Vehicle-to-Vehicle Communications for Platooning: Safety Analysis

Johan Thunberg, Nikita Lyamin, Katrin Sjöberg, and Alexey Vinel

***Abstract*—Vehicle-to-vehicle (V2V) communication is the key technology enabling platooning. This letter proposes an analytical framework that combines the characteristics of V2V communication (packet loss probabilities and packet transmission delays) with the physical mobility characteristics of vehicles (speed, distance between vehicles and their brake capacities). First, we present the feasible region of communications delays which guarantees safe emergency braking in platooning scenarios. Second, we derive a bound on the probability of safe braking. The presented framework is applied to understand the performance of the state-of-the-art V2V communication protocol for platooning.**

***Index Terms*—Platooning, safety, emergency braking, cooperative intelligent transport system (C-ITS), vehicle-to-vehicle (V2V) communications, dedicated short range communications (DSRC), ITS-G5.**

I. INTRODUCTION

A PLATOON consists of a number of highly automated vehicles following each other with a preset time headway [1], where vehicle-to-vehicle (V2V) communication provides the means to pull vehicles together. Shorter inter-vehicle distances enable slipstream effects contributing to better fuel efficiency, which in certain scenarios can be substantial, especially, for heavy duty vehicles [2], [3]. V2V complements other on-board sensors such as radar and camera by providing instantaneous status updates of vehicles beyond line-of-sight. This, in turn, increases the string stability of the system of vehicles travelling together, when compared to traditional adaptive cruise control (ACC) solutions solely based on radar [4]. The increased stability leads to a more safe operation. Shock-waves propagating through traffic is a sign of a system that is not string stable; vehicles are travelling too close to each other without the necessary information about what is happening upstream [5].

Platooning with trucks is one of the first connected and automated driving functionalities (cooperative intelligent transport systems, C-ITS) that will see the day of light. The first truck will be driven manually (i.e., the driver will be in the loop) and the rest of the trucks in the platoon will be automatically controlled longitudinally as well as laterally based on sensor information (V2V, radar, camera, etc.). There is a tight coupling between the performance of V2V communication and the resulting safety of the platoon, which is addressed in this letter.

Safety of braking in platoon-like vehicular formations is analyzed in [6], where the authors make a simplified assumption about constant V2V communication delays. Similarly, in [7] all the vehicles start braking simultaneously some milliseconds after the first one sends a brake command. Safety analysis in non-emergency braking scenarios from an automatic control perspective are addressed in [8]. Safe inter-vehicle distances are derived by solving a pursuit evasion dynamic game. It can be seen as an extension of the early works on collision avoidance, see, e.g., [9], to the more general platooning scenario under more realistic modelling of vehicle dynamics. Related simulation results for emergency braking are presented in [10], while this letter focuses on the analytical modeling. This letter differs from those above, in that we do not provide safe inter-vehicle distances. Instead we derive safe regions of communication time-delays. Furthermore, our approach is analytic and not based on simulations.

Our main contributions are summarized as follows:

- first, a feasible region of communication delays guaranteeing safe emergency braking in a platoon is analytically determined.
- secondly, a lower bound on the probability of a safe braking is derived.

The developed approach is used to evaluate the proposed V2V platooning protocol within the European research project ENSEMBLE [11], and scrutinizes for which situations it can handle harsh braking given the proposed message generation rate.

This letter is organized as follows. The system model is detailed in Section II and the safety analysis is developed in Section III, while numerical results are presented in Section IV. Finally, conclusions and future research directions are outlined in Section V.

II. SYSTEM MODEL

Let us consider a platoon of N vehicles moving at a constant speed v_0. The vehicles are enumerated from the front of the platoon, Fig. 1. The inter-vehicle distance between the i-th and the $(i+1)$-th vehicles is d_i. Each vehicle i has a maximum braking capacity with an absolute value a_i (the a_i's may differ among the vehicles).[1] Different braking capabilities are assumed due to road and weather conditions, trailer load, the status of brakes, the condition of tires, etc.

An emergency braking scenario is considered, where the first vehicle applies constant maximum deceleration and with time period T (i.e., frequency $f = 1/T$) starts transmitting packets with the warning over the dedicated communication

[1] The specific case $N = 2$ and $a_1 = a_2$ is considered earlier in [12].

