Development and simulation-based testing of a 5G-Connected intersection AEB system

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ABSTRACT
In Europe, 20% of road crashes occur at intersections. In recent years, evolving communication technologies are making vehicle-to-vehicle and vehicle-to-infrastructure faster and more reliable; with such advancements, these crashes, as well as their economic cost, can be partially reduced. In this work, we concentrate on straight path intersection collisions. Connectivity-based algorithms relying on 5G technology and smart sensors are presented and compared to a commercial radar AEB logic in order to evaluate performances and effectiveness in collision avoidance or mitigation. The aforementioned novel safety systems are tested in a blind intersection and low adherence scenarios. The first proposed algorithm is obtained by incorporating connectivity information into the original control scheme. The second proposed algorithm is a novel control logic fully capable of utilising the adherence estimation provided by smart sensors. Test results show an improvement in terms of safety of the control architecture and high prospects for future developments.

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1. Introduction

According to the World Health Organization (WHO), road traffic injuries are the 8th leading cause of death in the world, and the leading cause of death for children and young adults aged 5–29 years [1]. The main cause of road traffic accidents is the inappropriate behavior of drivers, such as: speeding, driving under the influence of alcohol or drugs, distracted driving, as well as the non-use of seat-belts or safety equipment. Moreover, the lack of safe infrastructure (such as the presence of blind-zone intersections) creates a barrier for drivers in taking the right decision at the right time. Although human safety is the primary concern, it is worth mentioning that fatal road crashes affect the economy as well, costing up to $280 billion in the USA [2] with a similar number in Europe [3].

With 20% of all road traffic fatalities in the European Union and USA occurring at intersections, their safety is of major concern [3]. In their 2020 Roadmap, Euro NCAP highlights the importance of developing AEB systems for avoiding and/or mitigating intersection crashes with a goal of adoption in 2020 [4]. It is noteworthy that nearly all accidents occur at signal-controlled (52%) or stop-controlled (46%) intersections [5]; hence, connected
advanced driver-assistance systems (C-ADAS) present the opportunity to help drivers navigate intersections in a safe manner. In fact, a study done by Scanlon et al. predicted that Intersection ADAS that deliver a warning only could prevent up to 23% of intersection crashes, while another that brakes the vehicle (i.e. AEB) as well as warns the driver could prevent up to 79% of crashes [5].

2. Literature review

Vehicle-to-vehicle (V2V) and Vehicle-to-infrastructure (V2I) technologies are bringing road safety to a new level. These technologies are expanding the scope of ‘preventable collisions’ to include blind-zone intersections. The upcoming 5G technology is rendering current AEB systems outdated; as state-of-the-art AEB systems do not utilise the full potential of the rich information that could be transmitted through 5G.

Forward Collision AEB is addressed very well in the literature. This is not the case for Intersection AEB (I-AEB), as it is a relatively new concept. It is noteworthy that Sander et al. explore various clustering methods to define a small number of representative intersection test scenarios, in order to validate any AEB logic developed as well as reduce the number of intersection scenarios tested due to their diverse nature [6]. Although no set of clusters that could group accidents into homogeneous groups is found, this paper is very insightful; through the results, it becomes clear that using simulation software is an inevitable part of testing and development, as physical testing will be very costly, in terms of money and time.

2.1. AEB collision risk indices

The main defining characteristic of current AEB algorithms is having a predefined static braking logic which is triggered or activated by a certain collision risk index: a quantitative measure about driving safety.

2.1.1. Time-to-collision

Time-to-collision (TTC) is the most widely used indicator. Usually, TTC is calculated using information given by the radar system using a constant velocity or a constant acceleration vehicle model, and after that, if the TTC is less than a certain threshold a warning is issued and if the driver doesn’t respond, autonomous braking takes place. Jeon et al. develop a method to take into consideration the road condition in the AEB logic. As mentioned earlier, the AEB is activated if the calculated TTC is less than a certain pre-defined threshold (usually 2 seconds). However, to consider various road conditions, the threshold is modified such that it increases as the friction potential decreases (the friction potential dictates the maximum deceleration that the vehicle could achieve), as seen in Equation (1):

\[
\text{TTC}_{\text{threshold}} = \frac{V_{\text{ego}}}{2\mu g}
\]

where \( V_{\text{ego}} \) is longitudinal ego vehicle velocity; \( \mu \) is the friction potential (imposed as a fixed parameter) and \( g \) is the gravitational acceleration.

