On the Potential of Accelerating an Electrified Lead Vehicle to Mitigate Rear-End Collisions

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Abstract: This paper analyzes the potential safety benefit from autonomous acceleration of an electrified lead vehicle to mitigate or prevent being struck from behind. Safety benefit was estimated based on the expected reduction in relative velocity at impact in combination with injury risk curves. Potential issues and safety concerns with the operation and implementation of such a system in the real world are discussed from an engineering and human factors stand point. In particular, the effect of the pre-collision acceleration in reducing whiplash injury risk due to change in head posture and reduction of crash severity is also discussed. In general, this study found that autonomously accelerating an electrified lead vehicle can mitigate and prevent rear-end collisions and significantly increase the safety benefits from existing systems such as autonomous emergency braking.

Keywords: Rear-end collisions, collision avoidance and mitigation, electrified vehicle acceleration, active safety

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1. INTRODUCTION

1.1 Background

The rear-end collision is one of the most frequently occuring accident types in most countries accounting for nearly a third of all accidents in the US [Singh (2003)] and a fourth of all accidents in Germany [Unger and Sandner (2013)]. The single most common injury sustained in these accidents are whiplash injuries which have been reported to account for up to 90% of all injuries [Watanabe et al. (2000)]. Compared to other injuries whiplash injuries have the highest risk of leading to permanent medical impairment [Gustafsson et al. (2015); Malm et al. (2008)] and in the US the associated cost of whiplash injuries sustained in rear-end collisions has been estimated to be $2.7 billion annually [NHTSA (2010)]. Reducing the number of whiplash injuries from rear-end collisions can therefore be expected to have high socio-economic impact.

While the Autonomous Emergency Braking (AEB) system (already available on the market from several manufacturers) is estimated to be able to completely avoid 35% and mitigate 53% of all rear-end collisions [Schittenhelm (2013)], the remaining cases still account for a large number of accidents which could potentially be improved by a novel active safety function.

A possible way to do so is to make the lead vehicle speed up in order to reduce the relative speed at impact. To perform such an intervention however, quick response is required in the propulsion actuator which is why a traditional internal combustion engine (ICE) cannot be used whose response can vary significantly depending on the speed, transmission type, gear, turbo lag, etc. Electric drives, on the other hand, have very fast response in the order of tens of milliseconds [Hori et al. (1997)] and can be used to perform this intervention. Therefore, the lead vehicle is assumed to be electrified (fully electric or hybrid) in this paper in order to be able to perform the intervention.

In order to evaluate the potential of such an intervention to mitigate or avoid rear-end collisions, a hypothetical active safety system that uses acceleration on the lead vehicle is envisioned and used for analysis. This system, which works analogously to the AEB, is termed the Automatic Emergency Acceleration (AEA) system further on in this paper.

1.2 Objective

The objective in this paper is to evaluate the potential of an Automatic Emergency Acceleration (AEA) system which accelerates an electrified lead vehicle to avoid or mitigate rear end collisions.

1.3 Assumptions

A few simplifying assumptions have been made in order to limit the scope of this paper, which are detailed below along with the motivation.

(1) *Acceleration capability is limited by friction, not by motor size*

Since electric motors deliver their peak torques at low speeds and can, for short periods of time, deliver torques several times that of their rated torques, it would be reasonable to assume that at low speeds, the acceleration possible is limited by the tyre friction limit rather than the motor size. Furthermore, since 70% of rear-end collisions involve stationary lead vehicles [Knipling et al. (1993)], the acceleration capability of the lead vehicle is assumed to be limited by the grip at the driven axle (since the electric motor typically drives only one axle).

(2) *The lead vehicle has the capability to detect following vehicles behind it*

The lead vehicle is assumed to be able to reliably detect following vehicles behind it. This detection can be done either using sensors or using connected systems (vehicle-to-vehicle or vehicle-to-infrastructure) or by any other method. Due to the advent of advanced driver assistance and autonomous systems, such capabilities are likely to make their way into vehicles of the future.