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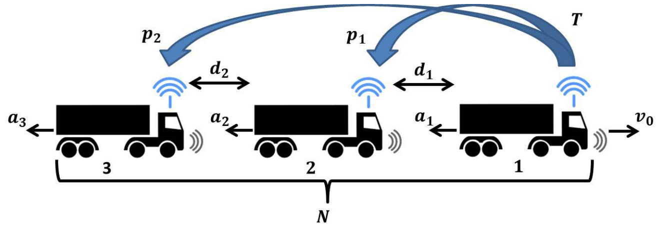

Fig. 1. Main notation of the system model.

channel. When the *i*-th vehicle receives the packet, it immediately starts braking by also applying its constant maximum deceleration.

The *i*-th vehicle either receives the packet with probability $1 - p_i$ or does not receive it with probability p_i. All packet receptions are independent. For each vehicle, the packet loss probability p_i remains constant during the entire braking process. This is realistic since distances d_i are small with respect to the length of vehicles and the platoon.

III. Safety Analysis

Four index sets for the vehicles are introduced: $I_N = \{1, 2, \ldots, N\}$, $I_N^+ = \{i \in I_N : a_i > a_{i+1}\}$, $I_N^- = \{i \in I_N : a_i < a_{i+1}\}$, and $I_N^0 = \{i \in I_N : a_i = a_{i+1}\}$. The delay is from the moment when the first vehicle starts braking and transmits a message until this message is successfully received by the *i*-th vehicle. Let $\tau = [\tau_1, \tau_2, \ldots, \tau_{N-1}]^T$ be the delays between vehicle 1 to vehicle 2 up to *N*, respectively (vehicle 1 does not have any delay, and thus it is left out). $\tau_{\max} = [\tau_{\max}^1, \tau_{\max}^2, \ldots, \tau_{\max}^{N-1}]^T$ is the vector of maximum delays guaranteeing safe braking between consecutive vehicles **independent** of τ. This means that whatever the choice of τ_{i-1}, as long as $\tau_i \leq \tau_{\max}^i$, there will be no crash (safe braking) between vehicle i and vehicle $i+1$. Subsequently $\tau_{\max}$ is used to define the largest feasible region of τ's guaranteeing safe braking and which **depends** on τ. This region is given as a polytope.

The following result about $\tau_{\max}$ is provided below. The next result, specifying the polytope of the feasible region, is given immediately after the proof.

Proposition 1: For each *i*,

1) $\tau_{\max}^i \geq \min\{\frac{d_i}{v_0}, \frac{d_i}{v_0} + \frac{v_0}{2}(\frac{1}{a_i} - \frac{1}{a_{i+1}})\}$,

2) $\tau_{\max}^i = \min\{\tau_{\max}^{i,0}, \tau_{\max}^{i,+}, \tau_{\max}^{i,-}\}$ where

$$\tau_{\max}^{i,0} = \frac{d_i}{v_0} \text{ if } i \in I_N^0, \text{ else } +\infty,$$

$$\tau_{\max}^{i,+} = \frac{d_i}{v_0} + \frac{v_0}{2}\left(\frac{1}{a_i} - \frac{1}{a_{i+1}}\right) \text{ if } i \in I_N^+, \text{ else } +\infty,$$

$$\tau_{\max}^{i,-} = \begin{cases} \sqrt{\frac{2d_i(a_{i+1}-a_i)}{a_{i+1}a_i}} & \text{if } \sqrt{\frac{2d_0 a_{i+1}}{a_i(a_{i+1}-a_i)}} \leq \frac{v_0}{a_i}, \\ \frac{d_i}{v_0} + \frac{v_0}{2}\left(\frac{1}{a_i} - \frac{1}{a_{i+1}}\right) & \text{else,} \end{cases}$$

$$\text{if } i \in I_N^-, \text{ else } +\infty.$$

1) provides a lower bound that can be shown to be tight for most practical scenarios. 2) has a somewhat more complicated structure, but can be shown to be a tight bound for all scenarios.

Proof: Let x_i and y_i be the front position and rear position of vehicle *i*, respectively.

