29 Steering and Evasion Assist

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Abstract: Steering and evasion assistance defines a new and future class of driver assistance systems to avoid an impending collision with other traffic participants. Dynamic and kinematic considerations reveal that an evasive steering maneuver has high potential for collision avoidance in many driving situations. Three different system layouts are described: driver-initiated evasion, corrective evasion, and automatic evasion assistance. Since an automatic steering intervention is a challenging and responsible task, the technological requirements for situation analysis and environment perception are stated. Many technical solutions for a steering intervention are conceivable; therefore several actuator concepts are discussed and assessed with respect to human machine interface (HMI) impacts. A short survey of research activities of industry and academia is given. As an example for a research level prototype, the Daimler automatic evasion assistance system for pedestrian protection is presented in detail. Based on binocular stereo vision, crossing pedestrians are detected by fusion of a pedestrian classification module with a 6D-Vision moving object detection module. Time-To-X criticality measures are used for situation analysis and prediction as well as for maneuver decision. Tested on a proving ground, the prototype system is able to decide within a fraction of a second whether to perform automatic braking or evasive steering, at vehicle speeds of urban traffic environment. By this it is shown that automatic steering and evasion assistance comes to reality and will be introduced stepwise to the market.

1 Introduction

Driver assistance systems available today support the driver during normal driving as well as in critical situations by warnings and – in case of an impending collision – by partial or full braking. Emergency braking systems are able to mitigate or even prevent a collision in many cases, but there are situations left where an obstacle appears suddenly, e.g., a pedestrian is crossing the road and even full braking is too late and will not avoid the collision. In these cases a steering intervention is an additional option to prevent the collision. Steering intervention has to be apprehended as a new and second path to resolve impending collision situations and therefore defines a new class of driver assistance systems. Up to now no product level system uses of a steering intervention to avoid a collision. This is caused by the complexity, the required challenging technologies, and the product liability aspect of such an intervention. However during the last 5–10 years several research activities of automotive manufacturers, suppliers, as well as universities could be observed. This chapter will give an overview about the safety potential of such a system (➲ Sect. 2), the technological requirements (➲ Sect. 3), as well as research activities as an example for future evasion assistance systems (➲ Sect. 4).

The safety potential of a steering and evasion assist depends on the situation and mainly on the relative velocity between the system car and the obstacle. ➲ Section 2 will point out the collision avoidance potential compared to systems with exclusive braking intervention.

What kind of system will a steering and evasion assist be? With the above given system description three different system characteristics are conceivable:

- *Driver-initiated evasion assistance*: The driver has to do the first step. If there is an obstacle in front and the driver indicates by his or her steering activity that he or she wants to circumnavigate the obstacle, the system will help him or her to perform the maneuver stable and safely.
- *Corrective evasion assistance*: If braking will not be sufficient to prevent a collision, but the amount of space needed for the evasion maneuver is somewhat small, e.g., half of the width of the car, the steering action is initiated by the system itself.
- *Automatic evasion assistance*: The steering action is initiated by the system itself, if braking will not be sufficient to prevent a collision. The amount of space needed by the system for the evasion maneuver is in principle not limited but depends on the situation.

These different system characteristics will be described in ➲ Sect. 3, where an explanation is given about the requirements for environment perception, the situation analysis, the applicable actuators, and the HMI and customer acceptance.

2 Potential of Evasion Versus Braking

In the following the safety potential of an evasion maneuver will be derived from dynamic and kinematic considerations.

Advanced driver assistance systems (ADAS) use sensors to observe the environment. Based on the environment data, an active safety system decides whether there is an imminent risk of collision and whether an automatic maneuver has to be performed to avoid or mitigate the accident. The driver remains responsible for the driving task also in presence of assistance systems. Therefore a design principle of active safety systems is to intervene not until the physically latest possible point in time. This point in time is defined by the driver's ability to avoid a collision by braking, steering, or a combination of both, or – in some cases – by accelerating.

To evaluate the potential of evasion vs. braking independently from a specific assistance system, the steering distance to an object ahead will be compared with the braking distance. The latter is easily computed on basis of the relative velocity between the vehicle and the object and the full braking deceleration of the vehicle in case of an emergency braking maneuver.

The steering distance S_{Evasion} at a given relative velocity depends on the driven maneuver trajectory T, the desired lateral offset y_{Offset}, and a predefined maximum lateral acceleration $\alpha_{y,\max}$. The lateral offset at least needs to reach the sum of half the vehicle width, half the object width, and a safety margin. The steering distance then is the distance needed to reach the lateral offset when driving trajectory T, see ➲ *Fig. 29.1*. Shorter steering distances can be achieved by changing the respective parameters.

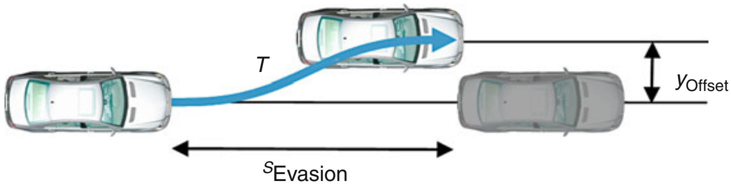

Fig. 29.1
Steering distance and lateral offset during an evasive maneuver

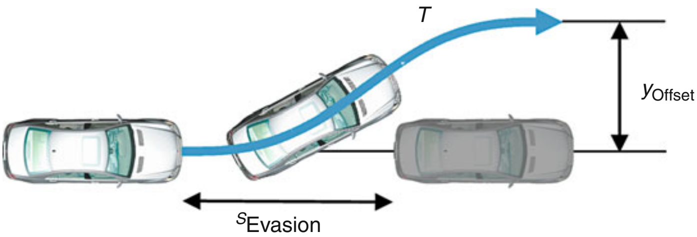

Fig. 29.2
Changing the evasive maneuver to a shorter steering distance yields a larger lateral offset

Typical trajectories for evasive maneuvers include clothoid and sigmoid functions, the latter yielding shorter steering distances than the first. The lateral acceleration is in principle only constrained by the physical limits, i.e., the current road friction coefficients, the wheel characteristics, etc. Increasing the maximum lateral acceleration leads to a shorter steering distance as well. Finally, the lateral offset can be increased, passing the object during the evasive maneuver – and not only reaching the end – thus also reducing the steering distance. Of course, this is only possible if other traffic and boundaries allow realizing this increased offset (➲ *Fig. 29.2*).

