

NEW INTEGRATED ASSISTANCE FUNCTIONS FOR REAL WORLD ACCIDENT SCENARIOS

Christoph Hartmann

Sakheen Harlapur

Thomas Brandmeier

Technische Hochschule Ingolstadt

Germany

Akshay Rajendra

Continental, Chassis & Safety Division, Advanced Driver Assistance Systems Business Unit

Germany

Holger Faisst

Continental, Chassis & Safety Division, Passive Safety & Sensorics Business Unit

Germany

Peter Lauer

Continental, Chassis & Safety Division, Systems & Technology

Germany

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ABSTRACT

Investigation of several accident databases consistently identified guardrail and embankment accidents as highly relevant in the context of real world accident scenarios that are not in the focus of today's vehicle safety functions. This work demonstrates the potential of future vehicle safety functions to reduce the severity of such accidents. To achieve this, two vehicle lateral controllers are in development that assist the driver in guardrail and embankment accident situations. A Linear Quadratic Regulator (LQR) approach, based on a single track model, is used to stabilize the vehicle in these situations with the goal to reduce the risk of secondary collisions and a rollover of the vehicle. Simulation results demonstrate the potential of the vehicle lateral controllers to stabilize the vehicle after a guardrail collision and to keep it in a safe area next to the guardrail. It is also demonstrated that the risk of a rollover in an embankment due to erroneous driver steering can be reduced. Further research is required to investigate the influence of driver inputs to the controllers in the mentioned accident situations. It needs to be discussed how the new controllers could be incorporated in the existing and future vehicle safety architecture.

INTRODUCTION

According to the World Health Organization (WHO), road traffic accidents are the eighth leading cause of death worldwide and the leading cause of death among young people aged 19-25. While countries with a high income level have been able to reduce this number in the last years, the fatalities in low and middle income countries have increased (WHO 2013). The WHO has initiated the "Decade of Action for Road Safety" with the goal to save five million lives in road traffic until 2020. The long term goal for countries with high safety standards is the "Vision Zero", meaning zero fatalities in road traffic. Car manufacturers, suppliers and legislative have worked hard on the improvement of vehicle safety in the last decades. The basis of today's passive safety systems is built on international standards and guidelines wherein the central components are highly reproducible crash tests. The PreCrash phase will have to be taken into account to achieve further improvement in the area of vehicle safety. Special attention should be put on real world accident scenarios that are not controllable by today's safety systems. Although the standardized laboratory crash tests are well representative for the majority of field crashes, it seems that a significant number of accident scenarios is not described completely (Allgemeiner Deutscher Automobil Club (ADAC) 2011). This requires the development of new Integrated Safety Algorithms based on the relevance of certain real world accident scenarios.

ACCIDENT RESEARCH

Analyses of several accident databases identified significant accident scenarios that can no longer be neglected in the development of vehicle safety systems. Data obtained from the German In-Depth Accident Study (GIDAS), the United States Fatality Analysis Reporting System (FARS), the General Estimates System (GES) database as well as the ADAC accident research (ADAC 2013), illustrate consistently road departure accidents as the main cause for accidents involving severe injuries. GIDAS data shows that 20% of all accidents involving injured occupants have their root cause in unintentional leaving the road. Road departure as the consequence of a previous accident has been excluded in this analyses. The importance of road departure situations increases even more when the injury value is put into focus. Almost 49% of accidents involving fatally injured occupants have a road departure event as the initial starting point. In consequence, the need for new Integrated Safety Algorithms arises that concentrate on road departure accidents. A deeper analysis of road departure accidents identified situations involving an embankment or guardrail as primary accident event as highly significant in this accident category.

