ROAD DEPARTURE PROTECTION - A MEANS FOR INCREASING DRIVING SAFETY BEYOND ROAD LIMITS

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Paper Number 15-0212

ABSTRACT

Despite great technical progress in vehicle safety, according to the WHO approximately 1.2 million fatalities occur on the world's roads every year. Thus great efforts are undertaken to reduce the number of road fatalities and serious accidents, or at least to mitigate their impact on road users. The introduction of environment perception based Advanced Driver Assistance Systems (ADAS) in road vehicles is expected to improve traffic safety significantly. In today's vehicles, the prevalent ADAS focus primarily on the longitudinal driving direction, e.g. Autonomous Emergency Braking (AEB) systems and Adaptive Cruise Control. Whilst the functional range of these systems continues to expand, there exists a very large portion of critical vehicle crashes which are not addressed, mainly caused by vehicles leaving the roadway laterally.

Today, Electronic Stability Control (ESC) is one of the only established Active Safety Systems covering emergency situations in the lateral direction, and always dealing within the physical limits of vehicle dynamics. Despite the very high effectiveness of ESC systems, there remain many cases in which it is not possible to prevent unintended lateral roadway departures, especially in cases of driver drowsiness or inattention, e.g. on American highways or European rural roads. Preventing roadway departure crashes, which cannot be covered by today's lateral guidance/lane keeping ADAS, is motivation behind developing a system for road departure protection. Road Departure Protection systems expand today's lateral ADAS by active road keeping in emergency situations before reaching the physical limits of vehicle dynamics. Based on environment perception means like road edge detection or road course preview, the system should actively intervene when unintentionally leaving the roadway. By automated vehicle control, the system keeps the vehicle on the roadway, thereby protecting against roll-over accidents or collisions with roadside obstacles or oncoming traffic.

This paper presents the roadway departure problem we face today via accident data and different use cases and gives insight into the state of the art Active Safety functions and research activities. The functionalities to address the selected use cases will be described, including functional architectures, a road edge detection algorithm, approaches to preview the course of the road, sensor fusion concepts, a function cascade, and activation strategies. First test data will illustrate the function and working area of a Road Departure Protection system.
A reliable and real-time capable perception algorithm will be demonstrated. For this algorithm, different image processing techniques are applied to mono camera images to estimate the parameters of a geometric model of the road edge. It works without any supplementary knowledge about the road infrastructure.

Two system architectures will be presented, which differ in the used surrounding sensors, actuators, functional capabilities, and system cost. One variant uses a radar sensor, stereo camera and an Electric Power Steering (EPS) system, whereas another solution uses a mono camera and an ESC system. The vehicle steering capabilities and limitations of the ESC based steering are discussed in the paper. Finally, an outlook to future work and possible extensions will be given.

INTRODUCTION

Despite a tangible increase in the volume of traffic in the United States (US), European Union and Japan for more than a decade, the numbers of fatalities in the same time have been significantly reduced. Along with traffic policy and road-safety education measures, the main contributory factors here have been safety technology measures such as the continuous improvement of active and passive vehicle safety.
Continental has demonstrated with the integral safety system ContiGuard that further development in traffic safety must include – in addition to the individual active/passive safety domains – in particular the complete network and the integration of vehicle surrounding information, including as well the Human Machine Interface (HMI). ContiGuard therefore covers all safety functions by integration of crash prevention and injury mitigation measures, vehicle surrounding sensors, HMI and Safety Telematics, including driver assistance functions. Instead of "Comfort ADAS", which addresses mainly enhanced driving comfort, this paper considers "Safety ADAS" to address challenging driving situations where the safety of vehicle occupants and other road users is endangered. To identify relevant use cases for new "Safety ADAS", US and German accident data is examined in the paragraphs below.

For the United States, the NHTSA "Traffic Safety Facts" 2011 and 2012 [NHTSA11, NHTSA12] report that approximately 1.6 million and 1.75 million single vehicle accidents happened in 2011 and 2012 respectively, of which nearly 55% were related to road departure crashes, out of which 36% caused fatalities or injuries. This amounts to approximately 6% of all accidents in the U.S. in 2011 and 2012. In 2011, of all road departure crashes, 311,000 crashes with fatalities or injuries were due to a collision with fixed objects, such as parked vehicles, poles, or trees. The same data shows, once a vehicle has left the road the risk of fatalities and injuries raises significantly.
On looking further, [NHTSA02] presents more data on crashes related to off-roadway and classifies them into different crash scenarios and their frequencies. As shown in Figure 1, departing road edge without losing the control of the vehicle (straight: 36%, curve: 17%, maneuver: 7%), a scenario which can easily be avoided, totaled to 55% (525,000) of all off-roadway related crashes.