(3) *It is safe to accelerate*

The lead vehicle is assumed to have the ability to detect threats ahead and that it would be safe to accelerate. While vehicles equipped with AEB have the ability to detect obstacles ahead, the lead vehicle in this work also needs to have the ability to ensure that there is no cross-traffic, that it is not at a traffic signal, etc. Once again, with the advent of cooperative functions in cars, such capabilities could probably be available in cars of the future. While acceleration may not always be possible nor even possible to ensure that such an intervention would be safe, in this work, we assume that the intervention can be safely performed and in later sections discuss alternatives which can help overcome some of these issues.

2. MANOEUVRE KINEMATICS

In order to predict the safety benefit that can be expected from AEA and put the same into context, kinematics of the scenario with a lead vehicle equipped with AEA and a following vehicle equipped with AEB are analysed. From the resulting analysis, expected relative velocity reductions for different cases are predicted which are in turn used to predict expected injury reduction and safety benefit.

In the following subsections, basic actuator and vehicle models similar to those used in Coelingh et al. (2010) are used to derive activation timings for the AEA and AEB system which are then used in a simulation environment to evaluate their performance.

2.1 Actuator modelling

Figure 1 shows the parameterization of the actuator dynamics that is used in the simulation model and, with additional simplifications as needed, in deriving the activation timings for the AEB and the AEA as well. Note that parameterization of steering is also shown since evasive steering has to be considered as a potential option for collision avoidance while determining the window of opportunity for activation of AEB and AEA.

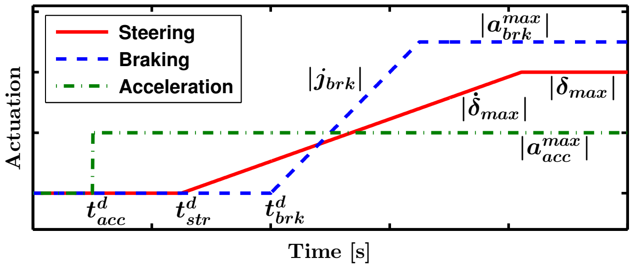

Fig. 1. Parameterization of different actuator dynamics.

The steering and brakes have been modelled with a pure delay, a ramp and a saturation to capture the relatively slow response and dynamics of these actuators. While the delays are mainly determined by the actuator response times, the saturation values are determined by the dynamic limits of the vehicle and the ramp rates by a combination of the two.

The motor on the other hand has been modelled with just a pure delay and a saturation, but no ramp since the dynamics of the motor are much faster. The saturation value here is determined by the grip at the axle driven by the motor. While this can vary significantly depending on the vehicle properties and which axle is being driven, a middle-ground approach is taken in this paper and it is assumed that each axle has half the grip of the entire vehicle.

2.2 AEA timing calculation

Since AEA involves speeding up which is inherently riskier, a conservative approach is taken here wherein AEA is not activated until the last point in time where the following vehicle could have avoided the collision by braking or steering. These activation timings are calculated by taking the minimum of three minimum Time-To-Collision (TTC) values at which: the following vehicle can avoid the collision by braking, by steering or the lead vehicle can avoid the collision by acceleration.

Since collision avoidance by braking or steering is done on the following vehicle about which the lead has limited information, the actuators on the following vehicle are assumed to have ideal performance. Even if the lead vehicle does have some information about the following vehicle actuators or can make some reasonable assumptions regarding the same, they cannot be used by the AEA algorithm. This is because, in a non-cooperative environment, the lead vehicle cannot reliably detect the state of the actuators on the following vehicle (whether they are in the ramp-up stage, operating at peak performance, etc) and therefore cannot count on their response times while estimating the minimum time required for the following vehicle to avoid a collision. As a result, the lead vehicle has to assume best performance of the actuators (no actuator dynamics) while estimating the time required for the following vehicle to avoid a collision. While such an approach reduces window of opportunity available for the AEA system and therefore reduces its effectiveness, it also minimizes the likelihood of a false intervention. Such a conservative timing approach also ensures that there is no detrimental interaction between the AEB and AEA.