The latter AEB logic is experimentally tested, and shows promising results. However, the main disadvantage of such technique is that full braking is employed once the TTC threshold is crossed, which is not very comfortable for the driver and not always safe [7].
2.1.2. Time-to-react
Time-to-react or TtR is defined as the remaining time until the very last possible driving manoeuvre that could avoid an imminent collision [8]. For example, if the possible driving manoeuvres considered are: Time-to-brake (TTB) and Time-to-steer (TTS), then TtR = max(TTB, TTS).

2.1.3. Braking distance
An interesting work incorporating this index is developed by Lee et al. The braking distance calculation takes into consideration the effects of the actuator dynamics of the braking system leading to a better prediction [9], as in Equation (2)

\[ d_{\text{brake}} = \frac{v_x^2}{2a_x} + \frac{v_x}{2J_{\text{act}}}a_x - \frac{1}{24J_{\text{act}}^2}a_x^3 \]  

Where \( v_x = \) current vehicle speed, \( a_x = \) desired deceleration, \( J_{\text{act}} = \) actuator response time.

It is also interesting to note that Seiler et al. highlight other types of AEB algorithms which use braking distance as the safety indicator [10]. Mazda’s algorithm [11] (developed for Forward AEB) defines the braking distance as obtained in Equation (3):

\[ d_{\text{brake}} = \frac{1}{2} \left( \frac{v^2}{\alpha_1} - \frac{(v - v_{\text{rel}})^2}{\alpha_2} \right) + v\tau_1 + v_{\text{rel}}\tau_2 + d_0 \]  

Where \( v = \) ego vehicle velocity, \( v_{\text{rel}} = v - v_{\text{preceeding}}, \alpha_1 = \) maximum deceleration of the ego vehicle, \( \alpha_2 = \) maximum deceleration of the preceding vehicle, \( \tau_1, \tau_2 = \) delay time, \( d_0 = \) headway offset.

The Mazda system issues a warning when the range is less than braking distance plus a parameter \( (d_{\text{br}} + \epsilon) \) where \( \epsilon \) is the system parameter. The brakes are applied when the range is less than braking distance \( (d_{\text{br}}) \). This systems attempts to avoid all collisions, even the extreme cases [10]; hence, warnings are issued frequently which could lead to an uncomfortable driving experience. It is noteworthy that in such systems, drivers become desensitised to warnings as such a conservative definition of braking distance intervenes with normal driving scenarios. Honda’s algorithm is also similar to Mazda’s algorithm and is explored in [12].

It is also interesting to mention the work of Malinverno et al. where the performance of a V2I collision avoidance system [13] is assessed. The proposed system relies on two parameters for judgment: TTC and braking distance. It is argued that these two parameters have a huge impact on the performance of the system. For example, relaxing them will lead to a system that triggers many alerts. On the other hand, being strict will lead to a system where collisions are not detected or may be detected late for the AEB to be effective. It is also noteworthy that their work is applicable for human-driven vehicles as well as autonomous ones. Testing is carried out in a virtual simulation environment to evaluate the reliability of the algorithm; these tests showed promising results.

2.2. Braking logics
In literature, there are many approaches to the implementation of the braking logic. In some cases, the braking logic depends on both the velocity and TTC [14] as illustrated in
Table 1. Thresholds calculated for the AEB logic.

| Velocity Region | Collision Level | Brake Profile |
|-----------------|-----------------|---------------|
| LOW             | Avoidance       | TTC < \( t_{LPB} \) | Full Brake |
| HIGH            | Mitigation      | \( t_{LPS} < \) TTC < \( t_{LPB} \) | Pre-Brake |
|                 |                 | TTC < \( t_{LPS} \) | Full Brake |

Figure 1. Alternative Braking Logic [14].