1) Safe braking or collision avoidance is to guarantee that it does not exist *t* and $i \in I_N$ such that $y_i(t) - x_{i+1}(t) < 0$. If the delay for vehicle *i* is $\tau_i > 0$, then the maximal allowable delay for vehicle $i+1$ is larger than if τ_i would be 0. Thus, to compute $\tau_{\max}^{i+1}$, the following assumption is made: $\tau_i = 0$. In the following within this proof, to simplify notation at the expense of overloading it, $i+1$ is referred to as *j* and τ_i is referred to as τ.

Suppose $i \in I_N^0$. For this case it has already been established [12] that $\tau_{\max}^i = \frac{d_i}{v_0}$.

Suppose $i \in I_N^-$. Let $x_j^0(t)$ be an alternative solution to $x_j(t)$, where a_j has been made smaller to be equal to a_i. It holds that $x_j^0(t) \geq x_j(t)$ for $t \geq 0$, i.e., x_j^0 dominates x_j. Formally this can be shown by using the Comparison Lemma [13]. Thus, $\tau_{\max}^{i,-} \geq \frac{d_i}{v_0}$.

Suppose $i \in I_N^+$. This situation requires more analysis but without loss of generality it is assumed that $x_j(0) = 0$ and $y_i(0) = d_i$. The trajectories of vehicle *i* and *j* are split into two respective three segments, see Fig. 2 for an illustration. The two segments of vehicle *i* are defined as

Segment 1: $[y_i(t) = d_i + v_0 t - \frac{a_i t^2}{2}, \quad 0 \leq t \leq \frac{v_0}{a_i}],$

Segment 2: $[y_i(t) = d_i + \frac{v_0^2}{2a_i}, \quad \frac{v_0}{a_i} \leq t].$

The three segments of vehicle *j* are defined as

Segment 1: $[x_j(t) = v_0 t, \quad 0 \leq t \leq \tau],$

Segment 2: $[x_j(t) = v_0 t - \frac{a_j(t-\tau)^2}{2}, \quad \tau \leq t \leq \tau + \frac{v_0}{a_j}],$

Segment 3: $[x_j(t) = v_0\tau + \frac{v_0^2}{2a_j}, \quad \tau + \frac{v_0}{a_j} \leq t].$

In the definitions of the (in total) five segments above, overlapping end points are included to simplify the analysis.

There are potentially six ways that the two trajectory segments of vehicle *i* can intersect the three trajectory segments of vehicle *j*. Let the pair (*k*, *l*) represent a crossing between Segment *k* of vehicle *i* and Segment *l* of vehicle *j*. The notation "·" represents the set of all segment indices and the usage should be clear by the context.

As it turns out, five of the segment crossings can be omitted and focus is restricted to (2, 3). Intersections (·, 1) are the easiest to discard, and the details are omitted. By using the property that $a_j < a_i$, it can be shown that it is enough to consider the intersection (2, 3). Suppose that (·, 2) happens, then $x_j(t)$ in Segment 3 of vehicle *j* is larger than (the constant) $x_i(t)$ in Segment 2 of vehicle *i*; also, both x_j and y_i are monotonically increasing. Thus, the problem can be reduced to finding the largest τ such that (2, 3) does not happen. For illustration purposes a (2, 3) intersection is depicted in Fig. 2, where vehicle 1 (first vehicle in the platoon) transmits a message about emergency braking at *t* = 0 and after some communication delay the second vehicle will receive this message. There is a distance (*y* axis) between the vehicles from the beginning, which decreases as time (*x* axis) goes by due to the communication delay. If the two vehicles' trajectories in Fig. 2 cross each other then there will be a rear-end collision.

Now let us consider the intersection (2, 3) in detail. The smallest τ needs to be computed such that the following

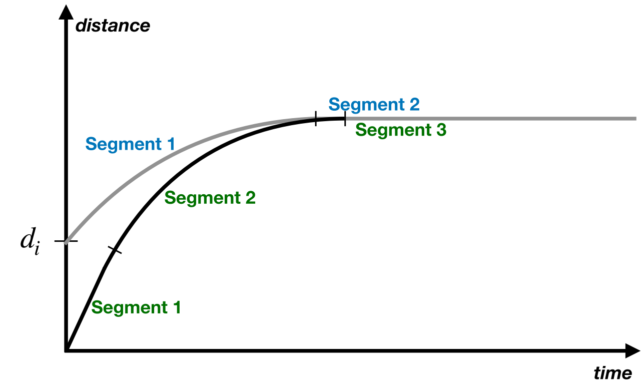

Fig. 2. Illustration of a (2, 3) intersection. Blue color is used for the segments of y_i and green color is used for the segments of x_j.