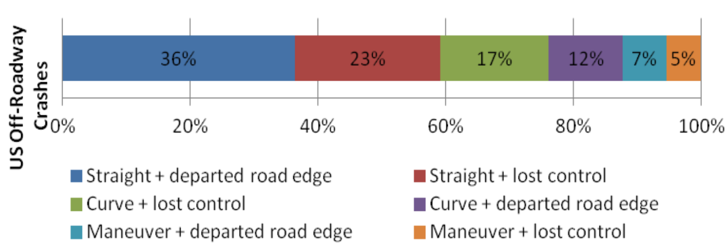

Figure 1: Off-Roadway crashes on US roads

In Germany, 60% of road accidents with fatalities and 25% of road accidents with non-fatal injuries occur on rural roads. In 2012, this accounted for 2,151 killed and 25,766 seriously injured persons. Out of all accident victims on rural roads, more than 60% are car occupants [DESTATIS13]. This makes the rural road a focus for developing new safety systems, particularly in passenger cars.
As demonstrated in Figure 2, a first more detailed analysis of rural road accidents shows that 47% of accidents are driving accidents that are caused by car drivers losing control of their vehicle. 86% of these driving accidents lead to the vehicles run-off the carriageway to either side (46% right, 40% left) [GIDAS13]. Car safety systems could address these accidents by stabilizing the vehicles or by protecting them from road departure.

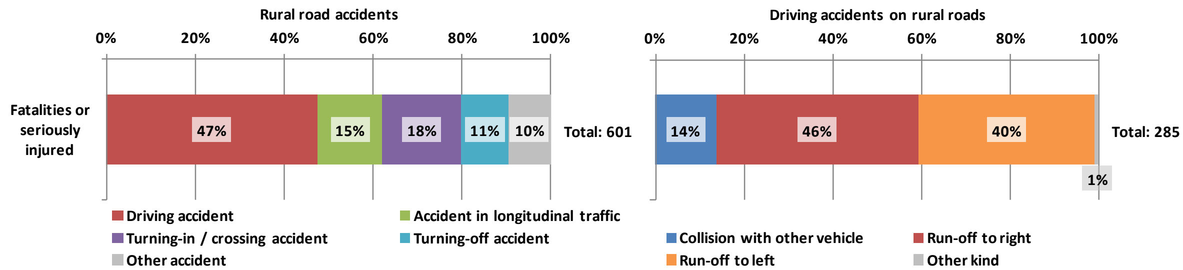

Figure 2: Accident types on German rural roads (left figure) and accident kinds of driving accidents on German rural roads (right figure) [GIDAS13]

In a second step, all car accidents on rural roads are analyzed, where the vehicle runs-off the road resulting from a driving accident, i.e. the driver losing control of the vehicle [GIDAS13]. Hereby, accidents with ESC-fitted vehicles are considered only, as those are regarded state of the art. The causes of accidents with fatalities or seriously injured are examined as this information delivers necessary input for the system development.
As shown in Figure 3, 38% of all driving accidents on rural roads with the vehicle running of the road are caused by "other mistake made by the driver" (e.g. inattention, drowsiness), 27% are caused by inappropriate speed (within speed limits) and 14% are caused by excessive speed (speeding).

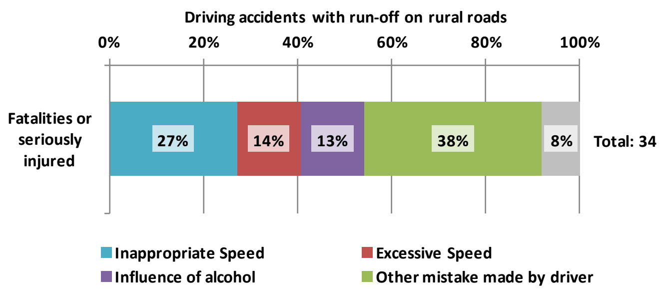

Figure 3: Accidents caused by cars on rural roads (accident type = driving accident, accident kind = run-off road, ESC fitted) [GIDAS13]

Similar to the provided US statistics, the German accident data demonstrates that there is a lack in vehicle safety regarding the protection from unintended road departure. Regarding vehicle dynamics, the relevant accidents can be divided into two main groups:

1.) Reaching the physical limits ("lost control", "speed") which counts for 45% (US) resp. 41% (GER) of relevant accidents (Figure 1, Figure 3).
2.) Not reaching the physical limits ("departed road edge", "other mistake") which counts for 55% (US) resp. 38% (GER) of relevant accidents (Figure 1, Figure 3).

To address the second group of these dangerous off-roadway related accidents, in this paper a comprehensive Road Departure Protection system is presented. The goal of such a function is to protect against unintended departure of a vehicle from the used roadway. If the risk of roadway departure is high, the driver will be warned. Should the driver not react to the warning, the Road Departure Protection system will intervene by automatically adjusting the vehicle course towards a safer, road departure avoidance path.

STATE OF THE ART

The first Lane Departure Warning (LDW) systems were introduced into the market in 2000. Lane Keeping Support (LKS) systems followed two years later [Winner09]. Since that time, the market increased and these systems are available for a magnitude of vehicles. Both types of systems monitor the lane boundaries to protect from lane departure. A study by the Highway Loss Data Institute finds LDW ineffective at preventing collisions in the field [HLDI12]. The authors of that study assume that drivers are getting too many false alarms, which could make them tune out the warnings or turn them off completely. Whatever the actual reason,

it seems that warning only systems are not effective and therefore active systems, which are not reacting solely on lanes, must be considered.
Among other topics, the European research project interactIVe (accident avoidance by active intervention for Intelligent Vehicles) investigated such systems. Towards the goal of accident-free traffic, the so-called run-off road prevention took a key role inside the project activities [interactIVe14].
A serial system addressing road departure accidents was announced by Volvo. In case of a detected run-off road accident, this system tightens the front safety belts to keep the occupants in position [Volvo14].