Figure 1. The thresholds reported are calculated as follows:

\[ t_{LPB} = \frac{v_{rel}}{2 \mu g} \text{ (Last Point to Brake)} \]

\[ t_{LPS} = \sqrt{\frac{2s_y}{\mu g}} \text{ (Last Point to Steer)} \]

where \( s_y \) represents relative distance between the vehicles and two velocity regions are considered. On the other hand, the AEB braking logic developed in [15] is TTC dependent:

- if \( 1.6s < \text{TTC} \leq 2.0s \) \( \rightarrow \) \( \text{decreq} = -3m/s^2 \)
- if \( 0.7s < \text{TTC} \leq 1.6s \) \( \rightarrow \) \( \text{decreq} = -6m/s^2 \)
- if \( \text{TTC} \leq 0.7s \) \( \rightarrow \) \( \text{decreq} = -10m/s^2 \)

where \( \text{decreq} \) represents deceleration requested. In their work, Kapse et al. present a detailed Simulink implementation of an AEB algorithm. The AEB logic implements cascaded braking, which consists of two partial braking stages and one full braking stage. It is interesting to note that the AEB logic (transition between stages) does not depend on pre-defined conditions, but rather on dynamic online-calculated thresholds [16]. These thresholds are velocity dependent and are defined based on the braking times, as follows:

\[ t_{\text{threshold,a}} = \frac{V_{\text{ego}}}{\text{dec}_a}, \quad t_{\text{threshold,b}} = \frac{V_{\text{ego}}}{\text{dec}_b}, \quad t_{\text{threshold,max}} = \frac{V_{\text{ego}}}{\text{dec}_\max} \]

where \( \text{dec}_a < \text{dec}_b < \text{dec}_\max \) are three predefined deceleration values. These parameters are combined to obtain the three stages braking manoeuvre:

- \( \text{TTC} < t_{\text{threshold,a}} \rightarrow \text{decreq} = \text{dec}_a \)
- \( t_{\text{threshold,a}} \leq \text{TTC} < t_{\text{threshold,b}} \rightarrow \text{decreq} = \text{dec}_b \)
- \( t_{\text{threshold,b}} \leq \text{TTC} < t_{\text{threshold,max}} \rightarrow \text{decreq} = \text{dec}_\max \)

It is important to note that in literature, most work done on connected ADAS is based on a 4G network. The characteristics of such network reduces the scope of the applicability of the work as the mean communication delay of such systems is noted in literature to
be in the order of hundreds of milliseconds [17,18], which is much higher than milliseconds required [19]. Moreover, the availability and reliability of 4G limits its use to warning systems without actuation.

The use of 5G communications instead of 4G allows incorporating extra information in safety algorithms. Consider the case of a blind-zone intersection: current commercial safety systems rely on radar sensors or GPS information for target vehicle detection. However, for this case, this is not enough or might not be available. 5G facilitates the use of extra sensors that are not usually used in slower forms of communication. For example: a camera feed could be used to detect target vehicles and communicate relevant information with the ego vehicle. Moreover, the high availability and reliability (very low chance of communication failure) of 5G makes it viable to rely on it for actuating the vehicle [19].

3. Description of the set-up

3.1. Current system architecture

The architecture of the current commercial system considered in this work is shown in Figure 2(a).

Figure 2. Overview of Commercial AEB System. (a) Commercial System Architecture (b) Scheme of Commercial AEB Logic.
The ‘Radar Sensors’ block is responsible for perception, computation of TTC, and finally issuing the deceleration request to the braking system module, which in turn regulates the brakes pressure to reach the desired deceleration.