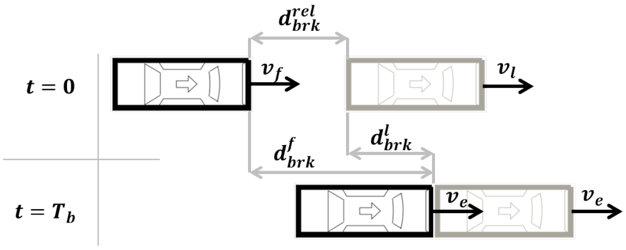

Fig. 2. Collision avoidance by braking

A collision can be avoided by following vehicle braking when the following vehicle can slow down to a speed equal or lower than that of the lead vehicle. Figure 2 shows this case with $t = 0$ representing the final time instant at which the collision can be avoided by following vehicle braking. Assuming that the initial following and lead vehicle speeds are v_f and v_l respectively and that the lead vehicle has an acceleration a_l, the time T_b required for the following vehicle to slow down to a speed equal to that of the lead with deceleration from maximum braking a^{max}_{brk} can be calculated as follows.

$$v_l + a_l T_b = v_f + a^{max}_{brk} T_b \tag{1}$$

$$T_b = \frac{v_l - v_f}{a^{max}_{brk} - a_l} \tag{2}$$

The minimum TTC at which the collision can still be avoided (henceforth simply called the minimum TTC) can then be calculated from the relative distance and speed between the two vehicles at the start of the intervention ($t = 0$). The relative distance at the beginning can in turn be calculated from the distance travelled by the two vehicles (d^f_{brk} and d^l_{brk}) during the intervention (see Fig. 2).

$$d^f_{brk} = v_f T_b + a^{max}_{brk} \frac{T_b^2}{2} \tag{3}$$

$$d^l_{brk} = v_l T_b + a_l \frac{T_b^2}{2} \tag{4}$$

$$TTC^{min}_{brk} = \frac{d^{rel}_{brk}}{v^{rel}_{brk}} \tag{5}$$

$$= \frac{d^f_{brk} - d^l_{brk}}{v_f - v_l} \tag{6}$$

$$= \frac{v_f - v_l}{2(a_l - a^{max}_{brk})} \tag{7}$$

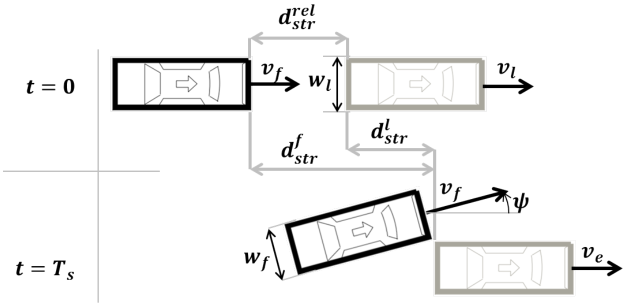

Fig. 3. Collision avoidance by steering

For the case of steering, assuming the following vehicle steers left (the problem is symmetric for turning the other way) and at constant speed v_f, the collision can be avoided when the front right corner of the following vehicle clears a lateral distance equivalent to the left edge of the lead vehicle. This case is shown in Fig. 3 with $t = 0$ representing the final time instant at which the collision can be avoided by evasive steering of the following vehicle. The condition for collision avoidance by steering can be expressed as (small yaw angle and zero side slip angle assumptions have been made):

$$Y_{fr} \approx Y_c + l_{fe}\psi - \frac{w_f}{2} = \frac{w_l}{2} \tag{8}$$

where l_{fe} is the distance from the center of gravity to the front edge of the vehicle and the yaw angle (ψ) and lateral center of gravity positions (Y_c) are given by:

$$\psi(t) = \omega_z t \tag{9}$$

$$\omega_z = \min\left(\frac{\delta_{max} v_f}{L + K^f_u v_f^2}, \frac{a^{max}_{lat}}{v_f}\right) \tag{10}$$

$$Y_c \approx \int_0^t (v_f \psi(t') + v_{y0})\mathrm{d}t' = v_f \omega_z \frac{t^2}{2} + v_{y0} t \tag{11}$$

Note that zero initial heading angle for the following vehicle has been assumed since it would be difficult for the lead vehicle to detect the same. It would be easier instead to augment the expression for the following vehicle lateral center of gravity position Y_c, with the intial lateral velocity of the following vehicle v_{y0}, which could possibly be detected by the lead vehicle sensors.