inequality holds.

$$d_i + \frac{v_0^2}{2a_i} \leq v_0\tau + \frac{v_0^2}{2a_j}.$$

The τ is given by

$$\tau = \frac{d_i}{v_0} + \frac{v_0}{2}\left(\frac{1}{a_i} - \frac{1}{a_j}\right) \tag{1}$$

Thus $\tau_{\max}^{i,+} = \frac{d_i}{v_0} + \frac{v_0}{2}(\frac{1}{a_i} - \frac{1}{a_{i+1}}) \leq \frac{d_i}{v_0}$. Thus, the proof of **1)** is concluded.

2) The right-hand side of (1) can be used for all i and is not restricted to I_N^+. However, for I_N^- it does not necessarily provide the tightest bound. To provide a tight bound, the intersection (1, 2) needs to be considered. For $i \in I_N^+$ an event can occur which we refer to as a *touch*. In such a case x_j becomes equal to y_i at some time when $\dot{y}_i > 0$, i.e., they touch each other, after which y_i grows larger than x_j again. Now, such an event can only happen if the condition

$$\sqrt{\frac{2d_0 a_j}{a_i(a_j - a_i)}} \leq \frac{v_0}{a_i} \tag{2}$$

is fulfilled. If (2) is not fulfilled, the maximum delay τ attains the familiar form given by (1). However, if (2) is fulfilled, such a τ given by (1) would lead to collision and the maximum delay has to be strictly smaller than that. The maximum delay is then instead given by

$$\tau = \sqrt{\frac{2d_i(a_j - a_i)}{a_j a_i}} \tag{3}$$

The expressions are obtained in the following manner. We consider the equation

$$d_i + v_0 t - \frac{a_i t^2}{2} = v_0 t - \frac{a_j(t-\tau)^2}{2}, \tag{4}$$

which is the intersection equation for intersections of type (1, 2). By using this equation, we compute the τ that leads to a candidate touch, which attains the form (4). This τ serves as a candidate for a tight upper bound. With this τ, we compute the time t_c at which this touch occurs. That t_c comprises the left-hand side of (2).

To guarantee that this touch actually happens between segments 1 and 2 of the trajectories, we need to make sure that the derivatives with respect to *t* at time t_c of the expression at the left-hand side respective the expression at the right-hand side of (4) are both positive. Should this not be the case, the touch would have happened after the starting time of trajectory segment 2 of y_i. The problem can be reduced to verifying that the derivative of the left-hand expression is positive at the time t_c. The intuition behind this is that y_i dominates x_j and the trajectories are both concave; if the two trajectories touch at a point, their derivatives are the same at those points. Now, the derivative of the left-hand side expression becomes 0 at time $\bar{t}_c = \frac{v_0}{a_i}$. Thus, if $t_c \leq \bar{t}_c$, the derivative is positive, see (2). ■

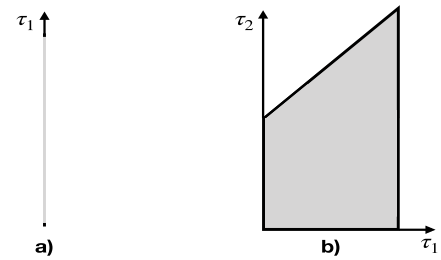

Fig. 3. Geometric illustration of Π for dimensions 1 and 2, respectively.

Now, it turns out that τ_{max} can be used to define the entire feasible region of τ_i's that guarantees safe braking. The feasible region is denoted as $\Pi \subset \mathbb{R}_+^{N-1}$.

Proposition 2: The feasible region of delays which guarantee safe-braking in a platooning scenario is $\Pi = \{[\tau_1, \tau_2, \ldots, \tau_{N-1}]^T \in \mathbb{R}_+^{N-1} : 0 \leq \tau_1 \leq \tau_{\max}^1, 0 \leq \tau_i \leq \tau_{i-1} + \tau_{\max}^i \text{ for } i \in I_N \backslash 1\}$.

Note that the feasible region is a convex polytope, i.e., it is defined by linear inequality constraints.