At first, information coming from the Radar Sensors about surrounding vehicles is evaluated to determine if the TTC should be calculated or not. The activation criteria for the AEB feature is the following:

- Target vehicles with orthogonal path: \(45^\circ < |\arctan \frac{v_y}{v_x}| < 135^\circ\)
- Target vehicle with \(|v_y| > 7.2\text{km/h}\)
- Ego vehicle with \(5\text{km/h} \leq v_{ego} \leq 60\text{ km/h}\)

where \(v_y, v_x\) are, respectively, the longitudinal and lateral velocities of the target vehicle. It is important to note that the AEB is intended to operate in *urban areas*. The choice of limiting the orthogonal path of the target vehicle is explained by the fact that the operation of the system is limited to intersection application. For example, the AEB system should not be activated when doing overtakes on a road.

The sensing architecture is composed of only three radar sensors, as reported in Figure 3(b) as well as a measurement of the ego vehicle velocity as provided by CAN. It is noteworthy that the side radars are short range ones (SRR) and the center one is a long-range radar (LRR). The Radar Deceleration Request is issued once the calculation of TTC calculated by the ‘Perception’ Block is < 1.5 s. In this work, the proposed commercial AEB logic provided by the ‘AEB Function’ block in Figure 2(a) is velocity-dependant.

- if \(v \leq v_b \rightarrow d_{\text{ec requested}} = \text{LevelCm/s}^2\)
- if \(v_b < v \leq v_a \rightarrow d_{\text{ec requested}} = \text{LevelAm/s}^2\) for 300 ms, followed by \(d_{\text{ec requested}} = \text{LevelBm/s}^2\)
- if \(v_a < v \leq v_{\text{max}} \rightarrow d_{\text{ec requested}} = \text{LevelAm/s}^2\)

It is important to note that the values of the deceleration levels could not be provided at the request of our research partners. A scheme is provided in Figure 2(b) as an illustration. To fully understand the logic, an example is given as additional support: consider the case where the AEB is triggered and the vehicle is travelling at velocity \(v\) where \(v_a \leq v \leq v_{\text{max}}\). The first stage of braking is A where the vehicle decelerates at level A until the velocity of the vehicle is equal to \(v_a\). Once \(v = v_a\), level A is maintained for an additional fixed \(t\) ms. This is followed by level B deceleration until \(v = v_b\). Lastly, the vehicle decelerates with level C until it reaches a complete stop.

### 3.2. Connected system architecture

The software architecture for the development of the novel connected AEB algorithms is presented in Figure 3(a). Comparing Figure 3(a) with Figure 2(a), several additions could be clearly noted. The system has additional information fed from two sources: the 5G Virtual Sensor as well as the smart tyre. Furthermore, the deceleration request out of the radar commercial system is no longer immediately connected to the braking system module, but rather to an on-board control unit able to manage the deceleration request from both the 5G AEB and the radar AEB.
Figure 3. Overview of Novel Connected System. (a) Connected System Architecture (b) Complete Sensor Configuration for Connected System Architecture.

Note that the radar safety system remains the same as that described in the previous section. It could be seen in Figure 3(b) that the additional sensors mounted on the vehicle of the connected system are the following:

- GPS Sensor with RTK Correction operates at 10 Hz for a global accurate localisation (error < 0.5 m).
- 5G Virtual Sensor receives information about other vehicles as well as potential ground friction (a digital map containing friction potential estimated by the smart tyre sensors of other vehicle who travelled on the road earlier).
• The smart tyre is able to measure the friction potential after braking takes place.
  
  It is noteworthy that through the use of Kalman Filters (for slip estimation), dynamic estimators (for force estimation) and pre-defined reference curves, the friction-identification algorithm is able to provide the friction potential with an accuracy dependent on that of the measurements provided by the accelerometers.

3.3. Testing scenario

The scenario under consideration in this work is described in Figure 4.

It is important to note that the simplified set-up is chosen for two main reasons:

• it is one of the most common intersection crashes schemes;
• it allows the work to concentrate on the power of connectivity and its potential influence on safety systems.

The scenario considered is a blind intersection where the initial velocity of the target vehicle is set to ensure that it crashes with the ego vehicle just before any braking takes place. It is also important to note that it is assumed that the ego vehicle, unlike the target vehicle, can be actuated.