SYSTEM OVERVIEW

System Functionality

Road Departure Protection expands today's lateral ADAS by active road keeping in emergency situations before reaching the physical limits of vehicle dynamics. The system continuously monitors the road ahead looking for road edges along with the vehicle position with respect to the road. A road edge is defined as the border of the drivable area. For instance, the transition from road surface to grass, gravel or a solid barrier like guard rails. In contrast to LKS systems, the Road Departure Protection system does not react solely on line markings.
Once an unintended road departure is detected, the driver is warned with visual and audible warnings. If the driver fails to correct the vehicle path, and also does not indicate that the departure is intended, the function actively intervenes with the intent to steer the vehicle back onto the roadway while at the same time aligning the vehicle with the boundary. In case the vehicle cannot be brought back onto the road within the system's operational constraints the Road Departure Protection function attempts to stop the departure and aligns the vehicle with the roadway. The operational limits and effectiveness are determined by the capabilities of the sensors, actuators, and functional safety analysis.

System Architecture

Figure 4 illustrates the Road Departure Protection system architecture of a Base System and an Enhanced System. At the upstream, the Base System gathers camera image and road surface roughness information as inputs, to extract attributes of lane marker, road edge and road surface roughness. In addition to mono camera image and road surface information, the Enhanced System utilizes data of a radar sensor and a stereo camera. As the curbstone detection module extracts an additional attribute, the occupancy map of the Enhanced System delivers further information for the detection of solid boundaries. All attributes are combined together to form a hypothesis of the existence and position of the road edge
At downstream, the Road Departure Protection function calculates the vehicle motion required to avoid the road departure and the request is sent to the actuator(s). To steer the vehicle back to the road, differential braking via Electronic Stability Control (ESC), controlling the brake pressures independently at each wheel, or optionally electrical steering via Electric Power Steering (EPS) is utilized.

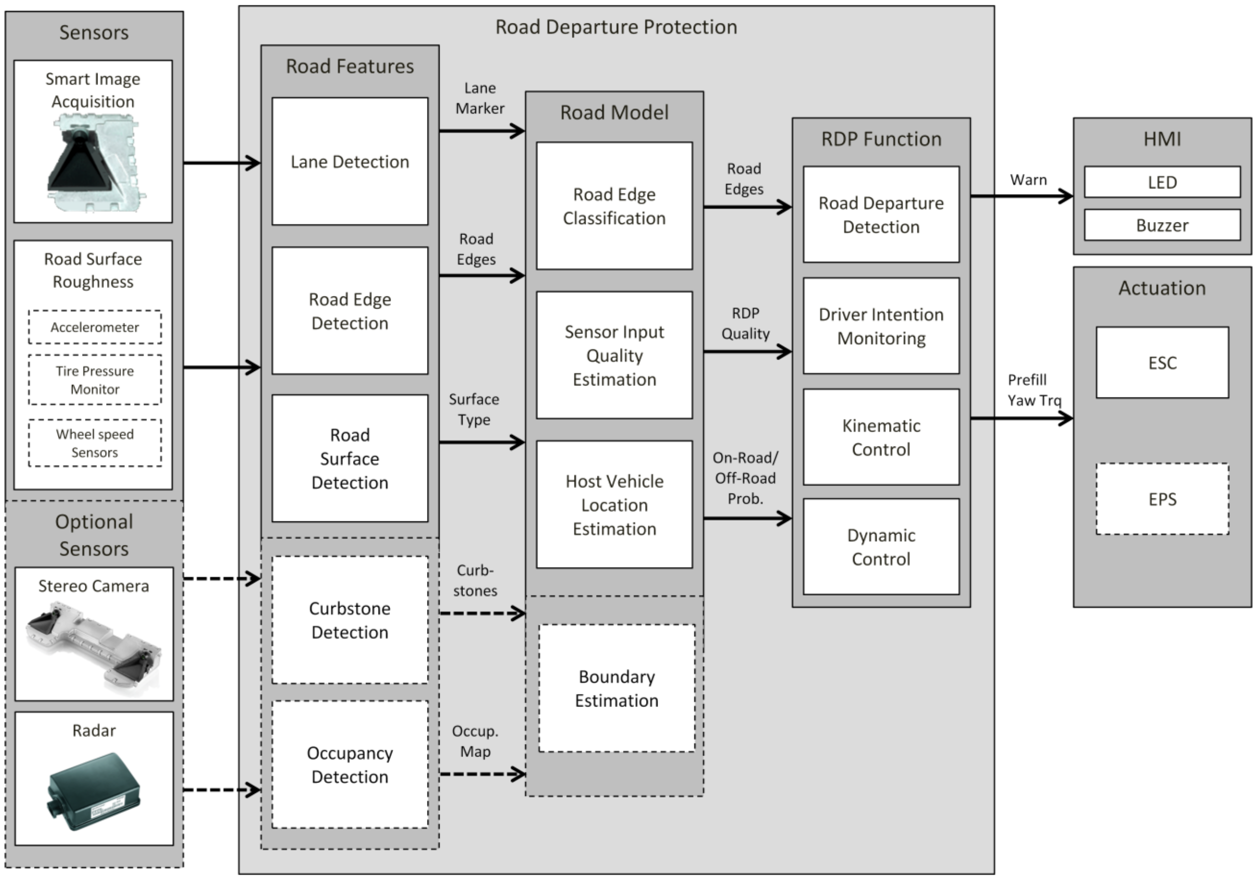

Figure 4: Road Departure Protection architecture (solid lines: modules of Base System, dashed lines: additional modules of Enhanced System)