To the left in Fig. 3, the feasible region for $N = 2$ are depicted (showing the maximum tolerable communication delay between vehicle 1 and vehicle 2 to avoid rear-end collision). Thus, there is only one delay to consider and the region of feasible τ's is depicted by the gray line segment in a). The feasible region for when $N = 3$ is shown to the right in Fig. 3, and there are two τ's, i.e., τ_1 and τ_2 representing delays between vehicle 1 and vehicle 2, and vehicle 1 and vehicle 3, respectively. Thus, combination of delays inside the polygon are feasible guaranteeing safe braking.

In Fig. 4, numerical simulations have been performed to verify the boundary of the feasible region. In this figure, a three truck platoon is used where the vehicle with the best braking capability is placed first and the maximum allowable communication delays are derived resulting in a polygon. Distances of 12-17 meters have been used between the trucks. The communication delays, τ_1 and τ_2, inside the polygon will result in a safe braking (no rear-end collisions).

Finally, a lower bound on the probability of safe braking $Q = \Pr\{\tau \in \Pi\}$ is provided, i.e., the probability that vehicles do not collide during an emergency braking.

Proposition 3: Safe braking probability Q justifies[2]

$$Q^* = \prod_{i=1}^{N-1} [1 - (1 - p_i)^{\lfloor \frac{\tau_{\max}^i}{T} \rfloor}] \leq Q.$$

given that $\tau_{\max}^i \geq T$ holds for each i.

Proof: From the definition of a feasible delay region it directly follows that $\prod_{i=1}^{N-1} \Pr(\tau_i \leq \tau_{\max}^i) \leq Q$. Condition

[2]Both 1) and 2) bounds from Proposition 1 can be applied here and it only impacts the precision of the lower bound.

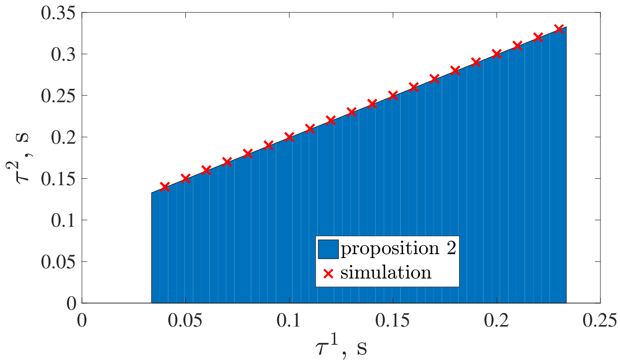

Fig. 4. Geometrical illustration of proposition 2. $N = 3$; $V_0 = 25$ *m/s*; $a = [4.5, 4, 3.5]$ *m/s*^{2}; $d_1 = \cdots = d_N = d_0 \in [12, 17]$ *m*.

$\tau^i_{\max} \geq T$ reflects the fact that at least one packet transmission attempt should be possible to get accomplished within a feasible delay region. ∎

IV. Numerical Results

A V2V platooning protocol is currently being developed within the European research project ENSEMBLE [11], collecting all European truck manufacturers. The first version of this protocol is publicly available in Deliverable 2.8 [14] and the V2V platooning protocol will be brought into standardization during the second half of 2019.

The selected V2V technology for communication between trucks in ENSEMBLE is ITS-G5, a.k.a. dedicated short range communications (DSRC) or IEEE 802.11p [15], [16], described in ETSI EN 302 663 [17] and the project benefits from the already standardized lower-layer protocols developed for supporting road traffic safety applications, so-called ”day one services” [18].

This V2V platooning protocol specifies messages for steady-state platooning as well as messages for joining and leaving a platoon. The steady-state message is called platooning control message (PCM) and contains, amongst other things, the acceleration of the vehicle. All vehicles participating in the platoon broadcast this message with a frequency of $f = 20$ Hz (i.e., $T = 50$ ms).[3]

Fig. 5 and Fig. 6 demonstrates the lower bound on the safe braking probability, Q, for different inter-vehicular distances $d_1 = \cdots = d_N = d_0$. The packet loss probabilities, p_i, account for both the collision probability of the IEEE 802.11p protocol and the path loss effects. The former is computed using the method presented in [19], while the latter corresponds to V2V measurements in a platooning setup reported in [20], collectively called packet error rate (PER) in the plots. In Fig. 5, vehicles are ordered according to their increasing braking capability, a_i. Thus the vehicle with the “worst” braking performance is the first vehicle and the last vehicle of the platoon has the “best” braking capability. In this setting, a Q values close to 1 are reached for a distance just below 2 meters between the vehicles for a 5-vehicle platoon and when 10 vehicles participate in the platoon, the safe braking capability of 1 is reached between 5-6 meters. The PER is determining the

[3]It is assumed that only the first vehicle generates a PCM containing the harsh braking value and does it synchronously with the beginning of the braking. Actually, calculated feasible region of communication delays is not influenced by this simplification, while stochastic analysis can be adjusted to include this initial system reaction delay component.