4. Simulink implementation and simulation

4.1. Scheme of connected commercial system

The summary of the developed Simulink model for the two control logics is presented in Figure 5. It is seen earlier that Figure 3(a) contains all elements present in Figure 2(a). Hence, Figure 5 is considered to be a schematic representation of Figure 3(a) (Connected System Model block) or Figure 2(a) alone (Current System Model block with the rest of the blocks deactivated).

![Figure 4. Scenario under consideration in the development and testing of the AEB systems.](image)
4.1.1. Current system model

As an initial step, the current system architecture (as modelled in Figure 2(a), and illustrated in 5) is modelled in the simulation software.

For the perception block, information from the radars of the ego vehicle about surrounding visible vehicles is analyzed to determine whether to activate the TTC Calculation block or not (according to the activation criteria defined in Section 3.1).

For the purpose of this work, Miller and Huang [20] and Jiménez et al. [21] are used to build the TTC calculation block in the Simulink model. The equations can be easily adjusted to take into consideration that the radar gives information relative to the ego vehicle reference frame. The point at which the intersection can be given by the following expressions, given by Equations (4) and (5). It is important to note that the IMU block is the inertial measurement unit that provides the logic with information about the ego vehicle velocity.

\[
x_+ = \frac{(y_{ego} - y_{target}) - (x_{ego} \cdot \tan \theta_{ego} - x_{target} \cdot \tan \theta_{target})}{\tan \theta_{target} - \tan \theta_{ego}}
\]

\[
y_+ = \frac{(x_{ego} - x_{target}) - (y_{ego} \cdot \cot \theta_{ego} - y_{target} \cdot \cot \theta_{target})}{\cot \theta_{target} - \cot \theta_{ego}}
\]

After finding the intersection point, the Time-to-Reach (TTR) values for each vehicle can be obtained by Equations (6), (7):

\[
TTR_{target} = \sqrt{\frac{(x_+ - x_{target})^2 + (y_+ - y_{target})^2}{v_{target}}}
\]
\[ TTR_{\text{ego}} = \sqrt{(x_+ - x_{\text{ego}})^2 + (y_+ - y_{\text{ego}})^2} \]  
\[ v_{\text{ego}} \]  
\( (7) \)

To consider a more realistic case, it cannot be said that the vehicles will crash only when \( TTR_{\text{target}} = TTR_{\text{ego}} \). Hence, it could be said that \( \delta \) is a safety parameter described by Equation (8), such that:

\[
\text{TTC} = \begin{cases} 
\min(TTR_{\text{target}}, TTR_{\text{ego}}) & \text{if } |TTR_{\text{target}} - TTR_{\text{ego}}| \leq \delta \\
\text{NaN} & \text{else}
\end{cases}
\]

\( (8) \)

To achieve similar performance between the simulated system and the reference real one provided by our partners, an expression of \( \delta \) as a function of speed is reached by tuning the system to achieve the results described in Figure 6(b) and (d).

In the latter figures, the white square means that the collision is avoided using the radar AEB logic, and the dark coloured square means that a collision occurred. The tuning of \( \delta \) is done taking into consideration speeds of vehicles that yield different collision configurations.

It is important to note that the AEB logic (discussed earlier in Section 3.1) is a temporal one. Hence, it required a finite state machine (FSM) implemented by means of Stateflow on MATLAB.

The acceleration controller block is a discrete PI controller with integral anti-windup that provides the value of the required brake pedal (between 0 and 1) to achieve the desired deceleration value. As illustrated in Figure 7, the control signal is calculated using the backward Euler discretisation method (where the gains were tuned), as given by Equations (9) and (10):

\[
\begin{align*}
u(k) &= \text{sat}\left( p_{\text{gain}} \Delta a_x + \text{sat}\left( i_{\text{gain}} \frac{T_s z}{z - 1} \Delta a_x, A, B \right), A, B \right) \\
\text{sat}(x, A, B) &= \min(\max(x, A), B)
\end{align*}
\]

\( (9) \)

\( (10) \)

Where \( p_{\text{gain}} 0.001, i_{\text{gain}} 0.001, T_s 0.001 \text{ s} \), A Lower Limit of Saturation (1), B Upper Limit of Saturation (0).