Figure 4 shows major components of the developed Road Departure Protection system, broadly classifying them in major functions interfaced with sensors and actuation system. With images as input from camera, the road edge detection function extracts road edge attributes such as lateral offset, relative heading angle and curvature. Similar attributes for lane markers and curbstones are collected by lane marker and curbstone detection functions respectively. Road edge, lane marker and curbstone detections provide primary confirmation of road departure and this can be strengthened by a secondary confirmation from a measured change in road surface roughness. Different sensors like accelerometers, tire pressure monitors or wheel speed sensor can be used to detect the change in roughness of the road. This choice of sensors allows the use of different sensor configurations with same Road Departure Protection system function.

Radar sensor and stereo camera of the Enhanced System allow the generation of an occupancy map which contains information about the occupancy state of a tessellated area in the vehicle's field of view. Based on this map, the boundary estimator module extracts the solid borders of the vehicle surrounding. This provides a further confirmation of road departure and potential collisions with solid borders (e.g. guard rails, construction site equipment).

The Road Departure Protection function shares some use-case scenarios with LDW and LKS. Though, it is not a sub-set of LDW and LKS however. The main environmental information used by LDW and LKS are lane markers. Lane departures are critical only if there is a risk of collision with other objects and/or a risk of leaving the road. Such scenarios and their criticality cannot generally be assessed by using lane markers only. Road Departure Protection limits and extends the operating scenarios of LDW/LKS to provide protection in a roadway departure event. The Road Departure Protection function can either be implemented as a standalone active safety function or as extension to functions like LDW, LKS, Lane Center Assist (LCA), and Active

Blind Spot Detection (BSD). In any case the integration of Road Departure Protection functionality into either of these functions is beneficial because of the similarity of concepts, designs, and implementations. LDW, LKS, and Road Departure Protection may be implemented as modes of a lateral departure protection function. An even higher level of integration can be achieved by combining Road Departure Protection, LDW, LKS, LCA, and Active BSD into a comprehensive Lateral Support Systems component. This way these functions jointly provide all lateral safety support to the driver.

Road Departure Protection integrates driver intention monitoring, road departure detection, kinematic control and dynamic control, calculating required yaw moment using inputs from road edge detection, vehicle states and driver's inputs such as steering torque, accelerator and braking. In the following sections, the two main components of the proposed system, road edge detection and Road Departure Protection function are discussed in detail.

ROAD EDGE DETECTION

In general, the road edge estimation is a challenging task in case of arbitrary combinations of lane markings and unmarked road sides. It has to deal with different types of roads as highway, country, rural, tunnel, etc., where lane markings are visible, scarce or missing at all. This problem is faced by combining the techniques of a multi-lane detection and road segmentation in order to determine the road boundary on asphaltic roads. Additionally, illumination changes like shadows or irregularities on the road surface make a separation from road to non-road area very difficult. There are a lot of approaches given in literature that deal with the multi-lane recognition on well-structured roads [Zhao12]. A particle filter is used to identify hypotheses for the road edges by analyzing image features. The integration of a multi-lane detection system makes the algorithm unaffected by the road type and the number of lanes.

A popular technique to separate the homogeneous road surface from the non-road area is texture analysis [Rasmussen04]. The approach is designed for country roads and might not return the road boundary if markings are present. In [Enzweiler13] a stereo camera system in combination with a high precision digital map is used, which has to contain some information about the road edge already. Although, color information [Alvarez11] seems to be a promising feature after a transformation to a color space that is more robust for illumination changes, a monochrome camera image is used here. In contrast to a feature based approach with a neural network like [Strygulec13] which requires a lot of training data for road segmentation, it is relied on the estimation of a geometric road model by online calculated image features without the need of any additional training data. A camera-only approach was developed that does not need any other sensor information. The basic concept has been shown in [Janda13a, Janda13b].

Nearly every road follows a clothoid, which is a curve with linearly changing curvature with respect to its run length. The calculation of a first-order Taylor approximation of this clothoidal model leads to a third order polynomial. Both road edges are defined in the same vehicle coordinate system. In our local vehicle coordinate system the x-axis points in the longitudinal direction of the vehicle, the y-axis points to the left and the z-axis points upwards. In ascending order, the coefficients of the polynomial identify, the distance to the center of the origin of the road coordinate system (o), the ascending slope between the longitudinal vehicle axis and the tangent at the start point (λ), as well as the curvature (c_0) and the curvature change rate (c_1). Furthermore an adequate dynamic model is used to represent the vehicle movement between two points in time, such that the change of orientation is compensated. Those parameters form the state space of the considered estimation problem. The state probability density of the state space is approximated discretely by a finite set of particles. Hence, a particle filter is applied. Each particle consists of a state hypothesis $x = (o, \lambda, c_0, c_1)$, which is a realization of the state space and an importance weight. The importance weight is proportional to the likelihood of state x for observing some measurements. Finally, a point estimation of the particles is utilized to get the most likely road edge hypothesis. The most challenging task is the identification of image features which are appropriate to deduce suitable weighting functions for the task of estimating road edges.