The potential of evasion arises in situations where the braking distance exceeds the steering distance, i.e., steering potentially still avoids a collision where braking does not. Such traffic situations comprise collisions with standstill objects or slowly moving vehicles and high relative velocity as well as accidents with perpendicular slow moving traffic participants (e.g., pedestrians, cyclists) where frequently a small lateral offset is sufficient to avoid the collision. In addition, if the friction coefficient of the road decreases, e.g., on a wet road, the benefit of evasion vs. braking expands to lower relative velocity.

➲ *Figure 29.3* compares braking distance and steering distance for a sigmoid trajectory at different velocities on a dry road. The vehicle reaches a lateral offset of 1 m at the inflection point of the evasive path and a total lateral offset of 2 m. In this example, the braking deceleration is assumed to be $-10\ m/s^2$ and the maximum lateral acceleration is bounded to $6\ m/s^2$.

Starting from about 35 km/h an evasive steering maneuver enables collision avoidance at lower distances to the object than full braking with increasing benefit at higher speeds.

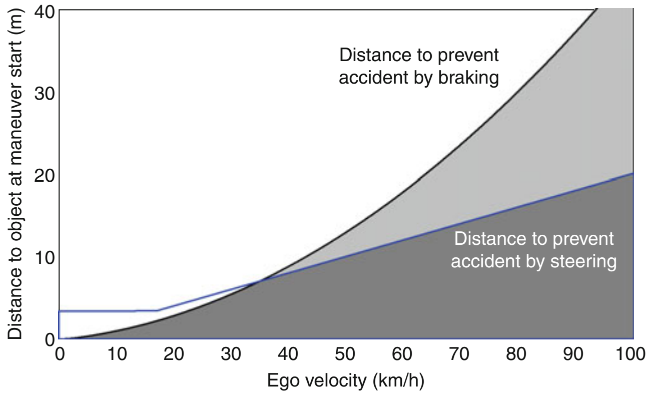

Fig. 29.3
Comparing braking distance and steering distance at different velocities

3 System Layout

3.1 Overview

Driver assistance systems can be classified according to the degree of automation. Regarding steering and evasion assist, three system concepts with increasing complexity have to be deliberated:

- Driver-initiated evasion assistance
- Corrective evasion assistance
- Automatic evasion assistance

A *driver-initiated evasion assistance system* supports in critical driving situations, in which the driver starts steering to drive around an obstacle in front. Such systems comprise at least one sensor like radar, lidar, or camera that detects obstacles in the driving corridor ahead. When an object is detected and the situation analysis predicts a collision, system activation requires the driver steers in a specific, speed-dependent distance section ahead of the object. Typically, this section will be closer than distances used for overtaking, hereby distinguishing a critical driving situation from a normal one. In those situations the system shall improve the driver's steering operation and vehicle maneuverability. This can be achieved by using a steering actuator which creates a torque that assists and guides the driver on a predetermined trajectory around the object. If available, an active suspension system like active dampers or active roll stabilization can additionally improve the handling performance of the vehicle. The system can be designed in such a way that the driver is always able to overrule the system intervention. Since the driver initiates the steering maneuver, the evasion assist system does not necessarily need to check for other traffic participants or obstacles in the evasive trajectory as this has been accomplished already by the driver.

A *corrective evasion assistance system* targets potential collision scenarios, where already a small lateral offset, e.g., half the width of a vehicle, helps to prevent an accident. Such scenarios vary from less critical situations like cycles or motorcycles driving ahead, parked or broken down vehicles, or other objects at the roadside extending into the traffic lane of the own vehicle up to dangerous scenarios where objects (e.g., pedestrians) are crossing the lane. Again, an appropriate sensor set perceives the object; the distance to the object has fallen below the braking distance, and a situation analysis module (cf. ➋ Sect. 3.2) predicts an impending collision. Then the assistance system automatically triggers an evasive maneuver to avoid the collision. In many cases it will be beneficial if the system combines evasion with braking. As the system starts the maneuver automatically, if the driver fails to react timely, a good knowledge about the traffic environment is needed. The system should ensure not to collide with other traffic participants nor objects during the evasive maneuver.

An *automatic evasion assistance system* is capable of coping with many different traffic situations. Here, the lateral offset and hence the amount of space needed to drive the maneuver is in principle not limited but depends on the demands of the situation. Such a system requires a widespread and detailed knowledge of the environment all around the ego vehicle. As before, when the system foresees an imminent collision and the driver neither brakes nor steers at the latest possible point in time, respectively, the system will perform an automatic evasive maneuver.

The requirements for such systems are described in the following sections.

3.2 Requirements for Situation Analysis

The objective of situation analysis in the context of advanced driver assistance systems (ADAS) is to understand and analyze a given traffic situation. Such knowledge can be exploited to derive automatic actions of the vehicle. Thus, situation analysis is closely related to the cognitive capabilities of intelligent vehicles (e.g., Stiller et al. 2007). Generally, situation analysis of an ADAS includes: *modeling* of the vehicle's environment (what is known about the current scenario?), *classification* of driving situations (what kind of traffic situation the system is confronted with? what are the current maneuvers of the traffic participants?), *prediction* (what are possible actions of all objects including the ego vehicle?), and *criticality assessment* (how severe are the results of these actions).

ADAS that mitigate collisions in longitudinal traffic by automatic braking have been studied extensively and commercial solutions are available on the market (e.g., the Mercedes-Benz PRE-SAFE® Brake, Honda's Collision Mitigation Brake System, Toyota's Pre-Collision System, and others). Typically, the situation analysis layer of such systems is relatively simple and can be sketched as follows: For ADAS in highly structured scenarios, the environment model consists mainly of other vehicles with position and speed information. These vehicles are classified as relevant objects by associating them to the ego vehicle's driving path and imposing thresholds on the object's confidence measures as provided by the sensors. If a collision with a relevant object is detected, the criticality of the current situation can be evaluated by the time-to-react (TTR, cf. Hillenbrand et al. 2006). The TTR is the remaining time for a human driver to avoid an imminent collision by emergency braking with full deceleration, steering with maximum lateral acceleration, or a kickdown maneuver. Thus, it can be computed as the maximum of the time-to-brake (TTB), time-to-steer (TTS), and time-to-kickdown (TTK).

