Exploring Safety in Platoons of Connected Autonomous Vehicles: Investigating Emergency Braking Conditions and Collision Severity

Seshadri Naik Moode*[1], Francesc Soriguera[2], Xiaoyu Zheng[1], Margarita Martínez-Díaz[3]

[1] PhD candidate, Barcelona Innovative Transportation, Department of Civil and Environmental Engineering, UPC BarcelonaTech, Spain.

[2] Associate Professor, Barcelona Innovative Transportation, Department of Civil and Environmental Engineering, UPC BarcelonaTech, Spain.

[3] Assistant Professor, Barcelona Innovative Transportation, Department of Civil and Environmental Engineering, UPC BarcelonaTech, Spain.

SHORT SUMMARY

Traffic accidents are a significant problem worldwide, resulting in human fatalities and economic losses. In the context of the platooning of connected autonomous vehicles (CAVs), maintaining safe distances and speeds within vehicles is crucial in order to reduce the possibility of rear-end collisions. The severity of such collisions depends on the relative impact speed between vehicles, and more research is needed regarding the emergency braking conditions of CAVs and their impact on platooning safety. This study examines how braking conditions affect the collision risk and severity during the emergency situations that may arise in CAVs platooning. Results indicate that the analyzed platooning algorithm is safe, even if the leader brakes at a high intensity of $1g$. In case one vehicle within the platoon suffering an accident, this can lead to subsequent rear-end crashes, involving 2-5 vehicles depending on the severity of the incident.

Keywords: CAV platoon, safety, impact speed, emergency situation.

1. INTRODUCTION

Traffic accidents are a pervasive problem that affects human lives and economic well-being. Therefore, avoiding traffic accidents is a prevalent challenge across various transportation domains and aligns with the fundamental principles of a safe system. Safe speed is one of the four key pillars of this approach, and it plays a crucial role in traffic safety initiatives like Vision Zero or Sustainable Safety in Europe. Since the late 1990s, there have been discussions in safe system infrastructure policy and planning, and on the impact speeds at which humans are likely to suffer fatal injuries. Multiple studies have confirmed that speed significantly increases the likelihood of crashes (Elvik et al., 2004). For instance, Nilsson (2004) and Elvik (2013) have demonstrated that lower average traffic speeds, resulting from the reduction of speed limits, can significantly decrease the probability of casualty crashes. In turn, Jurewicz et.al. (2016) reviewed the subject, raising questions about the adequacy of existing speed-fatality probability relationships as a foundation for future road safety strategies. Although they studied different collision types, namely:

---

* Presenting author. *E-mail address*: seshadri.naik.moode@upc.edu. *Postal address*: Jordi Girona 1-3, Building B1, Office 111, 08034 Barcelona (Spain)

head-on, side, and rear-end; in the present study only rear-end collisions are going to be considered as this is the most probable type of collision to occur in a platoon of vehicles. A platoon is defined as a group of vehicles traveling one behind another while maintaining a short distance between them to boost the road capacity. This implies that platooning directly affects the longitudinal configuration of traffic and the possibility of rear-end collisions. Collisions that occur from the rear-end cause comparatively less injury than other types of collisions such as head-on or side crashes. It is difficult to determine an acceptable level of risk, while aiming for zero risk is impractical and overly ambitious as noted by Hakkert et al. (2002). The critical impact speed for rear-end crashes, in which the vehicle struck is stationary, is around 15 m/s with a 10% risk of serious injury, according to Jurewicz et al. (2016). However, Doecke et al. (2020) reviewed these speeds and updated to 24.4 m/s for the same 10% risk of serious injury, and to 30 m/s for a 50% risk of serious injury. Table 1 gives a summary of the impact speeds considered for a serious injury with a probability of 10%.