At first, each road edge hypothesis is transformed to the image domain. This is done by sampling the polynomial up to a certain distance. Then, each of the sampled points is projected into the image domain with the help of the known camera calibration. Finally, the sampled and projected points are approximated, to get a continuous representation of a road edge hypothesis in the image. A weighting function for a hypothesis takes into account either the image area covered by a hypothesis of a road edge or the neighborhood of a hypothesis in the image. Given a road edge hypothesis x, the pixels that belong to the projected hypothesis are indicated by $B_R(x)$. Pixels in a neighborhood on the left of the road edge hypothesis for right borders are denoted by $B_A(x)$ and pixels in a neighborhood on the right of the hypothesis are contained in $B_G(x)$. Remember, that for a left road edge hypothesis the meaning of these two sets changes. An important requirement is to know the image areas which are covered by road markings. However, it is sufficient to identify longitudinal road markings in the direction of motion. Image processing algorithms are applied exclusively to pixels which do not belong to any road marking. Removing road markings in the preprocessing makes the road edge estimation algorithm more robust and more accurate.

Importance functions for edge gradient images and texture images were introduced in [Janda13b]. Longitudinal contours in images might be the result of a road edge. For each pixel in $B_R(x)$ the distance to the pixel with the biggest gradient norm within a local neighborhood of ten pixels is calculated. A weighting function for contours takes into account the biggest gradient norm in the neighborhood of a road edge hypothesis. The weight $w_K(x)$ is the geometric mean of the biggest gradient norms in the neighborhoods of the pixels of $B_R(x)$. By contrast, the texture feature evaluates $B_A(x)$ and $B_G(x)$. Furthermore, a two dimensional discrete cosine transform is applied to those image areas taking into account another 8x8 sized pixel neighborhood. As described in [Janda13a], the result of the transform is 64-dimensional vector. The first value is the mean gray value over the 8x8-window. The remaining entries contain the frequency spectrum of this part of the image. The variance of these 63 coefficients is computed and it shows that for asphalt the variance is slightly lower than for most of the other image parts. Consequently, the ratio of the geometric mean of the variances belonging to $B_G(x)$ and the geometric mean of the variances that belong to $B_A(x)$ are interpreted as an importance weight $w_T(x)$. If one of the three sets $B_R(x), B_G(x)$ or $B_A(x)$ is empty, the weight is set to one. Finally, the overall weight for a hypothesis is the product of the results of the single image weighting functions: $w(x) = w_K(x)\, w_T(x)$.

ROAD DEPARTURE PROTECTION

Road Model

As mentioned, the Road Departure Protection function receives camera images as input from which attributes and confidence of lane markings along with road edge is extracted. This is fused with the change in road surface roughness information to estimate the confidence of detected road edges. The advantage of using this approach of fusing the inputs from different sensors to reinforce the confidence of road edge is to keep the sensor interface open and extensible. The sensor fusion can easily be extended to include the objects or infrastructure details like road side curbs, guardrails, barrels and dividers, improving the ability of road model function to identify the road edges and their relative confidence.

The fusion is based on Bayesian Belief Network [Barber12] where the inputs include, but are not limited to, probability of adjacent lane, marker position, color, quality, type, road edge, probability of road merge, road exit and road surface roughness. The Road model function provides the estimates of left and right road edge along with the attributes such as lateral offset from vehicle center of gravity, relative heading angle, curvature and curvature derivative, to represent them as clothoids [Dickmann92] which is used for estimation of road departure.

Road Departure Detection

The Road departure detection component is responsible for correctly identifying the road departure scenarios based on inputs from road model and the vehicle motion with respect to the road. It estimates Distance-to-Edge (DTE), lateral offset from the vehicle to closest road edge, Time-to-Edge (TTE), a time estimate of when the vehicle might cross the road edge, and the corresponding lateral Velocity-to-Edge (VTE).

Before Road Departure Protection interventions are activated, the impending road departure is notified to the driver in two stages, pre-warning and acute warning. The pre-warning is an early warning, suggesting a mild corrective action by the driver, whereas, a more aggressive intervention is needed to correct the vehicle course after the acute warning. Road departure detection component calculates Time-to-Steer (TTS), which corresponds to the available time to steer the vehicle to avoid road departure while limiting the lateral acceleration (a_y) to a pre-specified safe value. TTS can be customized by selecting the maximum allowable a_y values for pre-warning and acute warning, to suit the reaction time and potential of the driver to avoid road departures.