For evasive steering, however, the requirements for modeling, prediction, and criticality assessment are significantly more challenging. Since changing the vehicle's course could lead to a collision with another traffic participant, a reliable understanding of the vehicle's environment is of paramount importance. The environment model should not only include objects in the front and relevant side. It should also incorporate information about trafficable road (limited by curbs, lane markings, etc.).

The accurate prediction of the trajectories of all objects in the vehicle's environment imposes high requirements on the sensors (cf. Sect. 3.3). If the evasive maneuver exceeds the own lane, accurate measurements are needed, e.g., of the velocity of an oncoming vehicle in an adjacent lane or the motion of a crossing pedestrian. To predict the possible emergency actions of the ego vehicle, the system has to plan a safe route that will not result in collision with obstacles. The generated trajectory has to be feasible with respect to the vehicle's dynamics. In robotics, such tasks are often referred to as non-holonomic motion planning problems with dynamic obstacles. A variety of solutions has been proposed in the literature (LaValle 1998; Fiorini and Shiller 1996), yet the computational complexity of many of the proposed algorithms prohibits the application on current automotive hardware. To overcome this limitation, efficient planning algorithms to evaluate possible avoidance maneuvers in highly structured scenarios have been introduced (Schmidt et al. 2006). The DARPA Urban Challenge gave rise to several interesting approaches on trajectory generation (Ziegler and Stiller 2009; Werling et al. 2010) that may become feasible for realization in ADAS.

Current collision mitigation systems by braking usually consider only one single object in our lane. Decisions for evasive steering, however, require a criticality assessment that considers multiple objects. In addition, situation analysis has to ensure a reliable decision making even in presence of reasonable sensor and prediction uncertainties. Recent work on handling uncertainty in situation analysis and on the theory of hybrid reachable sets may prove beneficial to accomplish this task (Althoff et al. 2009; Schubert et al. 2010). To ensure a collision-free automatic evasive maneuver, situation analysis has to be closely coupled with vehicle control. Ideally, the prediction of the ego vehicle's behavior will account for the controller characteristics as described in Sect. 4.

3.3 Requirements for Environment Perception

As stated in the preceding section, evasion poses significantly higher demands on the environment perception than pure braking. Roughly speaking, in a certain range depending on the current speed and the possible evasion trajectories relevant moving objects should be detected and classified, their motion state and size should be determined, and the free space limited by static obstacles should be measured by means of a proper set of sensors. Assuming a maximum speed of 20 m/s (i.e., 72 km/h) of both, the ego vehicle and an oncoming car, and a time of 1 s until the laterally intruding obstacle is passed and another second to steer back or to come to a full stop, the required look-ahead distance is approximately 80 m. This may act as a rule of thumb for the following discussions. If the task is restricted to slower urban traffic and concentrates on vulnerable road users, in particular pedestrians, the requirements are less demanding.

One could argue that it is sufficient to survey the area in front of the car only. In case of an emergency, most human drivers will not check the areas beside the car but will react immediately. This works usually fine since the probability that someone is overtaking exactly that moment when an evasion situation occurs is extremely small. However, an active safety system should take into consideration that possible evasion trajectories could intersect with the driving path of currently overtaking cars or motorcycles. Fortunately, there are several types of so-called blind spot monitoring systems (based on vision as well as radar) on the market that could be used for this task. If the side area is not checked, the risk of an unwanted lateral collision can be reduced if the evasion trajectory is optimized for minimum lateral deviation. The knowledge of the lateral position of existing lane markings that define "my" lane may also be useful in this optimization step.

As long as the system is designed for urban traffic, there seems to be no need to additionally monitor the area behind the car. Since steering is an option for higher velocities only, relative speeds are small and the risk to endanger approaching traffic participants seems to be negligible. This may be different for highway situations which are out of the scope of this chapter.

As the surveillance of the area besides and behind the car is a well-understood problem, the system can concentrate on the area in front of the car. For the sketched tasks, several active as well as passive sensors could be used:

- *Radar*: Recently developed automotive long range radar sensors have beams with a horizontal angle of less than 1°, a field of view of more than 20°, and operating distances which are large compared to the requirement in the urban as well as rural scenario. Therefore they are optimum for the detection of oncoming traffic objects. However, they are still not the preferred sensor for static as well as crossing objects, in particular pedestrians that have a relatively small radar cross section.
- *Lidar*: Laser scanners became famous in 2007, when most finalists of DARPA's Urban Challenge based their autonomous cars on a high-end sensor developed by Velodyne. This sensor offers 64 scan lines with 4,000 measurements per turn, 10 turns per second. The range is about 70 m, the precision is within centimeters. In contrast to radar systems, speed cannot be measured but only estimated by tracking of objects. However, at the time being no scanner fulfills the requirements "performance" and "price" at the same time.
- *Camera*: Vision has become a powerful and cheap solution for driver assistance. Lane Departure Warning and Traffic Sign Recognition are well-established systems, but also

obstacle detection based on a combination of stereo and classification is commercially available. Camera systems are not restricted to the visible range; in fact far infrared sensors are used to detect animals and pedestrians especially at nighttime. Thanks to the high spatial and temporal resolution, cameras will become increasingly important for advanced driver assistance. A large research community working on sophisticated computer vision algorithms is constantly pushing the limits. The problem of camera-based systems is their sensitivity with respect to adverse weather and lightning conditions.

These three types of sensors can operate autonomously, independent from infrastructure. Of course, environment perception as well as situation analysis can be supported by map information as well as vehicle-to-vehicle communication. The latter will help to detect other vehicles earlier, especially if they are hidden by other objects.

It is evident that the performance of the aspired safety system will highly depend on the reliability and accuracy of the sensing system and the time it needs to detect potentially dangerous situations. As a matter of course an automatic evasion system will try to maximize availability and reliability by proper sensor fusion. The current trends in sensors for driver assistance indicate that a fusion of radar and vision is the most promising combination.

In the following, the requirements shall be reconsidered in more detail. ➲ *Figure 29.4* shows an urban situation with a pedestrian coming from the right side. The parking car partially hides the pedestrian, while an oncoming vehicle blocks the space necessary for an evasion maneuver. A correct interpretation of this situation requires that:

1. The oncoming car is detected, which is trivial. A vision-based algorithm (Barth and Franke 2009) was published that allows estimating the complete motion state including the yaw rate of moving vehicles.
2. The endangered pedestrian is detected and his or her motion (i.e., velocity and acceleration) is estimated, even if he or she is partially hidden (Enzweiler et al. 2010).