Table 1. Impact speed thresholds for a 10% probability of serious or fatal injury

Impact type	**Doecke et al. (2020)**	**Jurewicz et al. (2016)**	**Wramborg (2005)**
	(Serious Injury) - [m/s]	(Serious Injury) - [m/s]	(Fatality) - [m/s]
Head on	14.73	8.34	19.45
Side	19.72	8.34	13.89
Rear-end	24.45	15.23	–

In order to avoid read-end collisions it is imperative to maintain a safe distance between moving vehicles. The incorporation of advanced communication features leading to the concept of CAV platooning makes a significant shift towards proactive risk mitigation. In CAV platoons, where vehicles operate in coordination, safety can substantially improve while vehicles travel at short distances (Fig.1). Beyond enhancing structural integrity, CAV platoons leverage advanced technologies to establish a robust safety framework. In situations such as unexpected obstacles or hazards, the platoon control algorithm can apply the brakes to stop vehicles, thus minimizing the collision risk for given emergency braking decelerations. Xiao et al. (2017) developed a realistic model for Cooperative Adaptive Cruise Control systems, testing it with various collision scenarios to demonstrate its safety in normal driving conditions, however, they have not studied any emergency scenarios.

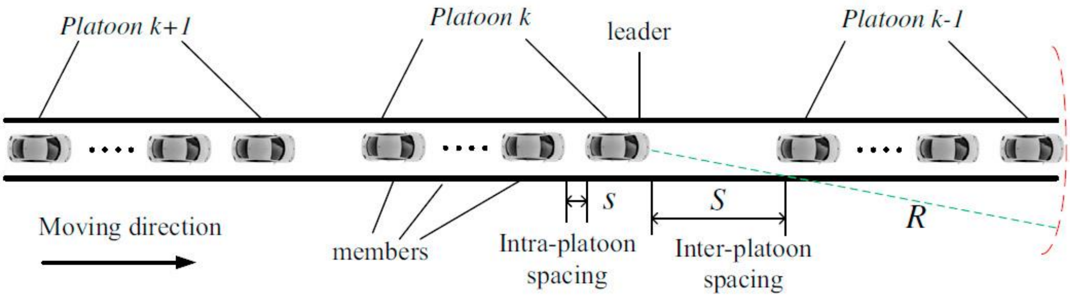


Fig.1 Platoon-based cooperative driving pattern (Jia & Ngoduy (2016))

While safety is a primary concern in the acceptance of CAV platooning, the majority of studies focus on string stability, with safety being a secondary outcome. Even when both are related, there is a need for more research on the emergency braking conditions of platooned CAVs and their impact on safety. Imagine a scenario where the leading vehicle applies a higher deceleration than that acceptable in comfortable driving conditions (i.e., an emergency situation) and stops within a short time and distance. In such scenario, it is crucial to analyze the platoon safety, quantifying how many vehicles will be involved in a potential crash and at what impact speed the collisions may occur. This paper deals with this issue, focusing on the platoon safety evaluation in emergency conditions. Different emergency scenarios are analyzed for a CAV platoon that follows the safe space-based CAV platooning algorithm proposed in Moode & Soriguera (2023). A safety analysis is carried out to understand the developed model behavior in emergency situations.

The rest of the paper is structured as follows. The description of methodology is presented in Section 2, followed by the results and discussion in Section 3. Finally, the main conclusions are outlined in Section 4.

Table 2. Variables and parameters used in the CAV platoon car-following model.

Variable	**Units**	**Description**
g_i, t	[m]	Platooning space gap between vehicles i and $i-1$ at time t.
$v_{i,t}$	[m/s]	Known speed of vehicle i at time t.
$a_{i,t}$	[m/s^2]	Decision variable. Acceleration to apply for vehicle i at time t according to the platooning car-following model.
$v_{i-1,t-\delta}$	[m/s]	Speed of vehicle $i-1$ at time $t-\delta$. Known by vehicle i at time t.
$a_{i-1,t-\delta}$	[m/s^2]	Acceleration of vehicle $i-1$ at time $t-\delta$. Known by vehicle i at time t.
Parameter	**Value used**	**Description**
g_{min}	0.5 [m]	Minimum gap between vehicles when all the vehicles are stopped
a_{min}	–1 [m/s^2]	Acceleration threshold for a comfortable braking of the vehicles.
j_{min}	–0.9 [m/s^3]	Jerk threshold for comfortable braking of the vehicles.
a_{min_e}	–9.8 [m/s^2]	CAVs maximum deceleration in emergency conditions.
j_{min_e}	–20 [m/s^3]	CAVs maximum braking jerk in emergency conditions.
a_{max}	1 [m/s^2]	Acceleration threshold for a comfortable acceleration process of the vehicles.
v_{max}	15 - 30 [m/s]	Maximum travelling speed of the CAV platoon. Range used in the different scenarios analyzed.
δ	0.1 [s]	Latency of communications between CAVs. It is also assumed that platoon followers adapt their acceleration every δ time units.
α	[-]	Differential braking parameter. Maximum deviation of braking capabilities between different CAVs that will be accepted in technical revisions. [Dimensionless]. Expressed as a fraction of a_{min_e}.
δ^*	0.3 - 0.5 [s]	Extended latency to account for platoon stability. Depends on v_{max} and α (see Equation (2)). Range resulting from $v_{max} = 15-30$ [m/s].