Guardrail Accidents

Accidents that have a guardrail as the primary collision object are identified as the second most relevant scenario in the area of road departure accidents. They stand for 4.5%, or almost 7,000 injured people in the GIDAS analyses and they are also the fifth leading cause of accidents on German highways. Deeper analysis shows that 75% of the vehicles are involved in multiple collisions after they collided with a guardrail. This can either be another guardrail (52%), a vehicle (24%) or a different object (24%) like a tree. This is notable as the injury severity increases with multiple collisions. The delta-velocity, the velocity that is decomposed in the primary guardrail collision, is relatively low with a maximum of 20 km/h for more than half of the accidents. Therefore a high energy potential is left for secondary collisions, as the average collision velocity is more than 70 km/h for 51% of the vehicles during the primary guardrail contact. The analyses show also that the root cause of guardrail accidents are driving situations that relate to loss of control, inattention or fatigue of the driver. If proper reaction by the driver is initiated after the first guardrail contact, the risk of multiple collisions will be reduced. Support of the driver in such situations is therefore goal of the new vehicle safety functions.

Embankment Accidents

Nearly 8% of all accidents involving injured occupants in a passenger car occur in the vicinity of an embankment, while the embankment can either go up or down. This corresponds to 12,000 people in Germany for the year 2010, according to the GIDAS analysis. Two thirds of the vehicles have a follow up collision after leaving the road. It is remarkable that 48% of the vehicles undergo a rollover that can be followed by a frontal or side impact. The initial angle between the vehicle's longitudinal axis and the roadside is for most of the accidents relatively small at the time the road is being departed; the maximum angle reached is 20° for in total 75% of the accidents. If attention is put on the root cause of such accidents, it is striking that over 90% of the accidents occur also due to loss of control, inattention or fatigue. This leads to the conclusion that a relatively harmless starting cause can lead to severe accidents, especially when a wrong reaction by the driver is initiated, like steering upwards in a downward embankment which increases the risk of a rollover. The new vehicle safety function currently under development aims on the support of the driver in such situations. The critical driving situation shall be detected by the function which leads to braking and steering actions by a vehicle lateral controller that brings the vehicle back to a state in which the driver can regain control over the vehicle.

METHODS

The new integrated vehicle safety functions that are currently under development actively mitigate the severity of embankment and guardrail accidents during which the driver unintentionally worsens the situation with false lateral (Steering) and longitudinal (Brake and Gas pedal) control inputs to the vehicle. Existing safety functions like Electronic Stability Control (ESC) might even increase the severity of the situation in case of a panic reaction of the driver. The guardrail and embankment controllers presented in this paper use both longitudinal and lateral control trajectory inputs to stabilize and maneuver the vehicle to a safe state. Here, the safe state is defined by the reference trajectory which in case of the guardrail controller is defined as close to and parallel

to the guardrail. The embankment controller's main task is the reduction of the rollover risk by stabilizing the vehicle's dynamics.

Vehicle Lateral Controller for Guardrail Accidents

The guardrail controller stabilizes and keeps the vehicle at a certain lateral distance to the guardrail after a guardrail collision is detected. The states to be controlled are sideslip angle β , yaw rate $\dot{\psi}$, deviation in yaw angle $\Delta\psi$ and deviation in lateral distance Δy . As cameras and other environmental sensors might not deliver trustable information after a collision, the curvature κ_{ref} of the road for the next 80 – 100 m is continuously stored and referred to when a crash impulse is detected. The deviation in yaw angle $\Delta\psi$ and lateral distance Δy is estimated using two fixed coordinate trajectory models, the vehicle trajectory model (VTM) and the virtual vehicle trajectory model (VVTM). The VTM calculates an estimated trajectory of the vehicle based on kinematic equations, while the VVTM acts as a reference trajectory and takes additionally the stored curvature κ_{ref} into account. The controller itself is based on a linear single track model (Rajamani 2006) which can be given in state space representation, Eqs. (1-2).

$$\dot{X} = A(v)X + BU \quad (1).$$

$$\begin{bmatrix} \dot{\beta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -\frac{C_f + C_r}{mv} & \frac{-C_f l_f + C_r l_r}{mv^2} - 1 \\ \frac{C_r l_r - C_f l_f}{J_z} & -\frac{C_f l_f^2 + C_r l_r^2}{J_z} \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \psi \end{bmatrix} + \begin{bmatrix} \frac{C_f}{mv} \\ \frac{C_f l_f}{J_z} \end{bmatrix} \cdot \delta \quad (2).$$