It is important to note that the acceleration controller module is activated only when the AEB is taking place. Note that for our work, it is required that the driver can no longer press the gas when the AEB takes into action.

4.1.2. Connected system model: type A

The connected system architecture shown in Figure 3(a) is reached by making modifications to the previously developed Simulink model to take into consideration information from GPS, 5G and Smart tyre. It is important to note that the activation criteria remains the same for both the radar and 5G systems, as it is a characteristic of the type of collision the system is aimed at avoiding.

Concerning 5G communications characteristics, literature suggests that the maximum value of delay accepted for this kind of applications is 10 ms. This guarantees the minimum safety requirements [19]. The exact characteristics of the 5G network provided by
Figure 6. Description of Open Field Case and Obstructed Field Case. (a) Open Field Scenario. (b) Open Field Results. (c) Obstructed Field Scenario. (d) Obstructed Field Results.

Vodafone were used in the development; however, they could not be mentioned here for confidentiality purposes.

Concerning the GPS information, the simulation software allows the modelling of the following errors:

- **Receiver Clock Error**: Arises because the receiver clock is not always synchronised with that of satellites. Standard deviation = 5 m with Correlation time = 3600 ms.
- **Ephemeris Error or Orbit Error**: Arises because of the small variations of the orbits of travel of the GPS satellites. Standard deviation = 3 m with Correlation time = 1800 ms.
- **Ionospheric Delay**: Arises because of ions in the ionosphere. Standard deviation = 5 m with Correlation time = 3600 ms.
Figure 7. Acceleration Control Architecture.

- **Tropospheric Delay**: Arises because of the refractions of the signal due to the variations of atmospheric conditions. Standard deviation = 2 m with Correlation time = 1800 ms.
- **Receiver Noise**: Pseudorange = 0.1 m, and Rated range = 0.05 m.

Concerning the smart tyre, it is mentioned earlier that it is able to provide information about the friction potential after braking takes place. Hence, the use of this information is not optimal for the commercial braking logic, as it is a static velocity-dependent logic. For example, even if the friction potential is measured to be low while braking is taking place, nothing can be done about it. Considering the current AEB logic, it is clearly seen that the nature of the logic prohibits utilising the ego Vehicle’s smart tyre to its full potential.

As an initial attempt to utilise information about friction potential, it is assumed that it is available from an active map. This assumption is realistic, for example, in a scenario where several vehicles are driving in the same area and sharing their friction potential estimation that is so collected in an active map available to the ego vehicle. For this reason,
it is reasonable to include braking distance in the logic. The scheme is shown in Figure 8. Now, the trigger to the system is no longer the TTC only, but also the braking distance. If the braking distance becomes equal to a certain threshold related to the distance to the collision point, the braking manoeuvre takes place.

It is noteworthy that the parameters of the braking logic were not modified: this first novel approach assumed that the ECU containing the AEB logic cannot be modified. In fact, this approach can be considered as an add-on with respect to the commercial configuration with the minimum modification required. The braking distance is calculated based on the braking scheme originally described in Figure 2(b). The maximum deceleration level is modified based on the friction potential measurement, as described in Figure 9, and then the braking distance is calculated by performing numerical integration.

It could be seen that the scheme provided in Figure 8 complies with the system architecture provided in Figure 3(a). Here, information coming from 5G about the position and speed of nearby vehicles is used to evaluate TTC, and the braking distance (BD) based on the received friction potential. Once either one of the triggers is activated, a deceleration request is sent to the acceleration controller.