Note: 1) a_{min} and j_{min} are not considered in Equation (1). They are used in order to detect emergency conditions (see Section 2). 2) a_{max}, a_{min_e} and j_{min_e} are not explicitly considered in Equation 1. However, the resulting accelerations from Equation (1) are bounded by these parameters, adapted from thebrakereport.com). 3) The comfortable driving condition parameters are adapted from Bae et al., (2019).

2. METHODOLOGY

The space gap is a crucial element of the control algorithm for CAVs platooning, as it defines the desired distance between consecutive vehicles. Choosing an appropriate space gap is critical for both traffic efficiency and driving safety. Equation (1) depicts the space gap for a CAV platoon, as proposed in Moode & Soriguera (2023). Its variables and parameters are defined in Table 2.

$$g_{i,t} = g_{min} - \frac{1}{2}\frac{\left(v_{i,t}+a_{i,t}\delta^*\right)^2}{a_{min\_e}} + \frac{a_{i,t}{\delta^*}^2}{2} + v_{i,t}\delta^* + \frac{1}{2}\frac{\left(v_{i-1,t-\delta}+a_{i-1,t-\delta}\delta^*\right)^2}{a_{min\_e}} \tag{1}$$

where:

$$\delta^* = \delta - \frac{1}{2}\left(\frac{v_{max}}{a_{min\_e}}\right)\left(\frac{\alpha}{1-\alpha}\right) \tag{2}$$

Equation (1) yields a quadratic function for $a_{i,t}$ which defines the dynamic car-following model for the CAVs in platooning mode.

Safety analysis

A safety analysis is conducted under emergency conditions, specifically when the platoon leader suffers an incident that involves emergency braking for the followers. When the incident happens, it is assumed that the leader travels at the maximum speed of the platoon, v_{max}, in order to face the worst conditions. Maximum traveling speeds of 15, 20, 25, and 30 m/s for the leader are considered. The scenario in which the platoon leader begins to brake at 30 m/s, arguably the platoon's maximum speed in any realistic context, is considered as the worst-case situation.

The severity of the incident is modeled according to the instantaneous deceleration experienced by the platoon leader. Specifically, instantaneous decelerations of $0.5g$, $1g$, $1.5g$, $2g$, $5g$, and $10g$ are considered. Note that g is defined as –9.8 m/s^2 so that the extreme case of a $10g$ deceleration (i.e. –98 m/s^2) could be analogous to the deceleration suffered by a vehicle hitting a wall while traveling at a speed of 10 m/s. It is considered that the incident ends when vehicles reach a full stop. The evaluation of the platoon safety depends on the followers' capacity to handle incidents of varying severity in a safe manner, considering the maximum thresholds in CAVs' emergency deceleration and jerk (i.e. a_{min_e} and j_{min_e}; see Table 2). This evaluation focuses specifically on two different scenarios in the managing of emergency braking within the platoon, namely: *Case 1 – Do nothing*; and *Case 2 – Set emergency mode*.