Fig. 29.4
One second before the collision. The camera system has estimated the motion state of the oncoming car, and, at the same time, has detected the crossing pedestrian

It would be highly advantageous if this task could be solved *before* he or she steps on the road, since our car can drive at a speed of 0.6 m/frame and some frames delay can make a significant difference

3. If there would be no oncoming traffic, the available free space would be limited by the trees, the parking cars behind the intersection and the curb. While the trees are well-visible objects for a camera system, the detection of the curb is more challenging (Siegemund et al. 2010).
4. Additionally, it would be highly desirable to derive some hints on the pedestrian's intention. Is the pedestrian going to stop – or will he or she go? This is a new question and research has just started.

Binocular stereo vision has the potential to generate a precise three-dimensional model of the current situation (Gehrig and Franke 2007), to detect independently moving objects in minimum time (Franke et al. 2005) and to classify pedestrians even if they are partially hidden. ➲ Section 4.2 will show the state-of-the art in stereo vision.

It is worth to mention that the situation analysis (and the function itself) does not only ask for a comprehensive detection scheme, but also for the confidence of the sensing system regarding the delivered data. This is an additional challenging requirement to be solved within future work.

3.4 Actuators

There are several technical possibilities to influence the lateral movement of the vehicle. Depending on the purpose of the assistance system they are more or less suitable. The following section describes the technical solutions, their advantages, and disadvantages.

3.4.1 Steer Torque Actuator

The actuator adds a steer torque to the torque which the driver applies via the steering wheel.

The driver can suppress the intervention right from the beginning and he or she is given a very intuitive feedback via steer torque and steer angle. The intervention normally is already technically secured by the electric power steering. The steer torque actuator is not appropriate for quick interventions with higher torque because of the risk of injury of the driver's hands. So the steer torque actuator is suitable only for less dynamic interventions but even over a longer time.

All the other actuators share the following advantage and disadvantage. They are appropriate for quick interventions because they are not turning the steering wheel and therefore cause no risk of injury of the driver's hands. But this also means that the driver may be irritated during longer interventions because there is no correlation of the lateral vehicle movement with the steering wheel angle. They also share the danger that a backlash of the driver on sudden interventions may lead to the wrong direction. This makes them suitable only for short interventions but even with high dynamic.

3.4.2 Steer Angle Actuator

This actuator adds a steer angle to the angle which the driver applies via the steering wheel. If there is no additional torque actuator the driver has to hold a small reaction torque if intervention should effect the vehicle movement and therefore he or she gets a haptic wrong feedback because reaction torque is contrary to the wanted vehicle reaction. The steer angle actuator is suitable only for short interventions but even with high dynamic.

3.4.3 Rear Wheel Steering

The rear wheels can be steered independently from the driver-steered front wheels. Rear wheel steering is suitable only for short interventions but even with high dynamic.

3.4.4 Warping the Suspension

If the wheel load is shifted from the left to the right at one axle and vice versa at the other axle this causes side forces which induce a yaw rate without causing a rolling movement of the vehicle body. This can be done by active suspension systems. But it has only a limited influence on the lateral movement (around 2°/s yaw rate) of the vehicle. Warping the suspension is suitable only for small and short interventions but even with high dynamic.

3.4.5 Single-Sided Braking

Braking the wheels only at one side of the vehicle causes a yaw rate. This can be done by ESP systems. This intervention normally is already technically secured by ESP. Problems are that any intervention also causes a deceleration and could be used only for rare interventions because it causes wear of the brake pads. Therefore single-sided braking is suitable only for rare and short interventions but even with high dynamic.

3.4.6 Torque Vectoring

Unequal drive torque between left and right wheels is causing a yaw rate, which can be realized by an active differential. This is only possible in situations when a positive drive torque is applied or with a wheel individual drive concept, e.g., with electric engines. Torque vectoring is suitable only for short interventions but even with high dynamic.

3.4.7 Discussion

Which solution is best differs widely with the purpose of the assistance system. A system which compensates disturbances like side wind or lateral slope will use other actuators than a system which wants to influence the trajectory of the vehicle to avoid a collision. If the purpose of the assistance system is an evasive maneuver two cases have to be distinguished:

1. The systems intention is to support the driver's steering action to avoid a collision. In this case it has to give the driver an intuitive advice to steer. This is done best directly at the steering wheel and therefore the steer torque actuator is recommended.
2. The system's intention is to avoid a collision by an automatically initiated evasion maneuver (with corrective or large lateral offset as mentioned in Sect. 3.1). In this case the following actuators are suitable.
   - Steer torque actuator with limited torque
   - Steer angle actuator
   - Rear wheel steering
   - Single-sided braking

   Their actions are quick and strong enough to change the trajectory of the vehicle significantly.

3.5 HMI and Customer Acceptance

The HMI design has to consider the specific situation of an evasive steering maneuver as well as the system layout. As mentioned in Sect. 3.1 the application scenarios vary from less critical situations, where only a light intervention is sufficient to resolve the situation, up to dangerous situations, where a sudden and unexpected collision with a crossing object, e.g., a pedestrian is imminent. In the latter case time is up for warning and even for braking and the HMI design has to concentrate basically on the modality of the steering intervention. Acoustical and/or optical warnings are reasonable if there is enough time for the driver to react. However, in case of sudden and unexpected collision a spontaneous intervention with minimal delay is essential. The intervention may be accompanied by acoustical or optical warnings, but this is not of decisive importance.

The goals of an efficient and ergonomic steering intervention are:

- To perform the evasion maneuver fast and stable
- To give the driver a good understanding "what's going on here"
- To give the driver a chance to overrule the intervention and overtake the responsibility as fast as possible
- Neither to irritate the driver nor to provoke wrong reactions

In Sect. 3.4 all kinds of appropriate actuators have been discussed and assessed. The specific HMI design depends on the functional concept and layout of the system.

Concerning *driver-initiated evasion assistance*, a very tight interaction between driver and system is necessary. The system intervention only has to support or complement driver's action and therefore the steer torque actuator will be the best choice to give the driver a direct feedback.