Driver Intention Monitoring

A crucial aspect of active safety systems like Road Departure Protection is to avoid intrusive intervention to the driver and therefore the system should always honor the driver's request to take over the control of the vehicle. If not done, drivers may lose confidence in the safety system and might even turn the function off thereby negating any benefit which otherwise may have been provided. The driver intention monitoring component is responsible for identifying different aspects of driver behavior like driver feedback, activity, lane change intention and intention to overtake, by monitoring the vehicle and actuators states like steering, brake and throttle pedals as well as the turn indicators and other driver inputs. These measures help to limit the Road Departure Protection system intervention to minimize the intrusion to driver, avoiding interventions when driver wants otherwise, and assisting when driver needs the intervention.

Kinematic Control

Kinematic control component takes the inputs from road model, driver intention monitoring component and vehicle states to calculate the intervention and classify it into cascaded phases, as shown in Figure 5. When an unintended departure is detected, a warning is issued and if no corrective action is taken by the driver, Road Departure Protection enters into a pre-fill phase, where the brake system is prepared for the further intervention. The prefill phase is later followed by a first lateral control phase (L1).

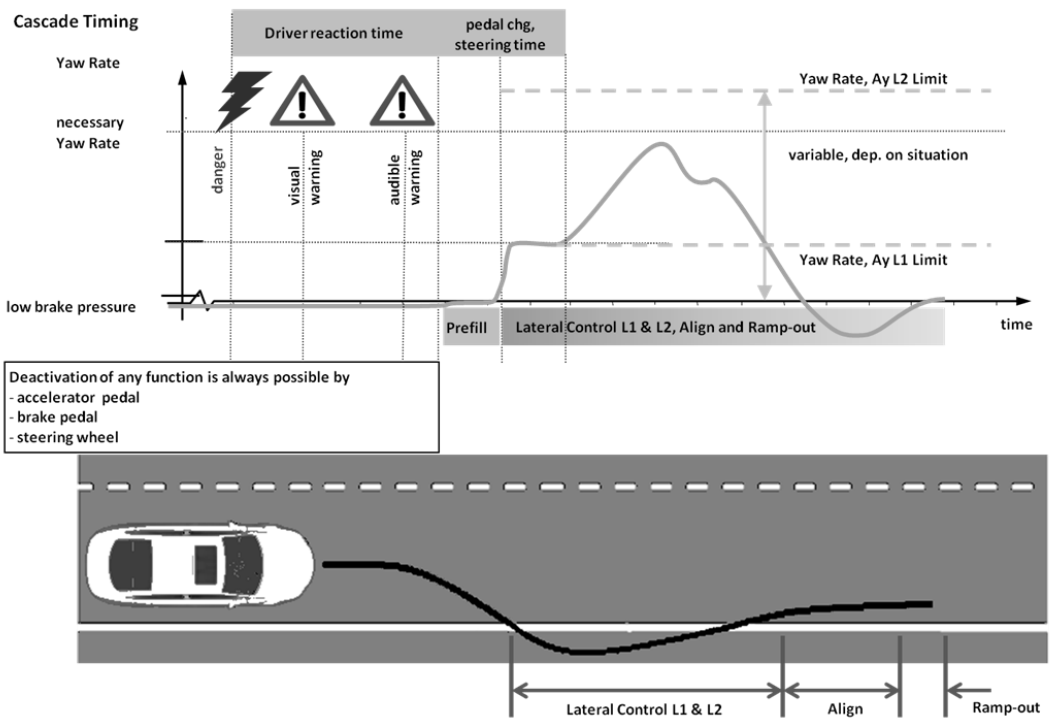

Figure 5: Road Departure Protection control phases

The L1 lateral control phase is further cascaded into a second lateral control phase (L2), followed by alignment and ramp-out sub phases. When in lateral control phase, the kinematic control calculates a correction path to correct the position and heading error of the vehicle with respect to the detected road edge. The correction of the heading error should always have a higher priority than the position correction as preventing or mitigating the road departure is of upmost importance. The calculated correction path is represented as a clothoid, from which the desired curvature is derived (Eq. 1).

$$C_{0\_latctrl} = 2 * \left(\left(\frac{\Delta Y_Y}{\Delta x^2} \right) W_y - \left(\frac{\Delta Y_\varphi}{\Delta x^2} \right) W_\varphi \right) \quad (1)$$

Based on the vehicle states and position of the vehicle relative to the road, available longitudinal distance for correction (Δx), available lateral distance for position correction (ΔY_Y), available lateral distance for heading angle correction (ΔY_φ), and a set of dynamic weights for position correction (W_y) and heading correction (W_φ) are computed. When the vehicle is getting closer to the road edge in an impending departure (departure scenario), these weights are computed to cooperate and request higher curvature whereas soon after the intervention when the vehicle is moving away from the road edge onto the roadway (return scenario), these weights compete to reverse the curvature request. This dynamic weighing helps in faster position and heading correction in departure scenarios and limits the overcorrection during return scenarios.
The lateral control intervention is further cascaded, to escalate the interventions from moderate to strong in order to give the driver additional reaction time while still offering support through the automatic path correction and the reduction in kinematic energy. The gradual increase of the steering authority may also be used to allow for higher a_y and yaw rate (ω_z) but still ensure driver controllability.
Following the lateral control phase, during the alignment phase, the objective is to ensure that the vehicle is aligned with the road edge before giving the control back to the driver. As the objective is to correct the heading, the position correction term is not included in curvature request calculation (Eq. 2).

$$C_{0\_align} = 2 * \left(\left(\frac{\Delta Y_\phi}{\Delta x^2} \right) \tan(\phi) \right) \quad (2)$$

In the final ramp-out sub phase, kinematic control prepares to give the control back to the driver by ramping down the curvature request to zero.