Note also that while the side slip angle is unlikely to be zero in such a manoeuvre, determination of the same requires even more information about the following vehicle which the lead vehicle is unlikely to have. However, since these calculations involve almost exclusively a single type of manoeuvre (manoeuvres which push the vehicle to the limit), it is easier to account for the discrepancy by choosing an appropriate value of the understeer gradient for the following vehicle (K^f_u).

Substituting the expressions in Eq. (8) and solving for time gives:

$$Y_{fr} \approx v_f \omega_z \frac{T_s^2}{2} + (l_{fe}\omega_z + v_{y0})T_s - \frac{w_f}{2} \tag{12}$$

$$T_s = \frac{-(l_{fe}\omega_z + v_{y0}) + \sqrt{(l_{fe}\omega_z + v_{y0})^2 + v_f \omega_z (w_f + w_l)}}{v_f \omega_z} \tag{13}$$

The distances travelled by the two vehicles (d^f_{str} and d^l_{str}) and the minimum TTC for evasive steering can be calculated as:

$$d^f_{str} = v_f T_s \tag{14}$$

$$d^l_{str} = v_l T_s + a_l \frac{T_s^2}{2} \tag{15}$$

$$TTC^{min}_{str} = \frac{d^{rel}_{str}}{v^{rel}_{str}} \tag{16}$$

$$= \frac{d^f_{str} - d^l_{str}}{v_f - v_l} \tag{17}$$

$$= T_s + \frac{a_l}{v_l - v_f} \frac{T_s^2}{2} \tag{18}$$

For collision avoidance by acceleration, a similar treatment as done in case of braking is done except that the motor

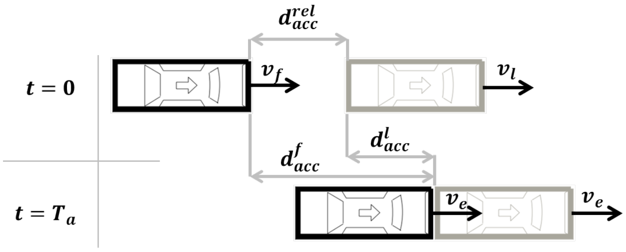

Fig. 4. Collision avoidance by acceleration

dynamics are taken into account. Figure 5 shows this case with $t = 0$ representing the final time instant at which the collision can be avoided by lead vehicle acceleration. Once again the collision is avoided when the lead vehicle velocity equals or is higher than that of the following vehicle.

$$v_f + a^{max}_{brk} T_a = v_l + a^{max}_{acc}\left(T_a - t^{d}_{acc}\right) \tag{19}$$

$$T_a = \frac{(v_f - v_l) + t^{d}_{acc} a^{max}_{acc}}{a^{max}_{acc} - a^{max}_{brk}} \tag{20}$$

The minimum TTC is then calculated from the relative distance travelled by the two vehicles and their relative velocities at the start of the intervention.

$$d^{l}_{acc} = v_l T_a + a^{max}_{acc}\frac{\left(T_a - t^{d}_{acc}\right)^2}{2} \tag{21}$$

$$d^{f}_{acc} = v_f T_a + a^{max}_{brk}\frac{T_a^2}{2} \tag{22}$$

$$TTC^{min}_{acc} = \frac{d^{rel}_{acc}}{v^{rel}_{acc}} \tag{23}$$

$$= \frac{d^{f}_{acc} - d^{l}_{acc}}{v_f - v_l} \tag{24}$$

$$= T_a + \frac{a^{max}_{brk} T_a^2 - a^{max}_{acc}\left(T_a - t^{d}_{acc}\right)^2}{2(v_f - v_l)} \tag{25}$$

As noted in Coelingh et al. (2010), use of the calculated TTC timings result in unncessarily late interventions and therefore a safety margin has been added which is expressed as:

$$t_{margin} = \max\left(\frac{d_{min}}{v_f - v_l}, t_{min}\right) \tag{26}$$

where d_{min} and t_{min} are the minimum safety margin distance and time respectively.