4.1.3. Connected system model: type B

This approach entails a deeper modification of the vehicle original hardware and software configuration in order to obtain better results in terms of safety. In an attempt for further development, braking logic block is modified. The reasoning behind this is that the current braking logic does not facilitate incorporating information received from the smart tyre. It is important to explore the option of giving the vehicle a reference deceleration that is adaptable to the road conditions: for example: increases exponentially throughout the braking manoeuvre. This approach tries to mimic the commercial braking logic, in that the braking logic requests an initial deceleration value of around 30% of the maximum possible deceleration, and reaches 80% of its maximum value (this allows the driver to still have control on the vehicle at maximum braking). The formulation is given by Equation (11):

\[ a(t) = A e^{\alpha t} \]  

Where \( A = - \max (k \min \mu g, a_{\text{current}}) \). The velocity profile is given by Equation (12):

\[ v(t) = v_0 + \int_0^t a(t) \, dt \]

\[ = v_0 + \frac{A}{\alpha} e^{\alpha t} - \frac{A}{\alpha} \]
The displacement of the vehicle is given by Equation (13):

\[ s(t) = \int_0^t v_0 + \frac{A}{\alpha} e^{\alpha t} - \frac{A}{\alpha} \, dt \]

\[ = \frac{A}{\alpha^2} e^{\alpha t} + Bt + C \quad (13) \]

Now, it is considered that the vehicle must reach a complete stop at time \( T \) (\( v(T) = 0 \)), such that \( a(T) \geq -\gamma_{\text{max}} \mu g \) and \( s(t) \leq d \), where \( d \) is the distance to the intersection and \( k_{\text{min}} \) and \( \gamma_{\text{max}} \) are tunable safety parameters that set the minimum and maximum reference decelerations the system issues. Due to complex nature of the problem, the following approach is considered, as seen in Figure 10:

At every loop, the \textit{trigger} block solves the following to get values of \( \alpha \) and \( T \):

\[ v(T) = 0, \quad s(T) = d \]

Once the values of \( \alpha \) and \( T \) are obtained, \( a(T) = A e^{\alpha T} \) is calculated. If \( a(T) \geq \gamma_{\text{max}} \mu g - a_{\text{tuned}} \) (where \( a_{\text{tuned}} \) is a certain threshold that is tuned, for our case it is \( 1 \text{ m/s}^2 \)), then the trigger is activated and the braking manoeuvre is initiated.

It could be seen that characteristics of the smart tyre (providing an estimate of the value of friction potential at the moment of braking) presents a drawback to the system. However, the advantage here is that the system is somehow adaptable, providing a higher deceleration value as a compensation. The adaptability of the system is highly affected by the value of \( a_{\text{tuned}} \).

5. Simulation testing results

5.1. Upgraded system type A: normal friction potential environment

The test is carried out with a friction potential coefficient equal to 0.85. The results present are for the case when both vehicles approach the intersection traveling at 60 km/h. It is
noteworthy that the system is tested for all velocity combinations as outlined in Figure 6(d). However, as a choice of displaying results in this paper, the case of having both vehicles traveling at high velocities is chosen, as it is usually the case causing collision without connectivity as well as with low friction potential. The modified system is tested in a normal friction potential conditions, as seen in Figure 11(a). It could be clearly seen in 11(b) that the maximum deceleration a vehicle can reach in normal friction potential conditions is approximately 8.3 m/s².

From Figure 11(a) it could be seen that the vehicle avoids the collision. Also, the vehicle approaches the intersection at a reduced speed, and the stopping takes place before the pre-defined collision point; this is quite important as the AEB action turns off when the vehicle reaches a complete stop.

Figure 11(b) shows the deceleration request as well as the actual one. Note that the value of −15 m/s² is the equivalent of no deceleration request. It could be seen in Figure 11(b) and (c) that once the condition described in Equation (8) is satisfied, the AEB system is activated.

5.2. Upgraded system type A: low friction potential environment

The modified system is tested in a low friction potential condition (μ = 0.4).