Dynamic Control

The dynamic control component takes the desired curvature request as input from the kinematic control and responds to it by calculating a steering angle request for EPS or a yaw moment request for ESC. In the second case, ESC accordingly applies differential braking by requesting brake pressures at each wheel. With ESC, the performance of steering correction is influenced by the vehicle's steering geometry, as higher positive scrub radius is favorable for steering with differential braking. The dynamic control limits the requested yaw moment and its gradient to a value which can be overridden, in case the driver wishes to do so, ensuring an additional layer of safety to avoid an excessive steering intervention.

EXPERIMENTAL RESULTS

Road Edge Detection

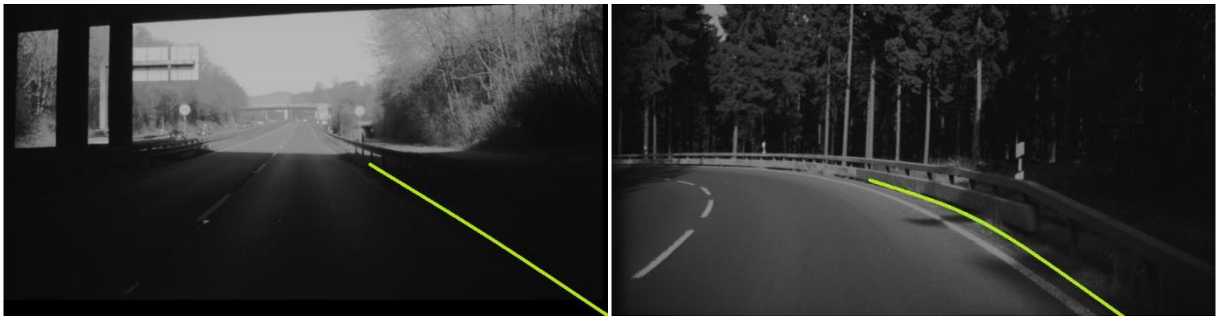

Figure 6: Road edge with line markings and guard rails under various lighting conditions

Figure 7: Roads with grass edge and partly shadowy surface

Figure 8: Road edge with gravel and with curbstone

In order to evaluate the capability of the road edge detection algorithm, test drives on various German roads were conducted. Figure 6 to Figure 8 show the estimated right road edge for sample driving scenarios. Various road edges like curbstones, guard rails, gravel, and grass were detected. Tests under various lighting conditions demonstrated the capability to detect the road edge also under harsh environment conditions, like partly shadowy road surface or bridge/tunnel passages.

Road Departure Protection

Prototype Vehicle Setup To develop and validate the whole Road Departure Protection function concept, two prototype vehicles were built. One, a pick-up truck, was equipped with the Base System and the other, a sedan, was equipped with the Enhanced System. For this paper, the test results for the Base System will be described. The developed prototype under test includes a mono camera, mounted near the rear-view mirror behind the windshield, and a pair of accelerometers, mounted on the upper control arm of each front wheel to measure the vertical acceleration of the wheel. For the purpose of this study, the road surface roughness detection was configured to detect rumble strips, which are very common in the U.S. to mark the road boundaries. In this prototype the Electronic Stability Control (ESC) system was used as the primary lateral control actuator.

Vehicle Steering Capability Before testing the Road Departure Protection function, the steering capability of the prototype vehicle was evaluated. Open loop curvature requests were sent to the lateral dynamic controller to investigate the maximum curvature capability and accuracy of the system control. This testing is especially important in the case of steering by differential braking as the steering capability depends highly on the vehicle's steering and suspension geometry. Figure 9 shows the curvatures defining the potential capability and limitations of the system relative to the possible road curvatures. 'Max. ESC Steer' represents the steering capability of the prototype, which, above the lower operational speed limit of 55km/h, exceeds the most extreme road curvatures, represented by 'Max. Road (e=10%)' (Maximum curvatures for a banking angle of

10%). The maximum curvature supported by the camera used in the prototype vehicle is shown in the plot as 'Max. Camera'. At approximately 80km/h and above the lane marker detection capability exceeds the steering capability and the maximum road curvatures. With the components currently used in the developed prototype, the region 'Avoidance' indicates the potential road departure avoidance region and region 'Mitigation' indicates the curvatures on which road departures can be mitigated. This however may change with components used and functional limits.