$C_{f/r}$ are the tire cornering stiffness on the front and rear axle, m denotes the overall vehicle mass, v the vehicle velocity, $l_{f/r}$ are the distances of the front/rear axle to the vehicle's center of gravity, J_z is the moment of inertia and δ is the steering wheel angle. The model is adapted to suit the needs of a lateral controller. The yaw moment M_z is included as a second input to the model which results after some modifications and approximations in the adapted single track model, Eq. (3).

$$\begin{bmatrix} \dot{\beta} \\ \dot{\psi} \\ \Delta\dot{\psi} \\ \Delta\dot{y} \end{bmatrix} = \begin{bmatrix} -\frac{C_f + C_r}{mv} & \frac{-C_f l_f + C_r l_r}{mv^2} - 1 & 0 & 0 \\ \frac{C_r l_r - C_f l_f}{J_z} & -\frac{C_f l_f^2 + C_r l_r^2}{J_z} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ v & 0 & -v & 0 \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \psi \\ \Delta\psi \\ \Delta y \end{bmatrix} + \begin{bmatrix} \frac{C_f}{mv} & 0 \\ \frac{C_f l_f}{J_z} & \frac{1}{J_z} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta \\ M_z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ v \\ 0 \end{bmatrix} \kappa_{ref} \quad (3).$$

The reference curvature κ_{ref} is added as a disturbance to the model. The objective of the lateral controller is to bring the vehicle to stability, i.e. $\beta \rightarrow 0, \Delta\psi \rightarrow 0, \Delta y \rightarrow 0$, by applying active steering and active braking to the vehicle. The controller is designed as a Linear Quadratic Regulator (LQR) controller wherein the states are fed back to the input with a suitable gain feedback matrix $U = -K_c X$ (Lewis 1998). The feedback matrix K_c is calculated by,

$$K_c = R^{-1}B^T P, \quad (4).$$

wherein P is calculated by solving the algebraic Riccati equation,

$$A^T P + PA - BPR^{-1}B^T P + Q = 0. \quad (5).$$

The matrices Q and R are weighting matrices between transient response and control effort. Larger Q causes the states decay faster to zero while larger R implies less control effort, e.g. less steering and/or braking. An approximate estimation method for Q and R is given in (Körtum et. al. 1993). The outputs of the LQR controller δ_{LQR} and $M_{z,LQR}$ are fed into a steer and brake controller respectively to convert steer angle to steer

torque and yaw moment to brake pressure. The steer torque is applied as an assisting torque to the steering wheel to support the driver while the brake pressure is used for wheel selective braking on the front axle to generate the required yaw moment. The complete controller concept is shown in Figure 1.

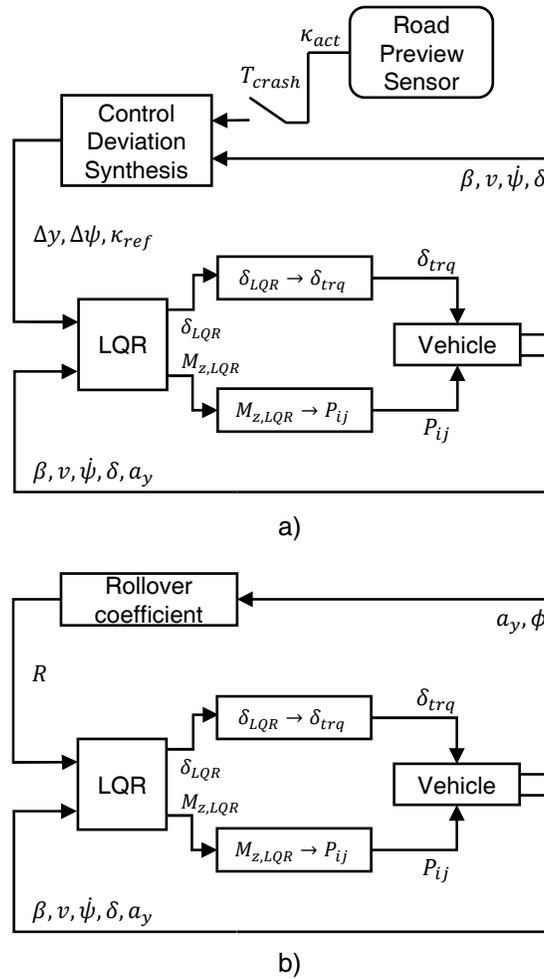


Figure 1. a) Flowchart of the lateral guardrail controller. b) Flowchart of the lateral embankment controller.