The activation timings so derived is expressed below and shown in Fig. 5.

$$TTC_{AEA} = \min\left(TTC^{min}_{brk}, TTC^{min}_{str}, TTC^{min}_{acc}\right) + t_{margin} \tag{27}$$

2.3 AEB timing calculation

For the determination of AEB activation timings, a similar method as detailed in Brännström et al. (2010) has been used and is hence not described in detail here. The primary differences here are that small sideslip angle assumption has been made, all manoeuvres start from steady state and straight ahead driving and that we also include a pure delay in the actuator response models. The first two result in a simplification of the method developed in Brännström et al. (2010). The pure delay on the other hand can be accounted for by simply adding a time duration equivalent to the corresponding time delay to the TTCs so determined. This is made possible due to the fact that all manoeuvres are assumed to start from steady state and straight ahead driving.

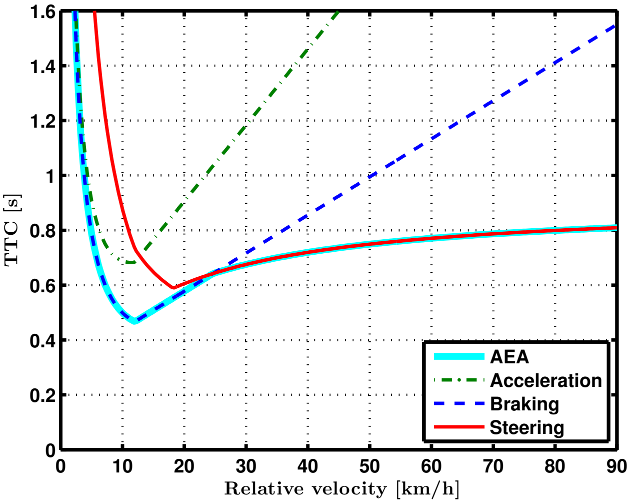

Fig. 5. Critical TTC for collision avoidance by braking, acceleration and steering manoeuvres and the activation timing for AEA. Brake and steering actuator limitations are not considered.

Finally, just as in the case of AEA, a safety margin (Eq. (26)) is added to the TTC timings. The minimum of these two timings for braking and steering is taken as the activation timing for AEB. These timings are shown in Fig. 6 for reference.

$$TTC_{AEB} = \min\left(TTC_{brk}, TTC_{str}\right) + t_{margin} \tag{28}$$

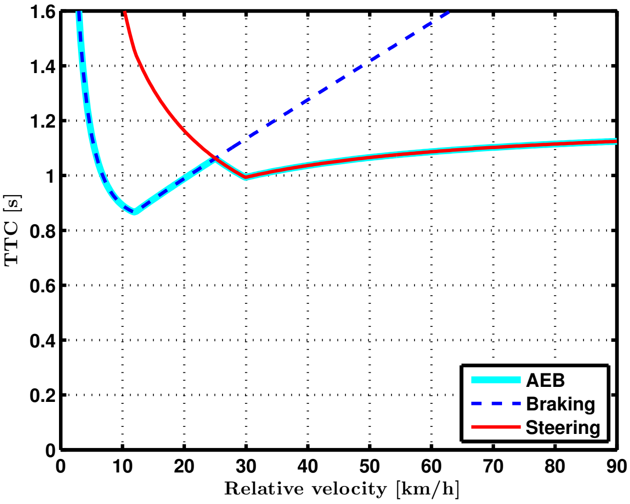

Fig. 6. Critical TTC for collision avoidance by braking and steering manoeuvres and the activation timing for AEB. Brake and steering actuator limitations are considered.