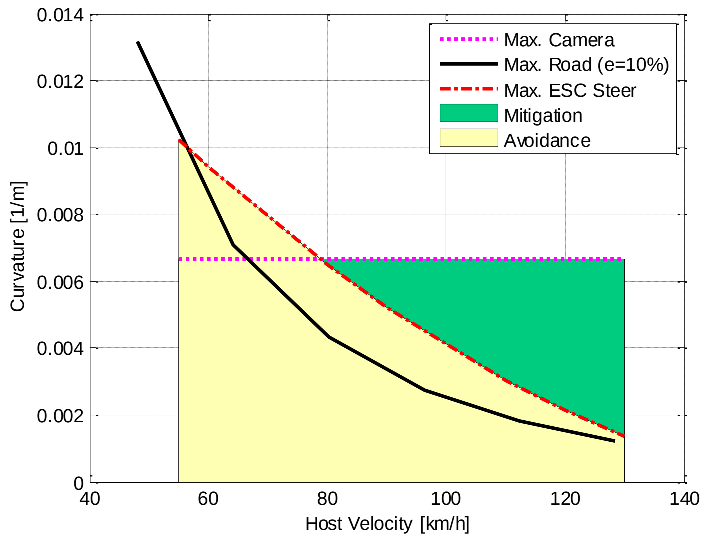

Figure 9: Potential benefits and limitations

<u>Use Case Validation Results</u> The use-case behavior and performance of the Road Departure Protection function has been tested on a closed course test track. To study the performance at different speeds, road departure use cases were tested at velocities between 64 km/h and 129 km/h (40 mi/h and 80 mi/h) in increments of 16 km/h (10 mi/h). Under curved road use case conditions, lower speeds were tested 64 km/h (40mi/h). In 23 out of 25 tested use cases, the road departure was completely corrected ending with the vehicle back on the road and aligned with the road boundary.

Figure 10 shows the effectiveness of intervention with DTE, intervention phases and requests on a straight road at 95 km/h speed. As the vehicle gets closer to the road edge and DTE drops to 0.4 m, a warning is issued. With the vehicle being 0.3 m over the edge, steering intervention starts with lateral control phase L1, honoring curvature request from kinematic control and requesting yaw moment at front and rear independently. The lateral control phase extends to L2 bringing the vehicle back onto the road. At approximately 8.3 s, Road Departure protection system enters into align phase and ending the intervention with ramp-out phase.

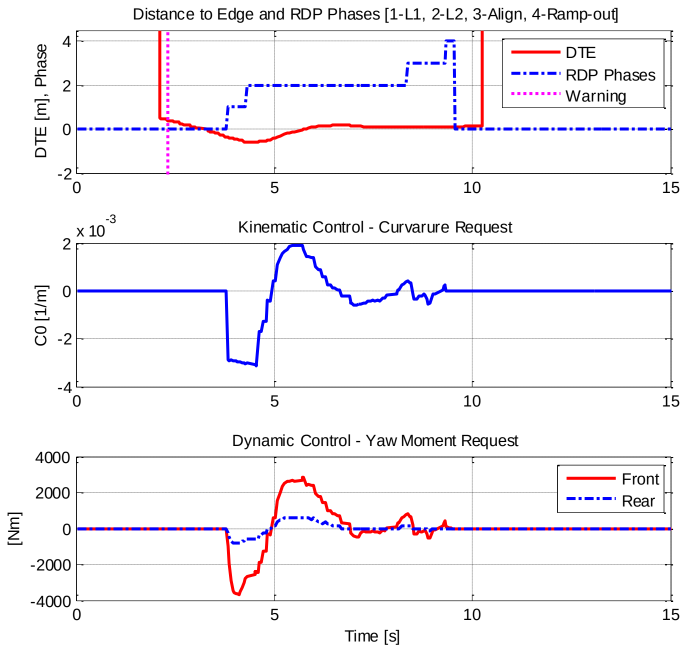

Figure 10: Road departure protection phases and requests

CONCLUSION AND OUTLOOK

The developed and presented Road Departure Protection system integrates an effective road edge detection function with cascaded kinematic and dynamic control functions to protect against unintended road departures. The proposed function can be integrated with different possible sensor configurations to enhance the ability to detect road departures. The steering capability of the prototype system proves that the differential braking based Road Departure Protection system is capable of avoiding road departures even on roads with very high curvature values in some vehicle configurations.

The presented system provides all required functionalities for Road Departure Protection. It has the potential to further increase vehicle safety and to contribute to traffic with zero accidents. Thus, product development is ongoing at Continental.

The tested Road Departure Detection system takes advantage of differential braking via ESC. Utilizing electrical steering via Electric Power Steering (EPS) offers further possibilities to keep the vehicle on the road and to protect from road departure.

The presented system reacts after an impending road edge crossing has been detected. In case of inappropriate or excessive speed, the influence on the vehicle dynamics is limited because the physical limits have been reached. These accident cases could be covered by PreView ESC which detects the course of the road before entering a curve [Schaefer12]. Based on the predicted upcoming road curvature the driver is supported when the vehicle is approaching the curve too fast. The new active safety system identifies the critical situation with road map data and on-board GPS. The target vehicle speed is a function of road curvature and friction. The function is initiated when the driver releases the accelerator pedal and starts steering in the curve direction. The function commands a smooth but resolute brake intervention as long as the vehicle is too fast. In the critical curve driving phase the vehicle is guided by ESC wheel individual brake intervention. Experiments have shown that in a situation where the vehicle is close to instability, the system is very effective to assist the driver safely through the maneuver. Research is ongoing in this direction.

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