Vehicle Lateral Controller for Embankment Accidents

The controller developed for embankment situations adopts the LQR approach for the design of the controller. Similar to the guardrail situation a triggering signal for the activation of the controller is needed, which indicates the vehicle is running into an embankment. This can be achieved by using inertial or environmental sensor based algorithms. The calculation of a rollover coefficient is used for the purpose of this work, Eq. (6). It is defined as,

$$R = \frac{F_R - F_L}{F_R + F_L} \quad (6).$$

The value of R is calculated accordingly to the changes in the normal loads on the wheels on the front axle. For example, if the right wheel lifts off, which is likely to happen in an embankment to the left side, the whole load is on the left wheel ($F_R = 0, R = -1$). As the normal loads can usually not directly be obtained from sensors, the calculation of R is approximated as given in Eq. (7), (Imine 2007).

$$R \cong \frac{2(h + h_R)a_y}{Tg} + 2\frac{h}{T}\phi \quad (7).$$

h is the height of the center of gravity (CoG) of the sprung mass over the vehicle's roll centre, h_R is the height of the roll axis, T is the track width and ϕ is the roll angle. A more general approach of the kinematic single track model is used for the concept of the embankment controller as trajectory planning is not implemented in the current version, Eq. (8).

$$\begin{bmatrix} \dot{\beta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} -\frac{C_f + C_r}{mv} & \frac{-C_f l_f + C_r l_r}{mv^2} - 1 \\ \frac{C_r l_r - C_f l_f}{J_z} & -\frac{C_r l_r^2 + C_f l_f^2}{J_z} \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \psi \end{bmatrix} + \begin{bmatrix} \frac{C_f}{mv} & 0 \\ \frac{C_f l_f}{J_z} & \frac{1}{J_z} \end{bmatrix} \cdot \begin{bmatrix} \delta \\ M_z \end{bmatrix} \quad (8).$$

The steering angle δ and the yaw moment M_z calculated by the model act as inputs to the controller for the stabilization of the vehicle and the reduction of the rollover risk. The calculation of the feedback matrix K_C and the matrix P is done accordingly to the guardrail controller as the controller tries to reduce the states β and ψ to a minimum.

RESULTS

Simulated test scenarios have been carried out in IPG CarMaker® to test the vehicle lateral controllers for guardrail and embankment accidents. The results of the tests concerning the guardrail controller are compared to results obtained by an ESC system and the simulated IPG Driver™ as guardrail accidents might also cause action by an ESC system due to high yaw rates induced by the crash impulse from the guardrail. Figure 2 shows a situation in which the vehicle left the road while it was driving through a curve and crashed into a guardrail on the right side of the road.