From Figure 12(a), it is seen that the vehicle avoids the collision. Also, the vehicle approaches the intersection at a reduced speed, and the stopping takes place before the
pre-defined collision point. Furthermore, comparing Figures 11(c) and 12(c), it could be seen that in low friction potential, the braking starts 34 m and 44 m before the predicted collision point, respectively.

It could be seen in Figure 12(b) that the vehicle is unable to reach the deceleration requested as a result of the ground condition. It is clear that the only way for the system to avoid the collision in this case is activating the AEB system earlier thorough the braking distance calculation which utilises a priori knowledge about friction potential. The difference could be clearly seen when comparing Figures 11(c) and Figure 12(c).

5.3. **Upgraded system type B: normal friction potential environment**

It could be seen from Figure 13(b) that the braking manoeuvre follows an exponential deceleration scheme. Hence, with respect to the stepped scheme in System A, System B provides a smoother profile that reflects an improvement in driving comfort.

When inspecting Figure 13(a), it could be seen that the vehicle successfully avoids the collision. Also, the vehicle stops completely before the collision point.

5.4. **Upgraded system B: low friction potential environment**

5.4.1. **Friction potential known A priori**

It would be interesting to investigate the case where the low friction potential value ($\mu = 0.4$) is known before the braking manoeuvre takes place.
It could be seen that the vehicle successfully stops before the intersection, and avoids the collision. It could be seen from Figure 14(b) that the braking manoeuvre is smooth and comfortable. When comparing the performance of System B in low friction potential case with that of System A Figure 12(b), it could be seen that the system manages to stop further away from the intersection. On the other hand, the tunability of System B allows the vehicle to be more under control (steerable) since the maximum value of deceleration requested can be set well below the maximum friction limit.

5.4.2. Friction potential retrieved from an active map

In this last case, a more realistic scenario is presented. Considering the presence of an active map containing inaccurate friction potential estimates (due to several possible factors such as old data, measurements errors, etc.). The value provided by the map ($\mu = 0.6$) is higher than the real value ($\mu = 0.4$).

It could be seen that with respect to the latter situation (as in Figure 14(b)), the system starts braking later. However, the maximum possible deceleration is reached as fast as possible to ensure that the collision is avoided. It could be seen that the safety is improved as the system is now more adaptive to the environmental conditions (Figure 15).

6. Conclusion

To conclude, the aim of this work is the following:
Figure 14. System Type B: Low Friction Potential, (a) Screenshots in Chronological Order: System Type B, Low Friction Potential. (b) Desired Deceleration vs. Actual Deceleration (c) Ego Vehicle Velocity vs. Distance to Collision Point.

Figure 15. System Type B: Low Friction Potential, (b) Desired Deceleration vs. Actual Deceleration (c) Ego Vehicle Velocity vs. Distance to Collision Point.(a) Screenshots in Chronological Order: System Type B, Low Friction Potential.
develop and test two novel intersection collision avoidance systems that rely on information from 5G, radar sensors, and a smart tyre;

• test the usability of 5G in safety systems of connected vehicles.

As presented in the paper, state-of-the-art AEB systems usually issue a predefined braking request based on a static trigger. The advantage of such existing systems is the simplicity which reflects the simple hardware and reduced costs. Starting from these consideration, a novel approach consisting of an upgrade of the original architecture in order to limit costs of the design of new hardware and software, is presented. While keeping the same braking logic adopted in the radar system, an additional trigger is added to enable braking based on braking distance. The results of the virtual testing have been positive in both normal friction potential and low friction potential environments. In order to fully take advantage of the friction potential estimate, a second novel AEB control logic able to adapt itself during the braking is proposed. In detail, a braking scheme with an exponential-scheme is adopted as it ensures smooth braking as well as high robustness and adaptability to road conditions as shown by virtual simulations and comparison to the previous AEB proposed. However, due to the complex nature of the equations to be solved (to find $T$ and $\alpha$), the system requires much higher computational power. Also, the tuning of the parameter $a_{tuned}$ presents a disadvantage, as setting a high value will make the system start braking very early but the system will be more robust, and setting it very low will make system start braking at normal time but this will limit robustness.

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