Case 1 – Do nothing

In this scenario, when the leader encounters an emergency situation and suddenly decelerates, the followers behave as usual, i.e., according to the platooning car-following algorithm. This means that there is no vehicle coordination in responding to the emergency situation. Specifically, the acceleration of the followers is computed as in Equation (3).

$$\hat{a}_{i,t} = Max\left(a_{i,t},\ a_{i,t-1} + j_{min\_e}\delta,\ a_{min\_e}\right) \tag{3}$$

Where $\hat{a}_{i,t}$ is the actual acceleration that follower i will apply at time t, and $a_{i,t}$ is the proposed acceleration based on the platooning car-following model in Equation (1). Note, however that it is imposed that $\hat{a}_{i,t} \leq 0$ when dealing with the emergency braking, as it could happen that due to the sudden speed reduction of the leader's speed and acceleration, the platoon car-following results in $a_{i,t} > 0$ in order to reach a reduced desired gap for such speeds. This would be an undesirable situation, which may arise because Equation (1) does not explicitly account for emergency situations.

Case 2 – Emergency mode

In this case, when the emergency condition is detected for the leader (i.e. the experienced leaders' deceleration violates the comfort thresholds a_{min}, j_{min} or both), the emergency mode is set and all the followers apply maximum emergency braking, as expressed in Equation (4).

$$\hat{a}_{i,t} = Max\left(a_{i,t-1} + j_{min\_e}\delta,\ a_{min\_e}\right) \tag{4}$$

It is clear that in this case, the platoon responds to the emergency in a coordinated way, which involves a much faster application of the emergency braking, especially for the followers far down in the platoon.

Setup for the collision analysis

A collision or crash is detected when the space gap between any two consecutive vehicles is zero. When this happens, at t^*, the collision is modeled by setting the speed and acceleration of the colliding vehicle equal to those of the vehicle in front (i.e. the vehicle that receives the rear-end collision) for all subsequent time steps, as both vehicles are considered to be like one in a crash situation. Specifically, this is formulated as in Equation (5).

If $g_{i,t^*} \leq 0$, then:

$$g_{i,t} = 0,\ v_{i,t} = v_{i-1,t},\ a_{i,t} = a_{i-1,t} \qquad \forall i;\ \forall t \geq t^* \tag{5}$$

To prevent negative speeds or vehicles moving backwards, which could happen as a result of the discreteness of the time steps considered in the trajectory calculation, an additional condition is imposed. If a vehicle's speed is expected to become negative while braking (e.g. at $t^{**} + \delta$), this speed, and the corresponding acceleration are set to zero from t^{**} and onwards. This is formulated as in Equation (6).

If $V_{i,t^{**}} + a_{i,t^{**}}\delta \leq 0$, then:

$$a_{i,t^{**}} = 0,\ v_{i,(t^{**}+\delta)} = 0 \qquad \forall i;\ \forall t \geq t^{**} \tag{6}$$

3. RESULTS AND DISCUSSION

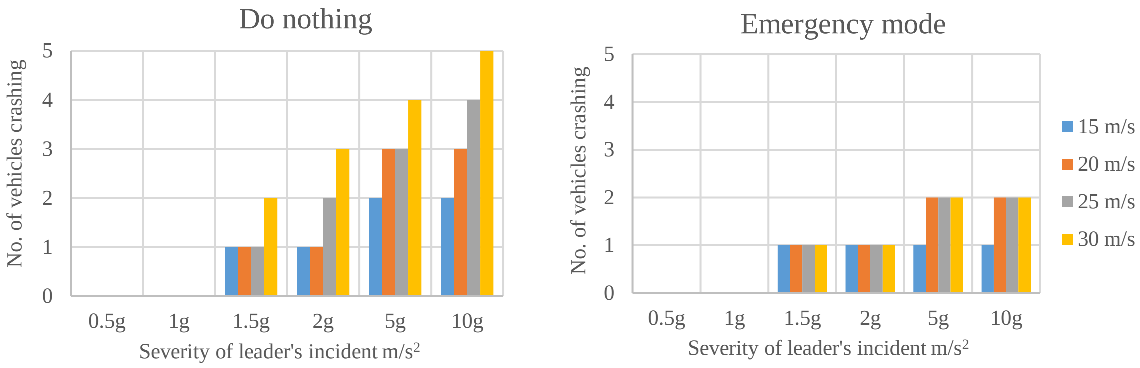
The analysis is carried out for the introduced emergency management scenarios, for different maximum speeds at the moment of the accident and for various severities of the incident experienced by the leader This section presents the obtained results in terms of the number of crashes and the relative speed at the collisions, as an indicator of the severity of the potential injuries suffered by the CAVs' passengers. Results are presented below in graphical form.