Concerning *corrective or automatic evasion assistance*, HMI design has to differ between light and strong interventions:

- Light interventions will not dramatically change the vehicle state and driving situation and therefore the driver must not directly feel the intervention "in his or her hands." As a consequence all proposed actuators are applicable (steer torque actuator, steer angle actuator, rear wheel steering, single-sided braking).
- Strong interventions provoke a significant change in driving situation. To safeguard an adequate driver reaction, he or she should clearly know what happens and understand where the evasive maneuver does come from. As motion and torque of the steering wheel immediately communicate the driver what's going on, the steer torque actuator seems to be the best choice. On the other hand the torque has to be limited due to the risk of loss of controllability as well as the risk of injury of driver's hands as mentioned in ➲ Sect. 3.4. Therefore, if the automatic motion of the steering wheel exceeds certain values (see next paragraph), the steering intervention should be supported by rear wheel steering or single-sided braking or should exclusively be realized with a steer angle actuator.

Strong steering intervention by additional steering torque has to consider several limits due to controllability and acceptance reasons. The most important parameters are steering wheel angle, velocity, and acceleration as well as the additional steering wheel torque itself. Basic studies investigated the interrelationship between those parameters and human behavior in terms of steering quality and controllability, e.g., Neukum (2010). As controllability has to be recovered after the maneuver, the design of the evasion trajectory itself has to take care for an easy handing over when the maneuver is completed: It has to be limited in short duration (e.g., <1 s), the vehicle course should be stable at any time, and the yaw angle and yaw velocity of the vehicle should be zero when it is finished. Anyway, controllability and customer acceptance have to be approved by real driving tests with a sufficient number of test persons.

4 Case Studies

Since the 1980s, several research programs on autonomous vehicles have been conducted, finally leading to the DARPA Urban Challenge in 2007. Numerous publications on path control for automated vehicle guidance, active steering systems, steering controllers, and the like have been released. A focused view on evasive steering support in research or production cars is given here.

4.1 Survey of Research Activities of Industry and Academia

From 2002 to 2006, Darmstadt University of Technology and Continental Automotive Systems conducted the PRORETA project which investigated the collision avoidance potential of emergency braking and emergency steering in case of standstill objects or objects cutting into the line in front of the own vehicle (Isermann et al. 2008). A demonstrator vehicle (Volkswagen Golf) was equipped with an electro-hydraulic brake and an active front steering and publicly demonstrated at the end of the project.

The system detects objects by a fusion of scanning laser and video. In case of a threatening collision and depending on the traffic situation, the system elects one of three possible intervention schemes: braking, steering, or a combination of both. In case of a suddenly appearing obstacle or unexpectedly blocked lane an automatic emergency evasion maneuver is conducted, if possible. Based on the information from the environmental sensors, the necessary evasive trajectory is calculated. A lateral controller then automatically guides the vehicle round the obstacle on the predefined evasive path. Different controllers were implemented and tested.

In February 2006, Toyota presented the Lexus LS 460 at the Geneva Motor Show, equipped with microwave radar and a stereo camera. The technical features include an emergency steering assist (Suzumura et al. 2007). When the system detects a possible collision with an object ahead, emergency steering assist enables the car to react more spontaneously on the driver's steering commands and thus improving evasive maneuvering initiated by the driver. For this purpose, variable-gear-ratio steering, vehicle-dynamics integrated management, and adaptive variable suspension are combined resulting in a more direct steering gear ratio, a selective use of the brakes, and a stiffer chassis suspension.

Recently Bosch and Continental independently published two similar approaches of an emergency steering assist, both based on the concept of driver-initiated assistance.

The Bosch system is called evasive steering support (Fausten 2010). It uses microwave radar to detect an obstacle in front. If there is a risk of a rear-end collision and the driver starts to steer, the system will support him or her to follow an optimal evasion trajectory according to the following support strategy: As long as the driver steers on the optimal trajectory, there is no support. If the driver overreacts, there is a corrective torque on the steering wheel. When the driver underreacts, the system supports the driver with an additional torque on the steering wheel. The system limits the steering torques and thus guarantees the controllability by the driver at any time.

The Continental emergency steer assist combines an environmental sensing with situation-dependent adaptation of electrically controllable chassis components such as electric power steering, electronic stability control, and optional rear wheel steering system (Hartmann et al. 2009). As before, microwave radar detects a leading object. If a potential collision is foresighted, the system prepares the vehicle for an optimal driving stability by activating specific modes of the electronic stability control and the rear wheel steering control. Already small instabilities of the vehicle are compensated by early and well-directed damping of vehicle overshoot reactions. Upon the driver starting to steer, the system supports on a maneuvering level to keep the vehicle on an optimal evasion trajectory by either an additional steering torque or torque vectoring. The system is designed in such a way, that the driver can overrule it at any time.

4.2 The Daimler Automatic Evasion Assistance for Pedestrian Protection

4.2.1 Motivation

The most vulnerable traffic participants are arguably the pedestrians; about 5,700, 4,700, and 2,300 pedestrians are killed yearly in traffic in the EU, USA, and Japan, respectively (IRTAD 2006). These figures correspond to approximately 18%, 11%, and 32% of all traffic fatalities in the respective regions.

Traditionally, pedestrian protection has been approached from a passive safety perspective. This has involved vehicle structures (e.g., bonnet, airbags) which expand during collision in order to minimize the impact of the pedestrian body hitting the vehicle. Although important, passive safety measures are limited in their ability to reduce collision energy because of the very short time span between initial bumper contact and the impact of the pedestrian on the bonnet or windshield. Moreover, passive measures cannot account for injuries sustained in the secondary impact of the pedestrian hitting the pavement.

There is a lot of interest, therefore, in the development of active driver assistance systems, which use sensors to search the vehicle surroundings for pedestrians. They can detect dangerous situations ahead of time, and warn the drivers or even automatically control the vehicle. Such systems are particularly valuable when the driver is inattentive (e.g., programming the navigation unit, or head turned to the back seat).

Gandhi and Trivedi (2007) provide a general survey on passive and active pedestrian protection methods, discussing multiple sensor modalities (e.g., cameras in visible/NIR/FIR spectrum, radars, laser range finders) and methods for collision risk assessment. Enzweiler and Gavrila (2009) focus in a more recent survey on techniques for video-based pedestrian sensing. A large image dataset is made publicly available for benchmarking purposes.

In this section, a recent research prototype system for active pedestrian safety is discussed, developed at Daimler R&D, which combines sensing, situation analysis, decision making, and vehicle control. Its most notable feature is its ability to execute automatic evasive steering maneuvers on crossing pedestrians. It is able to decide within a fraction of a second whether to perform automatic braking or evasive steering, at vehicle speeds typical of urban traffic environment (see *Fig. 29.5*).

