_{\mathrm{Y,ref}} \\ a_{\mathrm{Y,ref}} \\ j_{\mathrm{Y,ref}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{T^4} \end{bmatrix} B_{\mathrm{ref}}. \tag{17}$$

When the evasive maneuver is started, B_{ref} as input signal is set to B. Then an evasive trajectory in time-domain $y_{\mathrm{ref}}(t)$ is given as a step-response of this state space model. Furthermore $a_{\mathrm{y,ref}}(t)$ is calculated. This can be used for feedforward-control.

With the desired lateral acceleration the desired yawrate $\dot{\psi}_{\mathrm{ref}}$ can be calculated:

$$\dot{\psi}_{\mathrm{ref}} = \frac{a_{\mathrm{Y,ref}}}{v}. \tag{18}$$

Using the desired yawrate it is possible to calculate a desired steering angle, Schorn and Isermann [2006]:

$$\frac{\delta}{\dot{\psi}} = i_S \frac{l + v^2 \mathrm{SG}}{v}. \tag{19}$$

SG is the so-called understeer gradient and describes the steering behaviour depending on the velocity, Gillespie [1992], Kiencke and Nielsen [2000]:

$$\mathrm{SG} = \frac{c_{\alpha,\mathrm{r}} l_\mathrm{r} + c_{\alpha,\mathrm{f}} l_\mathrm{f}}{c_{\alpha,\mathrm{f}} c_{\alpha,\mathrm{r}} l}. \tag{20}$$

Feedback control Schorn [2007] investigated different controllers. Finally he ended up in the relatively simple PD-Controller, which is also used here.

As the one track vehicle model shows, the lateral behaviour depends on the velocity. Therefore M different controllers depending on the velocity of the vehicle are applied. The controller outputs are weighted with membership or activation functions and summarized as shown in Fig. 9. This approach uses local linear models (Fink et al. [1999]).

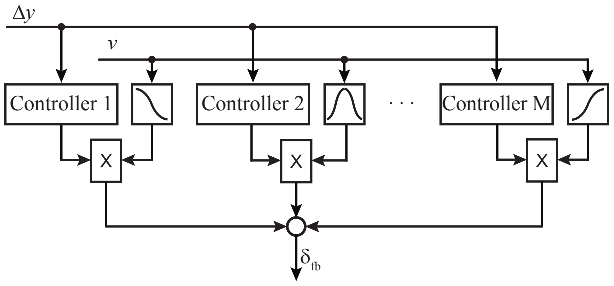


Fig. 9. Structure of velocity dependent controllers

The output of the local linear controller network is obtained from the weighted controller outputs:

$$\delta_{\mathrm{fb}} = \sum_{i=1}^{M} \delta_{\mathrm{LLM,i}} \Phi_i(v) \tag{21}$$

using

$$\Phi_i(v) = \frac{\mu_i(v)}{\sum_{j=1}^{M} \mu_j(v)} \quad \text{with} \quad \mu_i(v) = \exp\left(-\frac{1}{2}\frac{(v-c_i)^2}{\sigma_i^2}\right) \tag{22}$$

as activation function.

5. RESULTS

This section summarizes the results of the collision avoidance part. After introducing different testing scenarios, the results are presented. Here only the case of a large difference velocity is considered as an example.

5.1 Scenarios

Maneuver 1: High difference velocity, swerving possible In the first maneuver the ego vehicle drives with $100\,\frac{\mathrm{km}}{\mathrm{h}}$. In front of the own car is another vehicle, which drives very slow. On the left lane drives a car with higher speed, which will not disturb the evasive maneuver.

Maneuver 2: High difference velocity, swerving not possible The second maneuver is nearly the same like the first one. Only the car on the left drives with a higher velocity. So this car will block the evasive maneuver.

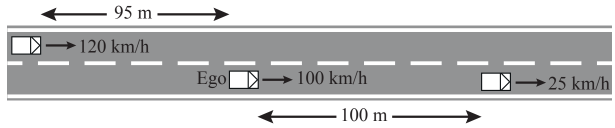


Fig. 10. Maneuver 1: High difference velocity, swerving possible

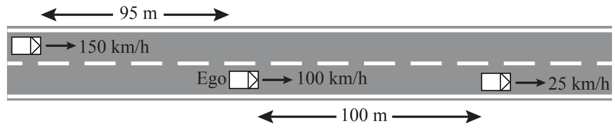


Fig. 11. Maneuver 2: High difference velocity, swerving not possible

5.2 Decision verification

For better illustration the maximum deceleration is now assumed with $5\,\frac{\mathrm{m}}{\mathrm{s}^2}$, because then the time interval between the last point to steer and the last point to brake is larger.