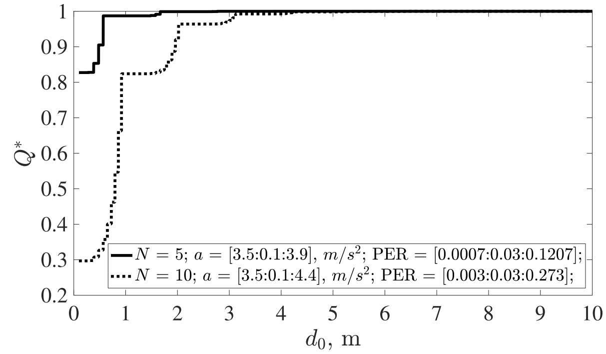

Fig. 5. Platoon ordering ($a_1 < \cdots < a_i < \cdots < a_N$) $V_0 = 22$ *m/s*, $f = 20$ Hz.

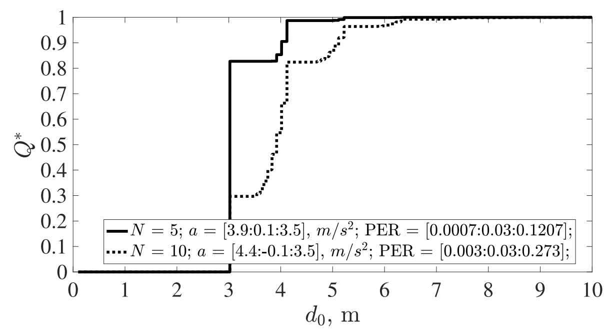

Fig. 6. Platoon ordering ($a_1 > \cdots > a_i > \cdots > a_N$) $V_0 = 22$ *m/s*, $f = 20$ Hz.

necessary distance between the vehicles to reach Q close to 1. The communication scenario in a platoon exhibits in general low PER due to that at least two antennas will be used on each truck, mounted on each side of the cabin or in the wing mirrors. This implies more or less always line-of-sight between transmitter and receiver antennas and given the default output power results in a favorable communication environment.

In Fig. 6, the vehicles are ordered reversely in terms of braking capability, a_i, where the vehicle with the “best” braking capability is the first vehicle and the vehicle with the “worst” braking capability is the last one. This results in that longer distances are a necessity between the trucks to reach a safe braking capability close to 1. Currently, a minimum time gap between the trucks of 0.8 second is perceived in the ENSEMBLE project as outlined in Deliverable D2.2 [21] and this corresponds to a distance of 17 meters when the platoon speed is set to 22 m/s. Thus, the ENSEMBLE protocol achieves a safe braking probability close to 1 for the settings provided herein even with a 10-vehicle platoon where the best braking truck is the leader.

V. Conclusion

Platooning holds great promise of increasing both road traffic safety as well as efficiency but the functional safety analysis of it is still benighted. This letter makes an attempt to analytically elaborate on maximum tolerable communication delays to guarantee safe emergency braking in platooning by combining V2V communication with simple vehicle dynamics (speed, acceleration capability, distance between vehicles). The framework is used to evaluate the platooning protocol approach developed in the research project ENSEMBLE, where a minimum distance of 0.8 seconds between the trucks is foreseen with a maximum platoon speed of up to 80 km/h and all platoon members will transmit messages with 20 Hz in steady-state platooning (including the important acceleration parameter). Our numerical and analytical results reveal that the ENSEMBLE approach can reach a safe emergency braking probability close to 1.

The following directions are considered for the future work:

- Derivation of a safe braking probability in addition to its lower bound which was provided here.
- Incorporating more realistic vehicles dynamics model, e.g., time-varying decelerations.
- Linking of the developed framework to the ISO 26262 functional safety analysis framework [22].

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