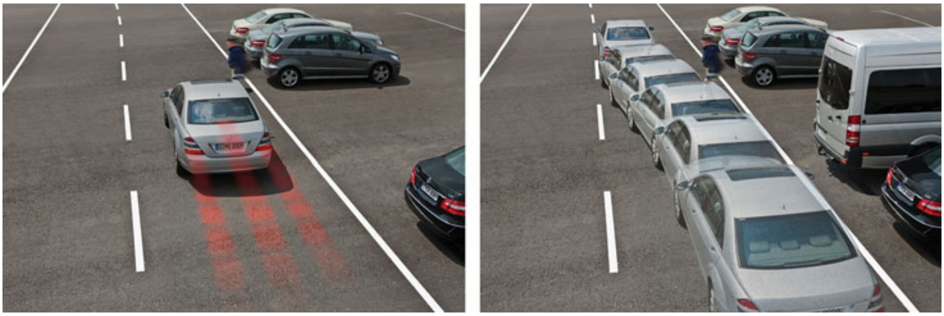

Fig. 29.5
Automatic braking or evasion? That is the question. The system needs to decide within a fraction of a second in response to a suddenly crossing pedestrian

4.2.2 System Description

The Daimler active pedestrian safety system consists of sensor processing, situation analysis, and decision and vehicle-control components. These are now discussed in turn.

Sensor Processing

The sensing component consists of binocular stereo vision (Gehrig and Franke 2007), which has the advantage to provide high-resolution measurements in both the horizontal and vertical direction, as well an accurate distance map. In order to increase robustness of pedestrian detection, two complementary cues are fused: appearance (pedestrian classification) and motion (moving object detection).

Pedestrian classification utilizes the HOG/linSVM approach of Dalal and Triggs (2005). In order to decide whether a certain rectangular image patch (ROI) represents a pedestrian or not, this approach overlays a spatial grid of cells over the ROI and computes gradient orientation histograms within each cell. A number of local contrast normalization operations are computed, and the resulting normalized histograms are concatenated to an overall feature vector which is used for classification using a linear support vector machine (linSVM). Once an image ROI is confirmed to represent a pedestrian, the distance to the latter is estimated using the computed dense stereo image. Because the exact contour of the pedestrian is unknown within the rectangular ROI, a probability mass function is used for distance estimation, as described in Keller et al. (2010). See *Fig. 29.6* for some examples of pedestrian classification in urban environment.

Moving object detection involves the reconstruction of the three-dimensional motion field and is performed by the so-called *6D-Vision* algorithm (Franke et al. 2005). This algorithm tracks points with depth known from stereo vision over two or more consecutive frames and fuses the spatial and temporal information by means of Kalman filters. The outcome is an improved accuracy of the estimated 3D positions and of the 3D motions of the considered points. This fusion necessitates knowledge of the motion

Fig. 29.6
Pedestrian classification in urban traffic (UK, left driving)

Fig. 29.7
Estimation result of the *6D-Vision* algorithm for the moving, partially occluded pedestrian after 0, 80, 120, and 240 ms from first visibility

of the observer, also called the ego-motion. It is estimated from the image points found to be stationary, using a Kalman filter–based approach. Objects are identified as groups of spatially adjacent, coherent motion vectors. Since the *6D-Vision* algorithm not only provides state estimates, but also their uncertainty, the Mahalanobis distance is used as a similarity measure in the cluster analysis. As there is a unique assignment from a tracked 3D point to an object, there is no need to perform an additional object tracking step. However, to increase the robustness, the assignment of the points to the existing object is verified for each frame and new points may be added to the object. See *Fig. 29.7* for some example output on a partially occluded pedestrian, moving sideways. The *6D-Vision* algorithm already provides after two frames (80 ms) a first estimation result. After three frames (120 ms) there is enough statistical evidence to establish an object hypothesis, even though the pedestrian is mostly occluded by the car in front.

Fusion

Inputs from the pedestrian classification and *6D-Vision* modules are fused using a Kalman filter. The state S of the filter is given by $S = \begin{bmatrix} x & y & v_x & v_y \end{bmatrix}^T$ with x/y being the longitudinal/lateral position of the pedestrian to the vehicle and v_x/v_y being its absolute longitudinal/lateral velocity in the world. Constant velocity is assumed for pedestrian motion. Recognitions from the pedestrian detection modules are represented using the measurement vector: $z_{\text{ped}} = [x \;\; y]^{\mathrm{T}}$, describing the position of the pedestrian in the vehicle coordinate system. Detections from the *6D-Vision* module contain the velocity and position of possible pedestrian detections. The measurement vector used for these detections is $z_{6\mathrm{D}} = \left[x \;\; y \;\; v_x \;\; v_y\right]^{\mathrm{T}}$.

As the pedestrian classification module can currently handle only un-occluded pedestrians, fusion with *6D-Vision* is beneficial to initiate tracks quickly in the case of partially occluded, lateral crossing pedestrians, as in *Fig. 29.7*. As shown in Keller et al. (2010), a further benefit of adding *6D-Vision* to a baseline pedestrian classification system is that lateral velocity estimation is more accurate, which is important for situation analysis.

Trajectory Generation, Situation Analysis, Decision and Intervention, and Vehicle Control

Figure 29.8 depicts the relationship between trajectory generation, situation analysis, decision and intervention, and vehicle control. Situation analysis predicts how the current driving situation will evolve and automatically evaluates its criticality using measures as, e.g., time-to-collision, time-to-steer, and time-to-brake. This criticality assessment serves as the basis for a decision and intervention module which triggers appropriate maneuvers for collision avoidance and collision mitigation. Such maneuvers are realized by