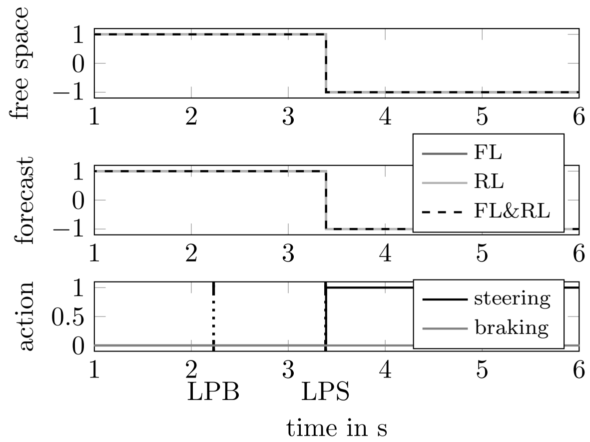


Fig. 12. Decision for scenario 1

Fig. 12 depicts the decision for scenario 1. At about 2.2 seconds at the last point to brake the decision is made. Because the forecast determines a free road, the evasive maneuver is started at 3.4 seconds which is the last point to steer.

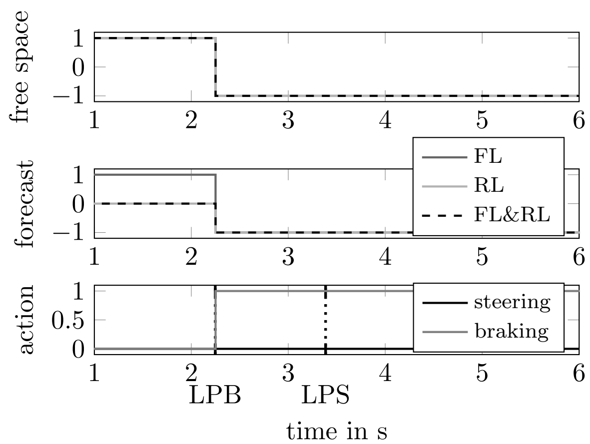
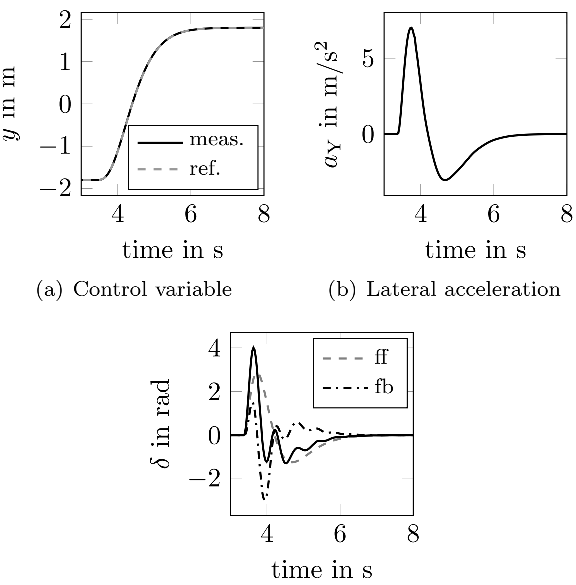


Fig. 13. Decision for scenario 2

In Fig. 13 the decision is also made at 2.2 seconds. But in this case the forecast determines a vehicle on the left lane at the last point to steer. So an emergency braking maneuver is started immediately. Hence it is illustrated, that the forecast determines the blocked lane already at the last point to brake even if there is enough space at this time instant, but not later.

5.3 Steering control



(a) Control variable (b) Lateral acceleration

(c) Manipulated steering angle

Fig. 14. Steering control

For the steering the controller described before is used. In Fig. 14 the reference and the driven trajectory, the lateral acceleration and the steering angle divided in feedforward and feedback part are shown. The car follows the trajectory well and the collision is avoided.

6. CONCLUSION

A driver assistance system was presented, which uses either the brake for the preventing of collisions or the steering. For swerving knowledge on vehicles of the adjacent roadway is required. A method was presented which takes the availability of the free space into account. Finally a decision is made based on the velocities, distances, given maximum accelerations and the estimated free space to avoid the collision. Stability limits of driving physics are considered by the specification of maximum lateral acceleration and maximum deceleration. These values have to be chosen depending on the road condition. The system tries to use the latest possible point for intervention if the driver does not react.

The next step is to optimize the developed system. Presently the driver has the possibility to intervent until the last possible point. But then the system reacts fully automatically. Therefore a warning system could be introduced. Further the inclusion of an appropriate interpretation of the driver's intentions can be investigated. To reduce the evasive time also a combination of braking and swerving is conceivable.

SYMBOLS

v	vehicle velocity	m/s
a_{Y}	lateral acceleration	m/s^2
$\dot{\psi}$	yaw rate	rad/s
δ_{H}	steering wheel angle	rad
i_{S}	steering ratio	1
c_α	cornering stiffness	N/rad
l	wheel base	m
TTC	time to collision	s
T_{brake}	braking time	s
T_{eva}	evasive time	s
s_{dX}	distance in x-direction	m
s_{dY}	distance in y-direction	m
v_{dX}	difference velocity in x-direction	m/s

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