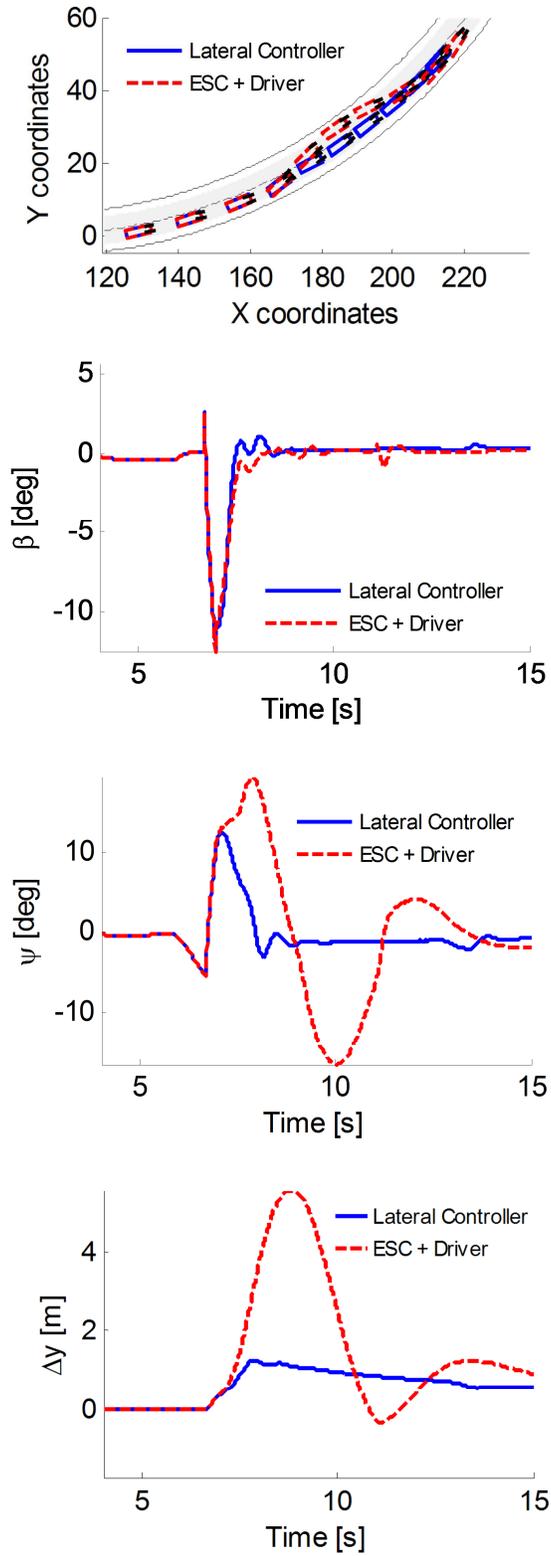


Figure2. Lateral Guardrail Controller, Situation 1: Sideslip angle β , yaw angle ψ and lateral distance Δy .

The initial velocity at the time of the crash was 70 km/h and the impact angle with the guardrail was 5.5°. It can be seen that the vehicle that is only equipped with an ESC system has a secondary impact on the other side of the road (146, 42) while the vehicle equipped with the lateral guardrail controller can be stabilized after the primary collision (139, 12). The sideslip angle and the yaw angle are also reduced faster to a minimum by the lateral guardrail controller as by ESC. Also the lateral distance to the guardrail is well under control as the vehicle stays in the safe area of 0.5 m next to the guardrail. The situation depicted in Figure 3 shows similar results.

