STUDY OF THE APPLICATION OF STEERING SUPPORT SYSTEMS TO COMPLEMENT AUTONOMOUS EMERGENCY BRAKING SYSTEMS FOR ACTIVE COLLISION AVOIDANCE STRATEGIES

Álvaro Esquer
Applus IDIADA
Spain

Andrés Aparicio
Sébastien Baurès
Laura Sanz
Applus IDIADA
Spain

Paper Number **17-0394**

ABSTRACT

The cause of many car collisions is the lack of braking or late braking due to driver distraction or misinterpreting the situation. Autonomous Emergency Braking (AEB) systems help to avoid these accidents or mitigate their consequences by executing a braking action over the vehicle. AEB systems have proved to be very effective in cities, where speeds are moderate and braking actions are the most appropriate manoeuvre to avoid an accident. However, as vehicle speed increases (i.e. in interurban environments) the most effective action to avoid the collision might be an evasive manoeuvre instead of braking. Several studies are analyzing the suitability of an automatic steering action as compared to the AEB using lane change testing. Last Point to Brake (LPTB) and Last Point to Steer (LPTS) values have been already studied taking into account vehicle speed and distance between vehicle and obstacle among other factors. The objective of this study is to further explore the automatic steering function on selected Car-to-Car and Car-to-VRU scenarios. It is considered that the steering actuation must ensure the collision avoidance as well as the safety of the vehicle occupants and other road users along the lane change process and until the end of the conflict.

INTRODUCTION

The figures of road fatalities in EU have fallen down dramatically since 2007 [1]. This success is in part due to advancements in road infrastructure and effective road safety campaigns, but also this has been caused by the notorious recent improvement in vehicle safety. Progress in passive safety, application of regulations to safety systems such as ABS and ESC and new developments in active safety systems have contributed to the enhancement of global vehicle safety. These road fatalities numbers are expected to continue decreasing in the coming years with the development of connected and automated driving systems.

Advanced Driver Assistance Systems (ADAS) supporting the driver to avoid collisions have been over the last few years being available in series production vehicles. These systems are focused on the avoidance of rear-end collisions by fully using the braking potential of vehicles, after the detection of accidents about to occur. This understanding of the environment is accomplished with the aid of a network of devices such as camera and/or radar sensors constantly monitoring the vehicle's surroundings. The first generation of such systems improved the Dynamic Brake Support (DBS), which assists the driver increasing the braking force in panic braking situations. Such system will notify the driver of a potential hazard by warning with audio-visual or haptic signals. The next generation of these systems offered automatic braking in imminent collisions situations, a system like this is the AEB (Autonomous Emergency Braking) system.

AEB systems evaluate the risk of impact and determines the time when to automatically brake and avoid or at least mitigate the crash with another vehicle or pedestrian. For each driving speed can be defined a distance which represents the last-point-to brake (LPTB) in order to prevent the accident. An accident cannot be avoided by braking when the relative distance among the vehicle and the obstacle is shorter than the LPTB. Moreover, the LPTB distance shows quadratic growth with the velocity and consequently the effectiveness of this manoeuvre decreases as the velocity rises [2]. Therefore, the conclusion here is that the AEB system is very useful on urban areas and in situations where the relative velocity among the vehicles is small, but it is not the best solution for interurban areas with higher speeds.

Apart from fully braking, it is also possible to perform an evasive manoeuvre to avoid the collision. Analogously to the DBS, it is conceived the concept of the Dynamic Steer Support (DSS). This conceptual system would make use of the environmental vehicle's sensors to detect hazardous situations and at the event of an accident, if the driver decides to dodge the obstacle, the DSS system would assist the driver to trace the most suitable trajectory to avoid the impact. A last-point-to steer (LPTS) distance can be defined for each velocity and each desired lateral motion and this distance increases lineally with the velocity.

This study compares the LPTS and LPTB values for different velocities and different size of obstacles with the objective to understand which system would be the most suitable to prevent accidents depending on the driving circumstances. In order to obtain the LPTS values the software PreScan [3] has been used to run simulations for a reference vehicle and a set of velocities. The trajectory used to describe the evasion path is the 5th order polynomial lane change given by the software trajectory planner. Some restrictions have been imposed to optimize as much as possible the trajectories.