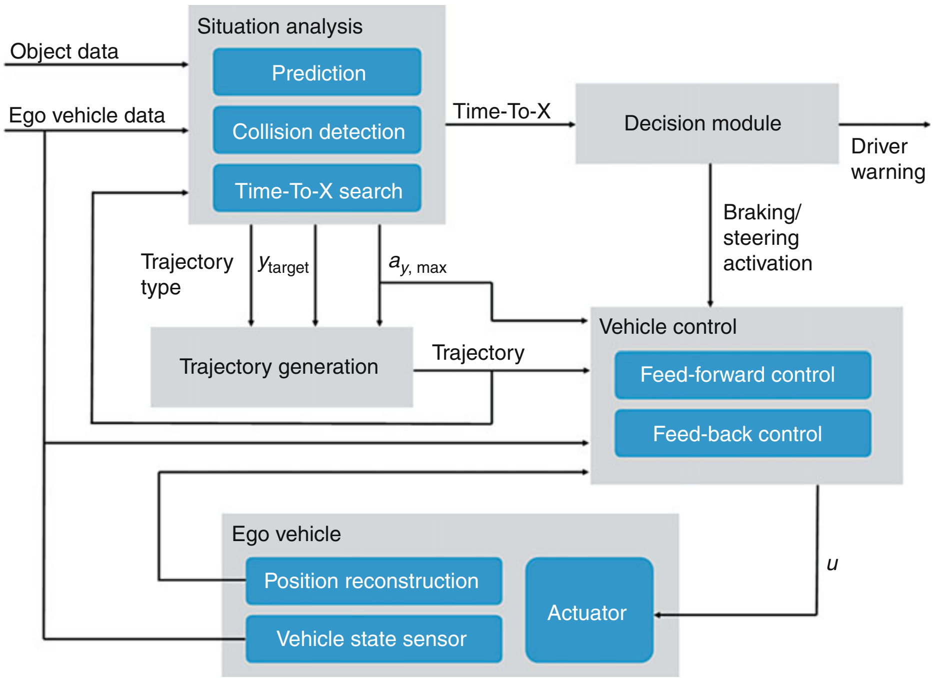

Fig. 29.8
Schematic overview of trajectory generation, situation analysis, decision and intervention, and vehicle control

specialized vehicle controllers. Naturally, vehicle control and situation analysis are closely coupled, since both rely on accurate, realistic models of evasive maneuvers. These models are provided by a trajectory generation module.

Trajectory generation has to provide accurate models of evasive maneuvers that fulfill several requirements: the generated trajectory for evasion should be as comfortable as possible, feasible (i.e., drivable by the ego vehicle), and should also lead to a safe transition with minimal side-slipping of the vehicle during the automatic evasive maneuver. Snatch of steering wheel can be dangerous and therefore must be avoided. Furthermore, trajectory generation should provide the reference input variables for lateral control such as yaw angle, yaw rate, etc. Different trajectory types have been investigated and a sigmoid transfer function based on a polynomial approach was selected to model the evasive maneuver path (Keller et al. 2010).

A numerical simulation method is employed, which allows efficient, real-time computation of Time-To-X criticality measures even for complex maneuvers and which also ensures collision-free evasive maneuvers, if available. As depicted in *Fig. 29.8*, the numerical simulation method consists of three main components: prediction, collision detection, and Time-To-X search. In the prediction step, a sequence $\{t_k, z_{\text{ego};k}, z^1_{\text{obj};k}, \ldots, z^M_{\text{obj};k}\},\ k = 1 \ldots K$ is computed, where t_k is the kth time stamp of the prediction, K the prediction horizon, $z_{\text{ego};k}$ a vector describing the ego vehicle's pose and motion at time t_k, and $z^1_{\text{obj};k}, \ldots, z^M_{\text{obj};k}$ the pose and motion of all M objects provided by the sensor data fusion. These predictions rely on appropriate motion models for all objects and the system vehicle and on assumptions on the ego vehicle's and object vehicles' behaviors. Given the dimensions of all objects in the scene, potential collisions between the system vehicle and objects can be identified by intersecting corresponding positions resulting from $z_{\text{ego};k}$ and $z^1_{\text{obj};k}, \ldots, z^M_{\text{obj};k}$ respectively. If a collision is detected, the maximum time step t_k is searched at which a modification of our system vehicle's behavior can still avoid a collision with any of the M observed objects. These time steps are discrete estimates of TTB and TTS and can be found efficiently using a binary search algorithm.

The "decision and intervention" is the core module of the assistance system, since it associates the function with the driver's behavior. Due to the high risk of injuries of a pedestrian in an accident, collision avoidance is the primary objective of the function. In order to identify the best way to support the driver, it is necessary to know the driver's current driving intention. The driver monitoring algorithm uses signals from the vehicle, e.g., accelerator and brake pedal position, speed, lateral and longitudinal acceleration, steering angle, and steering rate, to determine the current driving maneuver of the driver. If the driver is not reacting appropriately to the dangerous situation, an optical and acoustic warning will be given, so he or she can avoid the collision himself or herself. In case a function intervention is necessary to avoid the collision, full braking takes priority over the evasive maneuver. The full braking will be triggered when TTB = 0 and the driver is neither doing an accelerating nor an evasive maneuver. Only when the collision cannot be prevented with full braking any more (TTB $<$ 0), the evasive maneuver will be activated at TTS = 0 using the vehicle control to compute the necessary steering torque. The function ramps down the steering torque, when the evasive maneuver has finished. Afterward the function is available immediately, when needed. Automatic evasion results in a lateral offset of the vehicle of, e.g., 0.8 m.

Collision avoidance by steering requires precise lateral control of the ego vehicle. The controller permanently compares the reference position along the evasive maneuver trajectory to the actual vehicle position and thus requires accurate and reliable knowledge of the ego vehicle's pose. The position of the vehicle is reconstructed from odometers and inertial sensors readily available in today's vehicles. Using the measured lateral acceleration a_y and the velocity v, the vehicle's heading angle χ can be recovered following

$$\chi(t_k) = \chi(t_k - \Delta T) + \frac{a_y\ (t_k)}{\upsilon\ (t_k)} \Delta T$$

respectively. Here, ΔT denotes the sampling time step and t_k specifies the time stamp of the k-th iteration step. Using χ and the measured velocity v, numerical integration yields the longitudinal position x and the lateral position y with respect to the current lane

$$\begin{pmatrix} x\ (t_k) \\ y\ (t_k) \end{pmatrix} = \begin{pmatrix} x\ (t_k - \Delta T) \\ y\ (t_k - \Delta T) \end{pmatrix} + \upsilon(t_k)\Delta T \begin{pmatrix} \cos \chi\ (t_k) \\ \sin\ \chi\ (t_k) \end{pmatrix}$$

To account for the nonlinear lateral dynamics of the evasive maneuver, a control strategy combining feed forward and feedback control is used, i.e., the command signal u of the lateral controller comprises the components u_{ff} from a feed forward and u_{fb} from feedback controller, respectively. u_{ff} is computed from the trajectory curvature, that in turn can be derived from the underlying polynomial used. The feedback component u_{fb} is provided by a fourth-order state controller with state vector $\left(y_{err}; y^*_{err}; \chi_{err}; \chi^*_{err}\right)$. Here, $y_{err} = y_{trj} - y$ denotes the lateral position error between the reference lateral position and the reconstructed position, $\chi_{err} = \chi_{trj} - \chi$ the difference between reference and reconstructed heading angle. y^*_{err} and χ^*_{err} represent temporal derivatives which can be computed using either derivative lag (DT1) elements, state variable filters, or state observers.