Crash number analysis

Results show that the platooning car-following algorithm is safe when the incident severity is $0.5g$ and $1g$, for any given traveling speed. However, crashes occur in the platoon at higher incident severities.

Case 1 - Do nothing: It is observed from Figure 2(a), that a maximum of 5 vehicles can be involved in a crash at any given speed, being 30 m/s the worst situation. In addition, for traveling speeds of 15 and 20 m/s, until $2g$ incident severity, the maximum number of vehicles that crash is 1, whereas for 30 m/s case, the number of vehicles involved in crashes rises as the severity of the leader's incident increases, ranging from 2 to 5 vehicles.

Case 2 - Emergency mode: From Figure 2(b), it can be seen that a maximum of 2 vehicles are involved in collisions under any given speed condition if the emergency mode is on, even in the worst incident with a $10g$ severity. Actually, for speeds of 30 m/s and $10g$ incident severity, the number of collisions comes down from 5 to 2 in comparison to the *do nothing* case, showing the beneficial effect of the coordinated braking.



(a) (b)

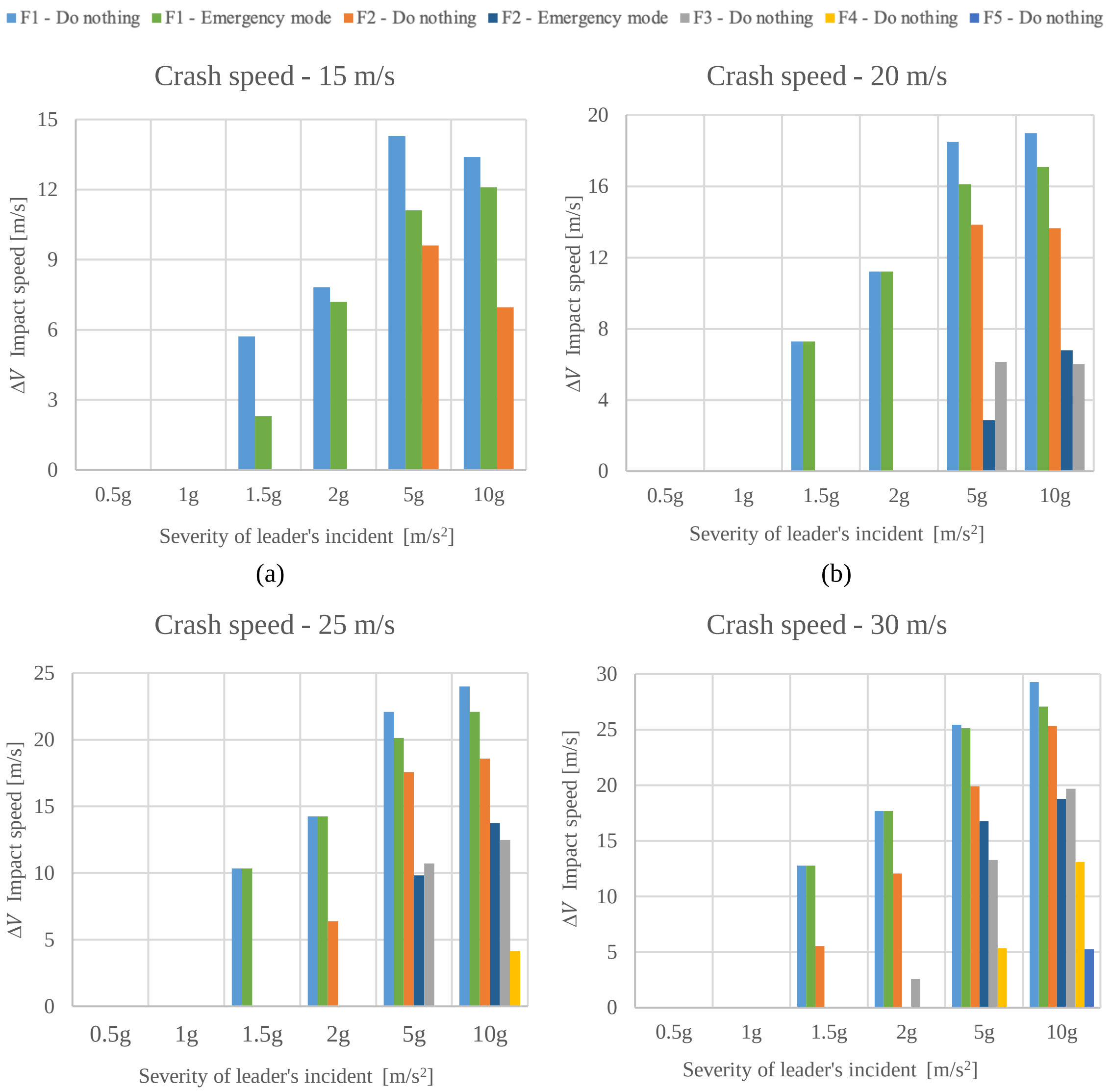
Figure 2. Number of vehicles crashing at different travelling speeds for various incident severities. (a) Do nothing; (b) Emergency mode.