Finally, the results obtained are compared using CCR [4] and VRU [5] Euro NCAP [6] based test scenarios to better understand the suitability of each system on the different scenarios.

METHODOLOGY

This section contains the procedure and the considerations taken to obtain the LPTS and LPTB values. The reference vehicle for the simulations and calculations is a compact car.

Definition of the evasive trajectory

The avoidance by evasive steering conceived in this research is a rapid lane change manoeuvre. With this strategy it is intended to guarantee that the emergency steering manoeuvre preserves the occupants' safety as it also stabilizes the vehicle after the first evasive manoeuvre. For this, a fixed 3,5m wide lane change is proposed. This width covers the case of avoiding big obstacles and is also valid for the avoidance of smaller objects. In these cases, after avoiding this small object, the trajectory could be modified by the system to a smaller lane change. The restrictions of this trajectory are given below:

- Steering wheel angle ≤ 160°
- Steering speed ≤ 1200°/s
- Lateral acceleration peak ≤ 10 m/s^2
- Absolute trajectory error ≤ 10 cm

The limitations regarding the steering wheel parameters aim to define a manoeuvre feasible for skilled drivers. The lateral acceleration peak and the absolute trajectory error are defined to avoid understeer and oversteer effects that could have a negative impact on the controllability of the vehicle. Briefly: the restrictions imposed define a feasible manoeuvre while maintaining high controllability.

The methodology used to find the optimum lane changes consisted on running multiple simulations with the software testing trajectories variations progressively increasing the performance within the defined restrictions. These iterations were conducted for a set of velocities between 10 and 120 km/h. Figure 1 depicts a sketch of a lane change with some measurement points.

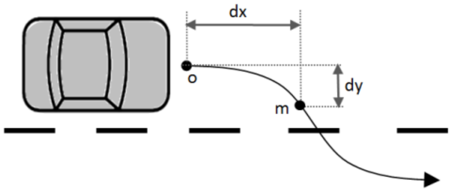

Figure 1. Lane change trajectory with measurement points

The vehicle's longitudinal displacement in each point is represented by *dx* while its lateral displacement is represented by *dy*. The steering manoeuvre starts in the position $o(x_o,y_o)$. This is the moment where the driver steers and from this point the system would assist the driver to trace am optimized trajectory. This point defines when the steering wheel angle is increased by 1°. The longitudinal and lateral distances travelled by the vehicle are calculated as $\overline{mo}\,(x\text{-}x_o,\ y\text{-}y_o)$, being $m(x,\ y)$ the interest point to measure.

Calculation of LPTB

In order to calculate the LPTB it is considered the moment when the brake pedal is depressed as the start point of the braking manoeuvre. Figure 2 shows the deceleration curve used for the LPTB calculation and its different phases.

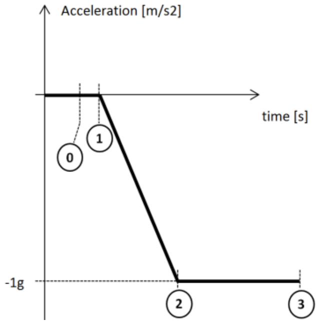

Figure 2. Deceleration profile with measurement points

Phase 0-1 represents the delay between the initial brake pedal input and the start of the deceleration; a representative value of 0,065s has been selected which corresponds to an average time for compact cars. *Phase 1-2* is a transient phase where the deceleration contains a constant jerk effect (25 m/s^3) and in *phase 2-3* the deceleration reaches and maintains a maximum value of 10 m/s^2 until the vehicle stops.

RESULTS

The results obtained regarding the last points and moments to intervene (LPTI and LMTI) are compiled on different graphs to be compared. These curves illustrate the threshold velocity from where it would be more effective to perform a steering manoeuvre rather than an action on the brake pedal. Furthermore, based on the results, it is evaluated the feasibility of performing such manoeuvres in Euro NCAP AEB CCR and VRU test scenarios.