Due to the nonlinear behavior of the vehicle, a gain scheduling approach is employed which adapts both the feed forward gain factor K_{ff} and the feedback gain vector K_{fb} to the current velocity and the maximum allowed lateral acceleration $a_{y;\max}$, i.e., $K_{ff} = f\left(a_{y;\max}; v\right)$ and $K_{fb} = f\left(a_{y;\max}; v\right)$. For more information, see Fritz (2009).

4.2.3 Experiments

The above mentioned research prototype system was integrated into a Mercedes-Benz S-Class limousine. The vehicle system was tested on a proving ground, where by means of

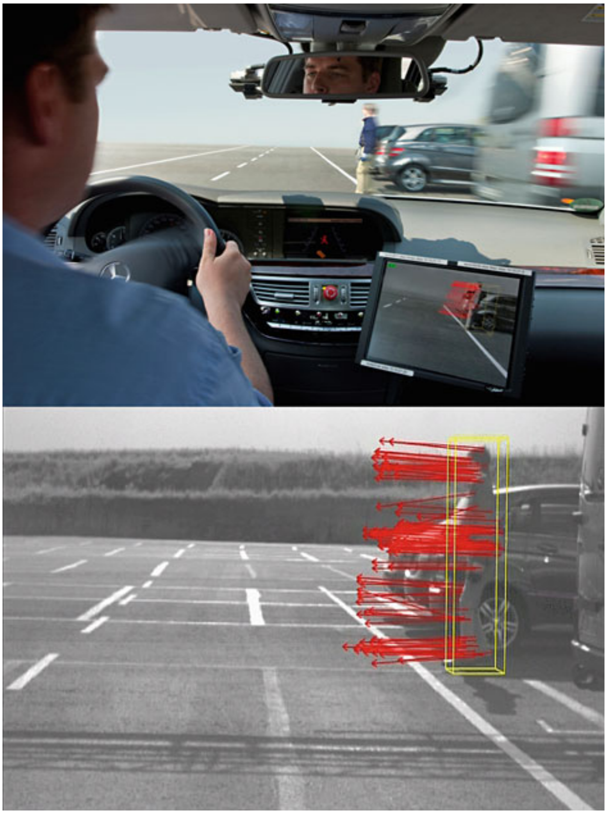

Fig. 29.9
Setup on the proving ground with the pedestrian dummy sliding along a traverse in front of the vehicle. View from inside the vehicle (*top*). Recognized pedestrian including motion estimate (*bottom*)

a traverse construction, a pedestrian dummy, hung by a set of wires, was moved across the road (see *Fig. 29.9* (top)). An electronic device allowed reproducible movement of the pedestrian dummy. The synchronization of the pedestrian dummy and the vehicle was achieved by a light barrier.

The integrated vehicle system was tested in two scenarios depicted earlier in *Fig. 29.5*. In both scenarios, the vehicle drives 50 km/h and the pedestrian dummy appears from behind an occluding car, with a lateral velocity of 2 m/s. The desired vehicle action is to brake, if still possible to come to a complete standstill, otherwise to evade. It was experimentally determined that the last possible brake time for the vehicle to come to a complete stop corresponds to a pedestrian distance of 20 m (taking into account various device latencies). Similarly, it was experimentally determined the last possible time to safely execute the evasion maneuver to correspond to a pedestrian distance of 12 m. These distances to the pedestrian could even be shortened, when increasing the total lateral offset from 1 to 2 m and driving the maneuver as depicted in *Fig. 29.2*. The resulting braking and steering distances for this maneuver are shown in *Fig. 29.3*.

In the first scenario, the pedestrian is first fully visible at about 24 m distance (3.8 m lateral) to the vehicle. This means that the system has only about seven frames (corresponding to 4.1 m driven) to determine pedestrian position and velocity, perform situation analysis, and make the correct decision to initiate braking. In the second scenario, the pedestrian is only first fully visible at about 15 m distance (3.1 m lateral) to the vehicle. This means that the vehicle cannot come to a full stop by braking, therefore the right decision is to evade. For the latter, it has about six frames time (corresponding to 3.5 m driven) to deploy.

Despite the flawless performance on the proving ground, a number of technical challenges remain before this research prototype system can be reliably applied to real traffic. In order to avoid false system activations, the sensing component will need to provide a more accurate pedestrian position and velocity estimation, and deliver increased recognition performance (correct vs. false recognitions). Sensor fusion (e.g., with radar, laser scanners) can provide an important contribution in this regard. The research prototype does not check for oncoming traffic or other obstacles within the commanded driving corridor. Product level systems will additionally require a free space analysis (Badino et al. 2008) to ensure that the automatic evasion maneuver can be safely performed indeed.

5 Conclusion

Steering and evasion assistance systems are a new class of driver assistance systems that open up additional potentials for collision mitigation. It was shown in this chapter that steering intervention is a sensible alternative or additional option for emergency braking systems in a collision speed range above 30 km/h. Steering intervention and evasion systems especially focus on surprising situations, where fast reactions are needed and no time is left for driver warnings. This requires high demands on environment perception as well as on situation analysis. Up to now environment perception algorithms concentrate on object and lane detection and measurement. A new requirement for driver assistance is the detection of free and drivable space, which has to be guaranteed to perform an evasion maneuver.

Three different system layouts were presented: driver-initiated evasion, corrective evasion, and automatic evasion assistance. Driver-initiated evasion only supports an intervention of the driver and therefore offers less safety potential, but due to less complexity it may soon be introduced to market. Corrective or automatic evasion assistance systems are currently investigated by industry and scientific research labs. Beside technical problems like the reliability of the environment perception, a lot of open questions have to be answered, e.g., customer controllability and acceptance. Therefore market introduction is not expected within the next 10 years.

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