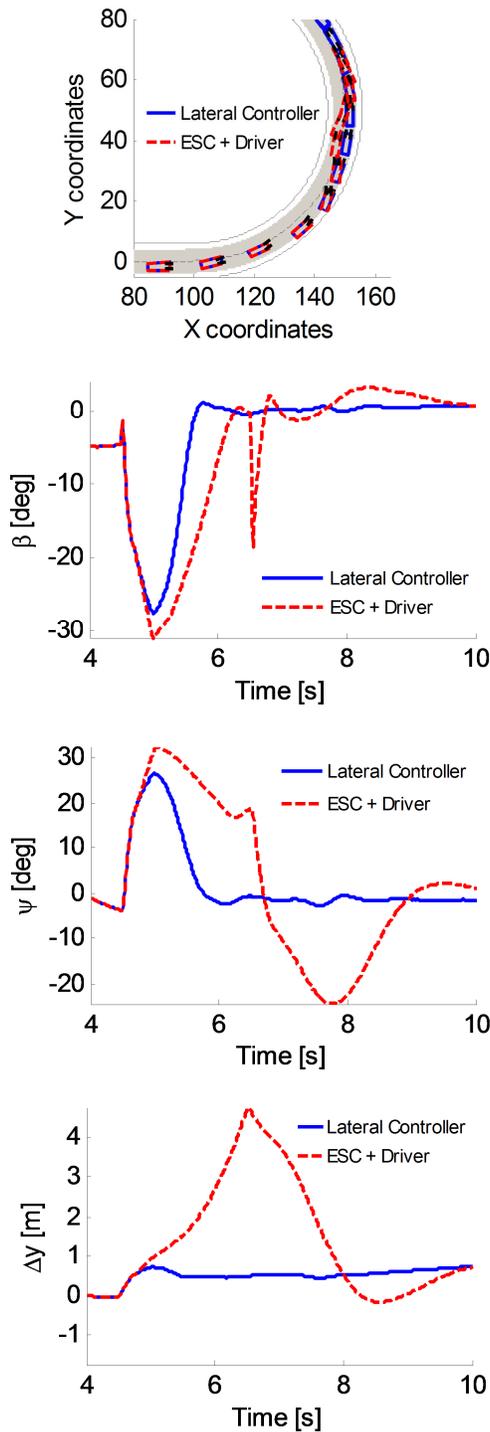


Figure3. Lateral Guardrail Controller, Situation 2: Sideslip angle β , yaw angle ψ and lateral distance Δy .

The driver of the vehicle only equipped with ESC is not able to keep the vehicle under control after the primary collision (166, 11) with 83 km/h and an impact angle of 4.2°, while the lateral controller keeps the vehicle within the driving lane. Also the yaw angle and side slip angle are reduced to a minimum within 1 s after the impact.

For the test of the embankment controller several downward embankments with an angle of 27° to 39° degree were created in CarMaker®, which represent the range of the standard embankments on German highways. The driving maneuver was constructed in a way that the driver wants to steer back onto the road after the vehicle went off the road and entered the embankment. This behavior is likely to cause a rollover as the lateral forces on the vehicle increase due to the embankment angle. Figure 4 shows a situation wherein the vehicle entered a 27° embankment while driving with 210 km/h.

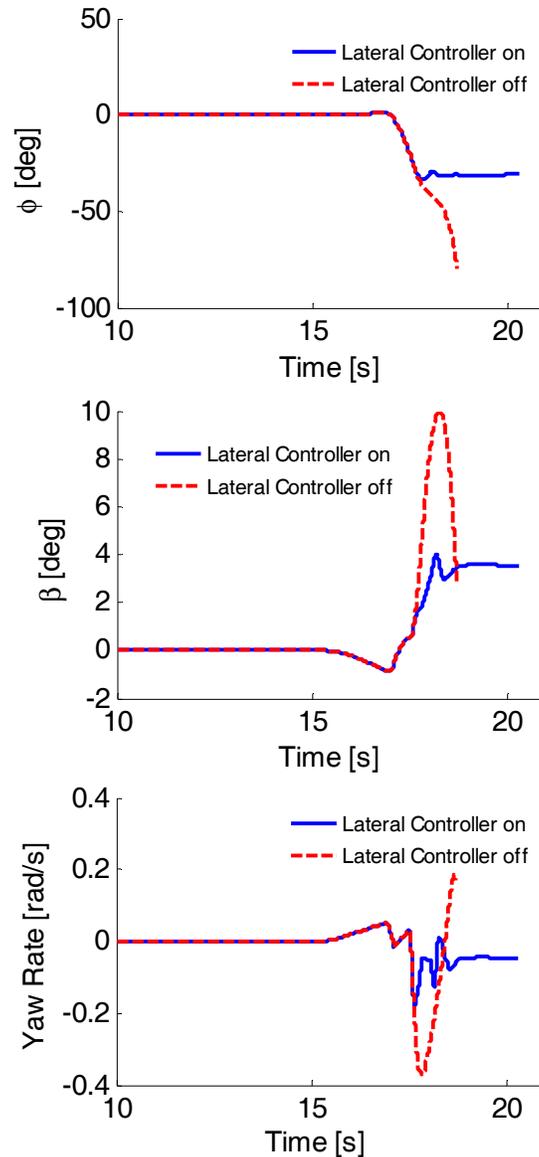


Figure 4. Embankment Controller, Situation 1: Roll angle ϕ , sideslip angle β and yaw rate $\dot{\psi}$.

