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Opportunities and limitations for intersection collision intervention—A study of real world 'left turn across path' accidents

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ABSTRACT

Turning across the path of oncoming vehicle accidents are frequent and dangerous. To date not many car manufacturers have introduced Automated Emergency Braking (AEB) systems addressing this type of conflict situation, but it is foreseeable that these scenarios will be part of the Euro NCAP 2020 rating. Nine out of ten collisions are caused by the driver of the turning vehicle. An AEB system evaluating the ego and conflict vehicle driver's possibilities to avoid a pending crash by either braking or steering was specified for application in various constellations of vehicle collisions. In virtual simulation, AEB system parameters were varied, covering parameters that are relevant for driver comfort such as longitudinal and lateral acceleration (to define avoidance possibilities), expected steering maneuvers to avoid conflict, and intervention response characteristics (brake delay and ramp up) to assess the safety benefit. The reference simulation showed a potential of the AEB system in the turning vehicle to avoid approximately half of the collisions. An AEB system of the straight going vehicle was less effective. The effectiveness of the turning vehicle's AEB system increases if spatial limitations for the collision-avoidance steering maneuver are known. Such information could be provided by sensors detecting free space in or around the road environment or geographical information shared via vehicle to cloud communication. AEB interventions rarely result in collision avoidance for turning vehicles with speeds above 40 km/h or for straight going vehicles with speeds above 60 km/h. State of the art field-of-views of forward looking sensing systems designed for AEB rear-end interventions are capable of addressing turning across path situations.

1. Introduction

Intersection accidents are frequent and have severe consequences. Approximately fifty percent of all injury crashes in the US occur at intersections, or are intersection related. Further, approximately thirty percent of road traffic fatal crashes occur at these locations (NHTSA, 2016). In Europe, about twenty-four percent of road traffic fatalities are caused by junction accidents (European Commission, 2015).

Advanced Driver Assistance Systems (ADAS) and active safety systems are expected to greatly increase road safety by avoidance or mitigation of accidents. Several systems are already on the market, and studies have shown their real world benefit. These studies cover systems such as Electronic Stability Control (Lie et al., 2006), Forward Collision Warning and Automated Emergency Braking (AEB) in car-to-car rear-end (Cicchino, 2016), car-to-pedestrians/bicyclists conflict situations (Rosen, 2013), Lane Departure Warning (Gorman et al., 2013), and Blind Spot Detection (Schaudt et al., 2014). The methods for the assessment of safety system effectiveness includes the analysis of normal driving, critical situations, and accident data, and/or utilizes controlled field tests, simulator studies, and virtual simulations.

To date, there are but a few car manufacturers that have introduced intersection support for drivers. Several EU financed projects concerning future smart vehicle solutions have shown that intersection accidents will be among the predominating scenarios when current ADAS, and active safety systems have penetrated the vehicle fleet to a greater degree (Svensson et al., 2014; Wohlecker et al., 2014). The European New Car Assessment Program (Euro NCAP) has stated, in their 2020 road map, that the next generation of AEB will be capable of addressing more complex accident scenarios, such as turning across path with oncoming traffic, or crossing a junction (European New Car Assessment Programme, 2015). Thus, it is foreseeable that these types of scenarios will become part of the 2020 rating schema.

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Left turn across path with traffic from oncoming direction (LTAP/OD) accidents between passenger cars including at least one involved person with moderate or more severe injuries (MAIS2+F) according to the Abbreviated Injury Scale (Gennarelli and Wozine, 2008) are as frequent as rear-end or straight crossing path accidents of the same severity. While the risk of death caused by a moderate injury such as an open fracture is below two percent, they often result in long-term consequences for car occupants, which are a major source of socioeconomic and private loss (Stigson et al., 2015).

2. Literature review

Left turn across path accidents in right hand traffic, where the opponent came from the opposite direction (LTAP/OD), have been studied under various aspects such as a) comfort boundaries and gap acceptance for left turn decisions, especially with respect to time pressure and elderly drivers, b) effect of turning lane offset, and c) threat assessment algorithm that are able to address various types of vehicle collisions.

Comfort boundaries and limits for pushing towards critical situations in left turn maneuvers were investigated with actual vehicles in a mock-up intersection (Bargman et al., 2015). In a LTAP/OD situation where all drivers (male and female aged 25–61 years) of the turning car felt they were in their comfort zone, all lateral accelerations were reported to be less than $5\frac{m}{s^2}$. Median and mean lateral acceleration were $3.2\frac{m}{s^2}$ and $3.4\frac{m}{s^2}$, respectively. When pushed towards more hectic driving and entering a dread zone, which the authors define as a spatiotemporal limit beyond which drivers will never go voluntarily, only 15% of the drivers exceeded a lateral acceleration of $5\frac{m}{s^2}$. The maximum recorded lateral acceleration for all drivers was $7\frac{m}{s^2}$. Drivers rated their left turn at the comfort zone boundary as significantly more comfortable and less risky than a left turn at the dread zone boundary. It appears that drivers will not cross the dread zone boundary, even with additional motives such as time pressure, though they still might be able to avoid crashes.