Last-point-to intervene

The last-point-to intervene encompasses the LPTB and the LPTS and represents the minimum distance with the obstacle to which full braking or emergency steering is effective. This distance depends on the velocity and presents different behaviour for each type of manoeuvre. Figure 3 shows the distance needed to stop the vehicle for different speeds and the distance travelled by the vehicle during evasive manoeuvres. The longitudinal distances needed for the lane change manoeuvres are shown for different lateral deviation from 0,25m to 2m. The LPTB required for small speeds is shorter than the LPTS; for velocities inferior to 30 km/h the braking action is more effective. For velocities superior to 60 km/h the LPTS is lower than the LPTB and the evasive manoeuvre becomes more efficient in lateral avoidances greater than 2 m. However, for velocities between 30 and 60 km/h the most suitable intervention depends on the lateral displacement needed to avoid the obstacle.

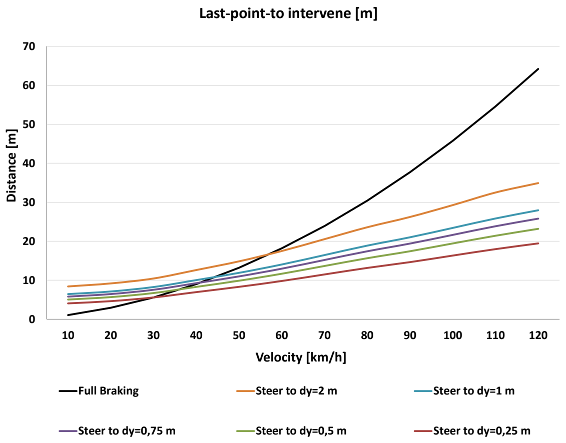

Figure 3. Last-point-to intervene for a set of velocities and lateral deviation

Last-moment-to intervene

The LMTI (expressed in seconds) is the result of dividing the LPTI by the relative velocity between the vehicles. Therefore it can be defined as well a last-moment-to brake (LMTB) and last-moment-to steer (LMTS). If the intervention is made after passing the LMTI, then the accident is unavoidable. The LMTS is high for small speeds mostly due to the low lateral acceleration reached in these manoeuvres because of the maximum steering angle limitation and low longitudinal speed. However for medium and high speeds the lateral acceleration gets closer to $10 m/s^2$ and the LMTS becomes constant (see Figure 4). The LMTB grows lineally as the velocity increases and would reach a maximum of 2 seconds before the collision when driving at 120 km/h.

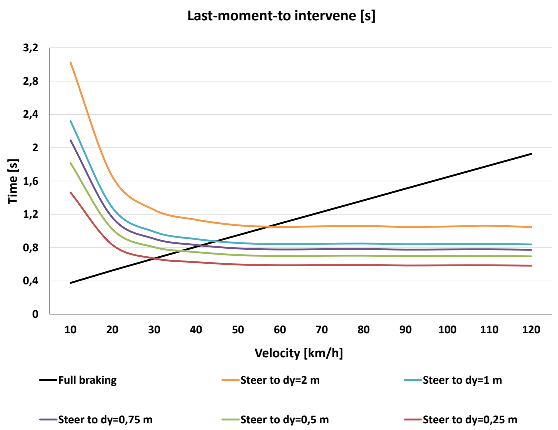

Figure 4. Last-moment-to intervene for a set of velocities and lateral deviation

Application of LPTI and LMTI results in CCR and VRU test scenarios

In this section the previous results are evaluated for different test scenarios. With this exercise it is expected to obtain an accurate overview of how DSS systems could complement the AEB systems in controlled environment. The test scenarios are based on the Euro NCAP 2016 test protocol for the assessment of AEB CCR and VRU systems:

- CCRs (Car-to-Car Rear stationary)
- CCRm (Car-to-Car Rear moving)
- CCRb (Car-to-Car Rear braking)
- CVNA25 (Car-to-VRU Nearside Adult 25)
- CVNA75 (Car-to-VRU Nearside Adult 75)

Additionally, some other scenarios are evaluated:

- CCRs-50 (overlap 50%)
- CCRm-50 (overlap 50%)
- CCRb-50 (overlap 50%)
- CVNA50-R (Car-to-VRU Nearside Running at 8 km/h Adult 50)
- CVNA10 (Car-to-VRU Nearside Adult 10)

The considerations followed to conduct this evaluation are shown next:

- The test vehicle is referred as Vehicle Under Test (VUT) and is 1,8 m wide, the target vehicle (TV) is 1,6m wide and the adult pedestrian is 0,36 m wide.
- All the evasive trajectories contain a “safety lateral margin” of 0,2 m between the VUT and the target at the moment of the avoidance.
- Assuming a right-hand driving, the evasive manoeuver is always directed to the left side.
- For the system’s assessment on scenarios involving vulnerable road users it has been defined a “minimum relative lateral distance” between the pedestrian and the vehicle from which the system will be allowed to intervene. Pedestrians need around 1 m to stop from motion [7] and therefore, in order to avoid wrong system interventions this “minimum relative lateral distance” is set to 1 m. Figure 5 illustrates such distance.

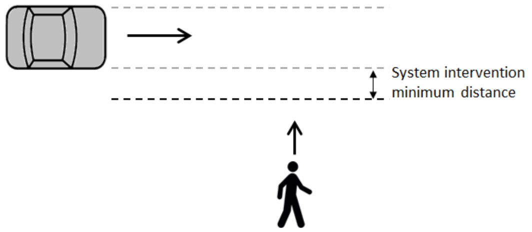

Figure 5. Representation of the system’s allowed intervention area

The results for the evaluation in the mentioned test scenarios are shown below. A table is included summarizing the LPTI and LMTI values at the threshold velocity:

CCRs test scenario Full braking intervention is the most suitable one for test velocities up to 50 km/h. For velocities higher than 60 km/h, the steering intervention is more appropriate (see Table 1).

Table 1.
Results for CCRs (test velocity=60km/h)

	Steering	**Braking**
Last point to intervene	16,8 m	18,2 m
Last moment to intervene	1,01 s	1,09 s

CCRs-50 test scenario For lateral overlaps of 50% between the stationary target and the VUT (see Figure 6) the steering action is more effective than braking from 50 km/h. The table 2 shows the LPTI and LMTI values for that velocity.

Table 2.
Results for CCRs-50 (test velocity=50km/h)

	Steering	Braking
Last point to intervene	11,9 m	13,2 m
Last moment to intervene	0,86 s	0,95 s

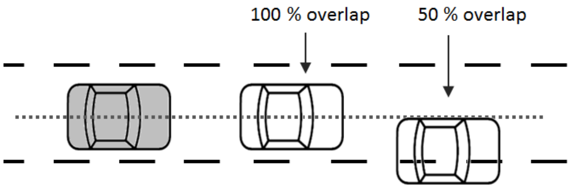

Figure 6. Lateral overlap examples

CCRm test scenario Braking action avoids the impact when the VUT velocity is lower than the target velocity. Last point to intervene is referred to the relative distance among the vehicles and last moment to intervene is in relative terms as well. Table 3 shows the measured values for the threshold velocity of 80 km/h.

Table 3.
Results for CCRm (test velocity=80km/h)

	Steering	Braking
Last point to intervene	17 m	17,8 m
Last moment to intervene	1,02s	1,07 s

(Relative measures among the vehicles)

CCRm-50 test scenario With 50% of overlap between the vehicles (as shown in Figure 6), the intervention upon the steering becomes the most suitable action for speeds from 70 km/h as Table 4 shows.

Table 4.
Results CCRm-50 (test velocity=70km/h)

	Steering	Braking
Last point to intervene	11,8 m	12,3 m
Last moment to intervene	0,85s	0,89 s

(Relative measures among the vehicles)

CCRb (12m, 0,6g) test scenario CCRb tests are all conducted at 50 km/h. To study the suitability of the systems, are compared the available distance to travel and the available time to react (both for the VUT) from the moment the leading vehicle initiates its braking until the accident is unavoidable. For braking cases, VUT only needs to reduce its velocity below TV velocity. Table 5 shows that the braking manoeuvre has 0,09s more to react than the steering action.

Table 5.
Results for CCRb (12m, 0,6g)

	Steering	Braking
Available distance to travel since target braking	18,25 m	19,44 m
Available to time to react since target braking	1,31 s	1,4 s

CCRb-50 (12m, 0,6g) test scenario In this case the steering manoeuvre has more available distance and time to react as described on table 6.