Here, the lateral controller is able to prevent the rollover while the roll angle of the uncontrolled vehicle increases until the simulation stops, around 80°. The same result is achieved for an embankment of 39° at 100 km/h as it can be seen in Figure 5.

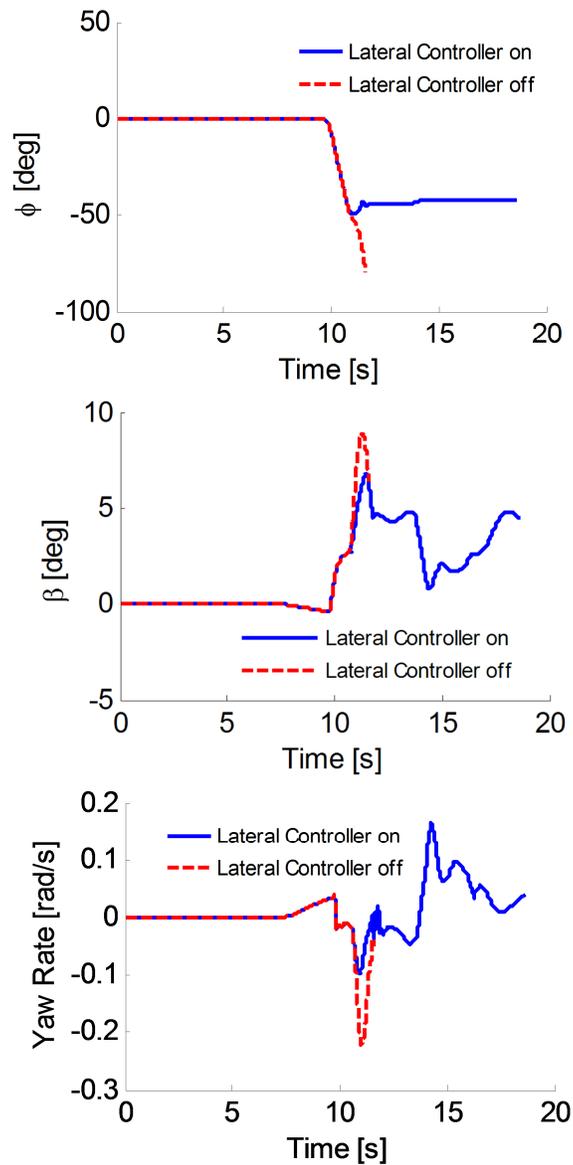


Figure5. Embankment Controller, Situation 2: Roll angle ϕ , sideslip angle β and yaw rate $\dot{\psi}$.

From the further depicted results represented by the side slip angle and the yaw rate of the vehicle, it is shown that the driver's inputs to the vehicle worsen the stability of the vehicle and lead to a rollover. However, if the controller is active then the outputs of the controller act opposite to the driver and prevent the rollover by stabilizing the vehicle.

DISCUSSION AND CONCLUSION

The analysis of several accident databases shows that accidents involving a guardrail or an embankment have a high relevance in the area of vehicle safety technologies. The developed vehicle lateral controllers for these two situations show that they have the potential to reduce the severity of such accidents by braking and steering interventions to the vehicle. Although the first simulation results are very promising, deeper analysis of the interaction between the vehicle and the driver in these situations has to be conducted. Governmental as well as functional safety requirements limit the maximum torque that can be superimposed onto the steering

wheel. This requires real world tests of the lateral controllers to understand the driver reaction to the applied torque. The introduction of an electronic steering and therefore the decoupling of steering wheel and steering axle might be a necessary step towards this topic. It is also necessary to investigate how a driving stability program like ESC interacts with the developed controllers. Usually, ESC tries to follow the desired driving direction of the driver, which in the discussed road departure situations might not always be the right choice. A discussion is needed to establish the new lateral controllers into the existing safety architecture. A highly automated driving level is needed in the mentioned guardrail and embankment situations as they are likely to be uncontrollable by the driver and today's safety functions alone.

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