2.4 Expected relative velocity reductions

In order to evaluate the performance of the AEA system and its interaction with an AEB, a simple 1-D kinematic model was built with an AEB on the following and a AEA on the lead vehicles respectively. The actuators (brakes and motor) are modeled as shown in Fig. 1. The activation timings for the AEB and AEA are determined as detailed in Sections 2.2 and 2.3 and Figs. 5 and 6. Simulations are then carried out with a range of initial velocities until either a collision occurs or is avoided which are determined as follows:

$$X_f(t) \geq X_l(t) \quad \rightarrow \quad \text{Collision occurs} \tag{29}$$

$$v_f(t) \leq v_l(t) \quad \rightarrow \quad \text{Collision avoided} \tag{30}$$

The velocity reductions achieved by the two systems and their combination is shown in Fig. 7. The data used is shown in Table 1. Comparing the relative velocity reduction curve for the AEB to the experimentally validated one presented in Coelingh et al. (2010) shows that they match remarkably well which supports the choice of method and the data used.

Table 1. Data used

Vehicle and actuator parameters							
L	2.75 m	t^d_{brk}	0.18 s	j^{max}_{brk}	$-20\,\mathrm{m/s^3}$	a^{max}_{brk}	$-10\,\mathrm{m/s^2}$
w_l	1.5 m	t^d_{str}	0.02 s	δ^{max}_{sw}	720 °	a^{max}_{lat}	$7\,\mathrm{m/s^2}$
w_f	1.5 m	t^d_{acc}	0.05 s	$\dot{\delta}^{max}_{sw}$	400 °/s	a^{max}_{acc}	$5\,\mathrm{m/s^2}$
n	16.25	v_l	0 m/s	d_{min}	1 m	K^f_u	0.003
l_{fe}	2.4 m	a_l	$0\,\mathrm{m/s^2}$	t_{min}	0.3 s	v_{y0}	0 m/s

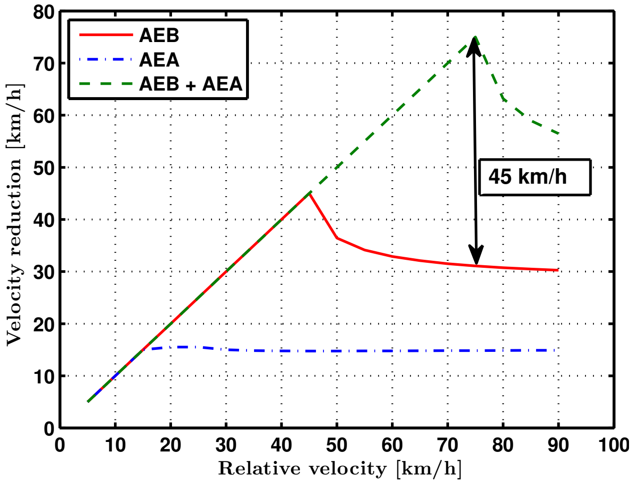

Fig. 7. Estimated velocity reduction capabilities for AEB on following vehicle, an autonomous acceleration system on the lead vehicle and a combination of the two.

As can be seen, even with conservative activation timings, the AEA system alone can achieve velocity reductions of up to 15 km/h when the following vehicle does not brake at all. When used in conjunction with AEB on the following vehicle, rear-end collisions with relative speeds up to 75 km/h can be completely avoided which represents a 45 km/h improvement over the outcome for the same case when AEB alone is used. These large velocity reductions achieved when the following vehicle brakes as well is in large part due to the fact that acceleration now not only reduces the relative speed, but also increases the distance available to the following vehicle for braking. Consequently, this benefit is obtained with relatively low increase in lead vehicle speed and distance travelled. This fact is illustrated in Fig. 8 which shows the velocity increase and displacement for the lead vehicle (from standstill) when the AEA is used for a range of initial following vehicle velocities. As can be seen, on average, a velocity increase and displacement of approximately 15 km/h and 2 m respectively can be seen. The peak speed increase is seen to be roughly 25 km/h in order to achieve a velocity reduction of 75 km/h. The corresponding peak displacement is approximately 5 m which is roughly equivalent to the length of a large car.