Table 6.
Results for CCRb-50 (12m, 0,6g)

	Steering	Braking
Available distance to travel since target braking	20,61 m	19,44 m
Available to time to react since target braking	1,48 s	1,4 s

CCRb (40m, 0,6g) test scenario The results in table 7 show that the braking action is more appropiate than steering. In such scenario, the target is already stopped when the VUT intervenes to avoid the impact and therefore the result is analogous to the CCRs scenario.

Table 7.
Results for CCRb (40m, 0,6g)

	Steering	Braking
Available distance to travel since target braking	46,4 m	47,44 m
Available to time to react since target braking	3,34 s	3,42 s

CCRb-50 (40m, 0,6g) test scenario Table 8 shows that the steering action could react later than the braking action and avoid the impact.

Table 8.
Results for CCRb-50 (40m, 0,6g)

	Steering	Braking
Available distance to travel since target braking	48,78 m	47,44 m

Available to time to react since target braking	3,51 s	3,42 s

CCRb (12m, 0,2g) test scenario The available distance and time of both manoeuvres varies a lot as table 9 reveals.

Table 9.
Results for CCRb (12m, 0,2g)

	Steering	Braking
Available distance to travel since target braking	36,25 m	42,08 m
Available to time to react since target braking	2,61 s	3,03 s

CCRb-50 (12m, 0,2g) test scenario Even for a lateral offset between the vehicles, the steering manoeuvre has less time to react when the target vehicle brakes smoothly.

Table 10.
Results for CCRb-50 (12m, 0,2g)

	Steering	Braking
Available distance to travel since target braking	38,61 m	42,08 m
Available to time to react since target braking	2,78 s	3,03 s

CCRb (40m, 0,2g) test scenario The result brings similar conclusions but again the braking action could be done later than the evasive manoeuvre as table 11 indicates.

Table 11.
Results for CCRb (40m, 0,2g)

	Steering	Braking
Available distance to travel since target braking	75,75 m	77,3 m
Available to time to react since target braking	5,45 s	5,57 s

CCRb-50 (40m, 0,2g) test scenario For an overlap of 50% the steering manoeuvre could be conducted slightly later than the full braking action.

Table 12.
Results for CCRb-50 (40m, 0,2g)

	Steering	Braking
Available distance to travel since target braking	78,11 m	77,3 m
Available to time to react since target braking	5,62 s	5,57 s

CVNA75 test scenario Steering manoeuvre is the best solution for velocities starting from 60 km/h as table 13 reveals. Furthermore, the evasive trajectory is able to avoid the collision from 20 km/h and will always result in a collision for lower speeds. Automatic braking could avoid the impact even for 100 km/h.

Table 13.
Results for CVNA75 (test velocity=60km/h)

	Steering	Braking
Last point to intervene	16,56 m	18,16 m
Last moment to intervene	0,99 s	1,09 s

CVNA25 test scenario Braking is more suitable in this scenario up to 50 km/h. The accident can be avoided by steering from 30 km/h and will always result in a collision for lower speeds. From 50 km/h the most appropriate action is to steer as table 14 shows.

Table 14.
Results for CVNA25 (test velocity=50km/h)

	Steering	Braking
Last point to intervene	11,27 m	13,2 m
Last moment to intervene	0,81 s	0,95 s

CVNA-50-R test scenario A pedestrian running at 8 km/h crosses from the nearside and the impact is predicted on the vehicle’s centreline. The steering manoeuvre is not able to avoid the impact for any of the velocities. A full braking intervention could avoid up to 40 km/h.

CVNA10 test scenario At 40 km/h the best solution is to steer rather than to brake as table 15 reveals. The accident cannot be avoided by braking at 50 km/h and it is possible to avoid it by steering from 30 km/h.

Table 15.
Results for CVNA10 (test velocity=40km/h)

	Steering	**Braking**
Last point to intervene	8,52 m	9 m
Last moment to intervene	0,77 s	0,81 s

CONCLUSION

This study proposes a method to define emergency lane changes for accident avoidance purposes and obtains last-point-to steer values, for a wide range of velocities, by means of simulation software. Furthermore, last-point-to brake values are calculated for a range of velocities as well. These last-point-to intervene values aim to represent the limits of the application of the so-called Dynamic Steering Support systems (for LPTS values) and Autonomous Emergency Braking systems (LPTB values) as frontal collision avoidance systems. In order to determine the applicability of such features, Euro NCAP CCR and VRU test scenarios (and some other inspired on the Euro NCAP ones) have been used for obtaining LPTS and LPTB values.