Impact speed analysis – Delta V (ΔV)

When the gap between vehicle i and the vehicle in front is zero (i.e. a crash), Δv_i, the relative speed between the vehicles at the impact, is computed as in Equation 7. Δv is directly related to the severity of the crash for the vehicles involved. Table 1 gives an overview of the impact speeds involving a probability of 10% for a serious injury, as reported by previous studies. Here, the most conservative approach is assumed, and $\Delta v = 15$ m/s is considered as the critical impact speed to have a significant probability (i.e. 10%) to cause a serious injury.

$$\Delta v_i = |v_i - v_{i-1}| \tag{7}$$

Figure 3 shows the impact speed at which the crashes of the affected followers (e.g. F1, F2, etc.) occur. Results are shown for different incident speed and severity, for the two considered emergency management scenarios.



(a) (b)

(c) (d)

Figure 3. ***ΔV*** **for all the vehicles involved in crashes at (a) 15 m/s, (b) 20 m/s, (c) 25 m/s, (d) 30 m/s.**

The observation of Figure 3 yields that, in case of collision, the impact speed decreases as the follower is farther behind the leader. Always, the first follower is the most vulnerable. It can be seen that the probability of experiencing potential serious injuries is directly related to the severity of the incident and to the position of the follower within the platoon. It is also observed the benefit of the coordinated emergency mode, which involves fewer crashes and lower impact speeds. This benefit is especially relevant when the incident happens at higher speeds and the crashes affect followers farther behind the leader. The effects of anticipation are more noticeable then. Specifically, the following detailed insights are obtained:

i) Incident at 15m/s: The most vulnerable first follower only suffers impact speeds near the 15 [m/s] threshold when the incident is very severe, like in the $5g$ and $10g$ cases. Regarding the second follower, even though it crashes in the *do nothing* case, it only experiences low impact speeds. Thus, there is a high probability that travelers can avoid serious injuries in this scenario.

ii) Incident at 20m/s: In comparison to the previous case, the higher speed at which the incident happens implies that, for the $5g$ and $10g$ cases, Follower 1 might experience serious injuries for the considered 10% probability threshold. Follower 2, may still experience a significant impact speed for the *do nothing* case, while in the in *emergency mode* it only crashes at a low speed. Follower 3 only crashes in the *do nothing* scenario. It is clear that the coordinated *emergency mode* starts playing a very significant role in the platoon safety.

iii) Incident at 25m/s: When the platoon leader suffers an incident at a speed of 25 m/s, it involves the crashing of followers 1 to 4 for the *do nothing* scenario, where followers 1 and 2 may experience serious injuries. In contrast, for the *emergency mode,* both Follower 3 and 4 can avoid the collision and only Follower 1 might experience serious injuries.

iv) Incident at 30 m/s: At the maximum platoon speed of 30 m/s, the incident implies that Followers 1 and 2 are susceptible to severe injuries. For the *emergency mode,* there is no other follower vehicle colliding, while for the *do nothing* scenario followers 3, 4, and 5 still crash for the higher incident severities.