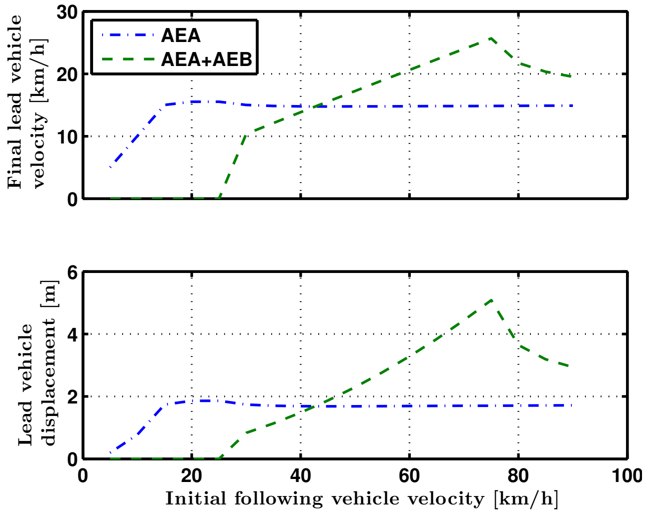

Fig. 8. Estimated increase in lead vehicle velocity and resulting displacement when the AEA is activated. Lead vehicle is stationary at the start of the intervention.

At low following vehicle speeds (less than roughly 30 km/h), when AEB is available on the following vehicle, it can be seen that there is no speed increase or displacement in the lead vehicle. This is because, at such low following vehicle speeds, the AEB is sufficient to prevent the collision and hence the AEA is not activated. While from Fig. 7 it can be seen that the AEB should be able to do so for speeds up to 45 km/h, after about 30 km/h, it is not able to prevent the collision with the required safety margin to spare and as a result, the AEA gets activated.

As noted, since just forward displacement of the lead vehicle can result in a safety benefit and since acceleration of the lead vehicle may not always be possible or advisable, a case of just moving the lead vehicle forward by a fixed distance without significantly increasing the final velocity is investigated.

Since such an intervention is less risky compared to hard acceleration, it can be done significantly earlier and as a result, the forward displacement can be achieved with relatively small or no increase in final velocity. An example use case for such a function could be when the lead vehicle is at a standstill at a traffic junction with a car length's gap in front and there is an imminent collision from a following vehicle behind. In such a case, this function could accelerate the vehicle forward and then decelerate so as to move it forward but also bring it back to standstill when the required lateral displacement has been achieved. This would allow increased braking distance for the following vehicle and thereby help in preventing or mitigate being struck from behind.

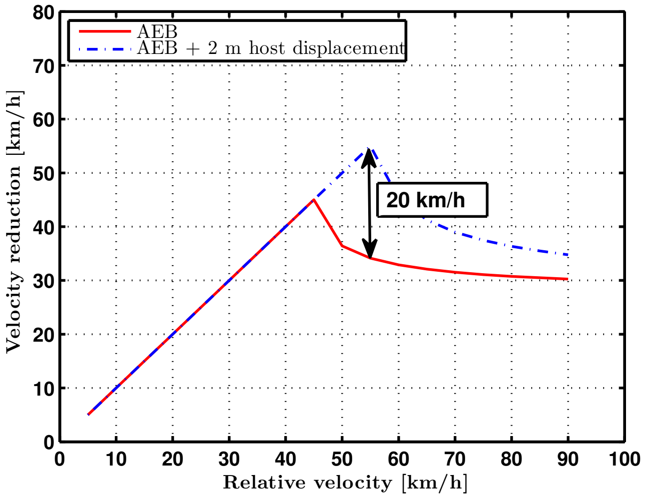

Fig. 9. Estimated velocity reduction capabilities for AEB on following vehicle, when lead vehicle moves forward by 2 m without a net speed increase.

The expected velocity reduction from such an intervention when the lead is moved forward by 2 m (approximately half the length of a small car) is shown in Fig. 9. As can be seen, up to a 20 km/h speed reduction over that of AEB alone can be achieved which represents over a 50 % improvement.