The results are summarized as follows:

- In CCRs test scenarios the DSS system avoids collisions more effectively than AEB from 60 km/h. This threshold velocity decreases as the lateral offset among the VUT and TV increases. For slow moving targets such as in CCRm, the DSS becomes more effective at the highest test speed, 80 km/h and 70 km/h with 50% offset.
- In CCRb test scenarios the steering manoeuvre resulted the optimum solution for a lateral offset of 50% between vehicles. However, in CCRb (12m, 0,2g) the evasive manoeuvre is less effective than the braking action.
- Regarding VRU test scenarios, evasive manoeuvres are able to prevent accidents from 30 km/h (when impact expected before the vehicle’s centerline) and from 20 km/h (when impact expected after the vehicle’s centerline). Nevertheless, braking is the most efficient manoeuvre up to 40 km/h (when impact expected before the vehicle’s centerline) and 50 km/h (when impact expected after the vehicle’s centreline). In case of a running pedestrian with reduced time for reaction the steering manoeuvre is not suitable.

As a main conclusion and based on the results, DSS systems could optimize the intervention at speeds below 60 km/h for small offset avoidances. For instance, impacts with lateral offset between the cars and with pedestrians predicted to impact on the vehicle’s right corner. For higher speeds and highway environments the braking becomes much less effective and an evasive manoeuvre is preferred.

The steering support concept system, as introduced in this research, is considered to act at the latest possible moment while using the maximum capabilities within the operational limits. Nevertheless, a similar system could also assist drivers in less risky situations. For instance, in real driving situations the driver would steer smoothly and with enough time in advance to avoid a clearly visible pedestrian rather than to fully brake. Therefore, such system it is not only limited to imminent accident situations and could support drivers in all evasive related manoeuvres.

It is necessary to highlight that reducing the vehicle speed when detecting a critical situation is always a good decision. The result of the action of the braking assistance system will always result in a mitigation of the severity of the collision compared to no actions from the driver. Evasive manoeuvres avoid the obstacle without necessarily reducing vehicle’s speed. In case of not avoiding the accident, the vehicle would collide the obstacle with a small or moderate overlap. Such collisions tend to result more destructive towards the vehicle body than a frontal collision with high overlap.

This investigation has studied separately both systems and has considered only simulated and calculated results. Further research will:

- Correlate the LPTS simulated results with experiment based lane changes in proving grounds
- Explore the application of combined braking and steering in test scenarios
- Consider Euro NCAP test protocol 2018

REFERENCES

[1] Mobility and Transport, Statistics European Commision . (2016). “Annual Accident Report 2016” [pdf] Available at: http://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/asr2016.pdf [Accessed April 3, 2017]

[2] Eckert, A., Hartmann, B., Sevenich, M., Rieth and Dr. P. R. (2011). Emergency steer and brake assist - A systematic approach for system integration of two complementary driver assistance systems. *The 21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV), 11-0111*

[3] PreScan © 2016 TASS International.

[4] Euro NCAP. (2015). European new car assessment programme (Euro NCAP) test protocol – AEB CCR test protocol Version 1.1 [pdf] Available at: http://www.euroncap.com/es/para-ingenieros/protocols/adult-occupant-protection/ [Accessed April 3, 2017]

[5] Euro NCAP. (2015). European new car assessment programme (Euro NCAP) test protocol – AEB VRU test protocol Version 1.0.1 [pdf] Available at: http://www.euroncap.com/es/para-ingenieros/protocols/pedestrian-protection/ [Accessed April 3, 2017]

[6] Euro NCAP. (2015). European new car assessment programme (Euro NCAP)

[7] Seiniger, P., Barlets, O., Kunert, M., Schaller, T. (2014). Test procedure including test target and misuse tests, based on test results [pdf]. *AsPeCSS D2.5*, 29. Available at: http://www.aspecss-project.eu/userdata/file/Public%20deliverables/ASPECSS-D2.5-FINAL-Active%20Safety%20Results-BASt-2014-06-12.pdf [Accessed April 3, 2017]