In conclusion, irrespective of the platooning emergency management scenario, followers 1 and 2 may suffer a collision with a significant probability of sustaining serious injuries if the platoon is travelling at high speed when the leader experiences a very severe incident. If the *emergency mode* is implemented, the incident involves no other vehicle crashing. Nevertheless, in the *do nothing* scenario the number of vehicles colliding may rise to five, in the worst possible conditions.

4. CONCLUSIONS

CAV platoons have the potential to increase capacity and traffic efficiency, however, because they can travel very closely spaced and at high speeds, safety remains at most concern in the application of these technologies, particularly in emergency situations. In this study, the safety analysis performed shows that the platooning car-following algorithm proposed in Moode & Soriguera (2023) is safe for incidents of the leader involving a sudden deceleration up to $1g$ at any traveling speed. For more severe incidents, several followers can experience collisions. In the extreme case of a very severe emergency, involving a sudden $10g$ deceleration of the leader while traveling at maximum speed of 30 m/s, a total of 5 followers crash. Still, if a coordinated response of the platoon to the emergency is implemented, involving a solidary emergency braking of all the followers immediately after the incident happens, the number of crashes can be reduced to 2. Such coordinated emergency management also implies a reduction of the impact speed in the crashes, which is more significant when the severity of the incident grows, as it affects more intensively the collisions farther behind the leader. Therefore, coordinated emergency management in the CAVs platooning has the potential to yield a lower number of collisions and of vehicles affected by potentially severe injuries. In fact, in the worst-case incident analyzed, just the first 2 followers after the leader suffered a collision at an impact speed with a significant probability of resulting in severe injuries.

ACKNOWLEDGEMENTS

This research has been partially funded by the Spanish Ministry of Economy and Competitiveness (Ministerio de Economía y Competitividad, Gobierno de España), Grant number J-02653 Platoon.

REFERENCES

https://thebrakereport.com/tbr-technical-corner-braking-requirements-for-optimizing-autonomous-emergency-braking-aeb-performance-part-1-out-of-3/

Bae, I., Moon, J., & Seo, J. (2019). Toward a comfortable driving experience for a self-driving shuttle bus. *Electronics*, *8(9)*, 943.

Doecke, S. D., Baldock, M. R., Kloeden, C. N., & Dutschke, J. K. (2020). Impact speed and the risk of serious injury in vehicle crashes. *Accident Analysis & Prevention*, *144*, 105629.

Elvik, R., Christensen, P., & Amundsen, A. H. (2004). *Speed and road accidents: an evaluation of the Power Model*. Transportøkonomisk Institutt.

Elvik, R. (2013). A re-parameterisation of the Power Model of the relationship between the speed of traffic and the number of accidents and accident victims. *Accident Analysis & Prevention*, *50*, 854-860.

Hakkert, A. S., Braimaister, L., & Van Schagen, I. (2002). *The uses of exposure and risk in road safety studies* (Vol. 2002, No. 12). SWOV, Leidschendam: SWOV Institute for Road Safety.

Jurewicz, C., Sobhani, A., Woolley, J., Dutschke, J., & Corben, B. (2016). Exploration of vehicle impact speed–injury severity relationships for application in safer road design. *Transportation research procedia*, *14*, 4247-4256.

Moode, S. N., & Soriguera, F. (2023). Microscopic modeling of connected autonomous vehicles platooning: stability and safety analysis. *Transportation research procedia*, *71*, 260-267.

Nilsson, G. (2004). Traffic safety dimensions and the power model to describe the effect of speed on safety.

Wramborg, P. (2005). A new approach to a safe and sustainable road structure and street design for urban areas. In *Proceedings of the Road Safety on Four Continents Conference* (Vol. 13, pp. 12p-12p). Conference Sponsor.

Xiao, L., Wang, M., & Van Arem, B. (2017). Realistic car-following models for microscopic simulation of adaptive and cooperative adaptive cruise control vehicles. *Transportation Research Record*, *2623*(1), 1-9.