A longitudinal acceleration analysis in normal driving situations was conducted by Moon and Yi (2008). In 1809 data sets of 125 drivers the mean braking deceleration for speeds below 40 km/h was $-1.7\frac{m}{s^2}$ with 5 and 95 percentile of $-0.8\frac{m}{s^2}$ and $-3.0\frac{m}{s^2}$. The maximum deceleration reached during the driving test was $-5.1\frac{m}{s^2}$. Drivers were not pushed into their dread zone.

Gelau et al. (2011) conducted a fixed-base driving simulator study with younger (22–37 years) and older (60–84 years) drivers negotiating a left turn with and without time pressure, and with and without an assistance function (time gap display). Time pressure led to a shorter time to collision (TTC) in all left turn situations in which TTC was defined as the time required by the oncoming vehicle to reach the point where intersected with the virtual trajectory of the turning vehicle. Additionally, with support of time gap assistance, a lower TTC was also recorded, but differences in TTC between younger and older drivers were more pronounced when there was no time pressure. Differences between age groups were smaller under time pressure.

An analysis of driver evasive maneuvers prior to intersection crashes showed that in eighty percent of all intersection scenarios the driver executed such a maneuver (Scanlon et al., 2015). Based on the analyzed event recorder data, the median average evasive braking deceleration was $5.7\frac{m}{s^2}$, and the median of the evasive vehicle yaw rates was 8.2° per second. For the LTAP/OD scenario, the direction of evasive steering for the straight heading vehicle was a little over 50% to the right towards the direction of travel of the turning vehicle. Most drivers of the investigated data set (57%) used a combination of braking and steering for crash avoidance, whereas 14% and 9% only braked or steered, respectively. Twenty percent did not conduct an evasive maneuver. The authors did not differentiate results between the different intersection scenarios 'straight crossing path', 'left turn across path with oncoming direction', and 'left turn across path with lateral direction'.

Gap acceptance for left turns among older drivers was studied in a field observation study at unsignalized intersections (Zhou et al., 2015). Gap acceptance was investigated by traffic flow observation cameras, and the driver age was estimated by on-site observers after specific instruction. An outcome of this study was that drivers over 70 years of age were less likely to accept gaps than drivers under 35 and drivers aged 55–69, whereas the latter group did not significantly differ from younger drivers. Further, there was no significant difference between drivers older than 70 years and drivers in the age group 35–54. Females were more conservative than males, and shorter gaps were more likely accepted at higher speed limits.

Naturalistic driving data was utilized by Hutton et al. (2015) to evaluate the effect of left turn lane offset at intersections. Negative offset was present in cases with no longitudinal overlap between lanes (including turning lanes) of opposite direction. At zero offset the left turn lanes of opposite direction were in line with each other, and with positive offset left turn lanes were placed more towards the left than oncoming left turn lanes, thus overlapping each other. Beside the gap length and post-encroachment time (time between the start of the left turn and the time the opposing vehicle reaches the stop bar of the intersection), the influence of sight obstruction on turning behavior was analyzed. In twenty percent of the cases where the gap length could be recorded in videos, a vehicle in the opposite left turn lane blocked the subject vehicle driver's view. The percentage was higher for negative offset left turn lanes compared to zero or positive offset turn lanes. In general, drivers tended to wait until their view was no longer obstructed before accepting a gap.

Kaempchen et al. (2009) presented an AEB algorithm addressing various vehicle-to-vehicle collisions, which considered all physically possible trajectories of the subject and principal other vehicle by consideration of both vehicles' dimensions and orientation. This made the algorithm applicable to different scenarios including rear-end, intersection, and oncoming vehicle scenarios. AEB intervened only if all trajectory combinations (braking, steering, accelerating) at the physical limit led to an accident. An iterative optimization algorithm was applied to search for a combination of all possible trajectories that would lead to collision avoidance. In case a combination was found, AEB was not activated. System latencies and measurement noise were not considered in the algorithm, thus the evaluation did not show for example erroneous engagement of the AEB due to inaccurate velocity estimation of the collision opponent. A similar approach was taken in another study, with the difference being that the driver of the vehicle would either steer, brake, or accelerate to avoid a collision (Brännström et al., 2010). Thus, the possible set of trajectories was reduced, but more realistic path prediction compared to the study of Kaempchen et al. (2009) was achieved by the use of a linear bicycle model. Driver preferences such as maximum lateral acceleration and the maximum lateral acceleration change rate were considered in the algorithm, which could then be applied to either warn the driver or automatically apply brakes. Besides simulations, the algorithm was implemented into a vehicle for physical testing of rear-end and intersection scenarios (Brännström et al., 2011).

3. Objectives

The objectives of this study are to present the identification and quantification of the opportunities and limitations of AEB systems