3. SAFETY BENEFIT

Whiplash injury is the most frequently sustained injury type in rear-end crashes [Watanabe et al. (2000)]. Several factors can influence the whiplash injury risk in these crashes, among them impact severity and occupant sitting position [Carlsson (2012)]. In an AEA equipped lead vehicle, impact severity may be reduced by considerably reducing the relative velocity between the colliding vehicles in a rear-end crash (up to 15 km/h, Fig. 7). Studies on whiplash injury risk based on data from real life crashes estimate that a reduction in change of velocity of 5 km/h for the struck vehicle can decrease the risk of sustaining whiplash symptoms lasting for more than one month by up to 65% [Krafft et al. (2005)]. In terms of initial symptoms the same amount of reduction in change of velocity could decrease the risk by up to 40% [Krafft et al. (2005)]. A reduction of change of velocity will also benefit the occupants of the striking vehicle. As an example, Kullgren et al. (2003b) concluded that the neck injury risk decreased from 33% to 27% in frontal impacts with a change of velocity reduction from 20 km/h to 10 km/h. From Krafft et al. (2009), it is known that a 10 % speed reduction before impact results in a 30 % reduction in fatality risk for the occupants of both vehicles. The potential injury risk reduction from a relatively small decrease in velocity change with AEA is therefore large.

Another potential contribution to the safety benefit could be the influence of the pre-collision acceleration on head posture. Occupant head posture with respect to the head restraint has been investigated in the past and several studies have suggested that increased distance between the head and head restraint is associated with increased risk of a whiplash injury [Jakobsson (2004); Farmer et al. (1999); Deutscher (1996); Olsson (1990); Nygren et al. (1985); Carlsson et al. (1985)]. Numerical simulations of the head-neck motion in a rear-end impact indicated that limiting the head-to-head restraint distance to 6 cm or less could minimize the risk of sustaining a whiplash injury by restricting head retraction and neck extension during impact [Stemper et al. (2006)]. Although it remains unknown how much rearward head motion would be induced by the acceleration of the AEA system, the resulting head repositioning has the prospective safety benefit of reducing whiplash injury risk by decreasing head-to-head restraint distance before impact. This benefit, however, should be evaluated in combination with other influencing factors such as head restraint geometry, height of the head restraint and car seat properties [Carlsson (2012)].

A safety system influencing the neuromuscular response of the occupant has been proposed as a potential way to mitigate whiplash injuries in rear-end impacts [Siegmund (2011); Mang et al. (2012, 2015)]. The system was suggested based on results from neck muscle activity measurements in volunteers subject to replicated rear-end impacts. The suggested system consisted of a loud tone pre-stimulus inducing neck muscle activity to inhibit potentially injury exacerbating startle reflexes during the impact. Startle reflex can be provoked by sudden forward acceleration [Blouin et al. (2006)] indicating that the acceleration from the AEA system could possibly serve as a protective pre-stimulus in a similar fashion as the loud tone. However, it is not clear what characteristics of the pre-collision acceleration pulse are necessary to elicit a sufficient startle response. An alternative would be to include a loud tone as a part of a rear-end collision warning system (see section 4). According to [Siegmund (2011); Mang et al. (2012, 2015)] the tone should be delivered 250 ms before impact and would therefore be the last resort action of the warning system.

Whiplash injuries can occur at relatively low velocity changes of the struck vehicle [Krafft et al. (2005); Kullgren et al. (2003a)], lower than can be achieved with the AEA system. However due to the low acceleration level of the pre-collision acceleration (0.5 g) the AEA intervention is not expected to evoke whiplash symptoms [Krafft et al. (2005, 2002)].

4. DESIGN CHALLENGES AND SAFETY CONCERNS

One other possible way to prevent being struck from behind is to steer away from the threat. However, as seen in Figs. 5 and 6, steering is not very effective at low speeds which is typically the case for the lead vehicle in such scenarios. Another possiblity is to use both steering and acceleration for avoidance. However, not only is it unclear whether it would provide significantly higher benefit, but such an intervention involving vehicle control at the limit using both steering and acceleration/braking brings with it an increased risk of loss of control accidents.

On the other hand, if steering is already turned at the start of an intervention and is deemed undesirable by the function, one way to correct for it would be to use the Electric Power Steering (EPS) to apply a corrective steering angle (for e.g., like in Active Lane Keeping assist). However, this is only possible if the steering angle is sufficiently small and if the vehicle is equipped with an EPS. Another possible way to correct for small steering angles could be to use differential braking. The disadvantage in this case is that it could potentially reduce the acceleration level that can be achieved. When the steering angle is large on the other hand (for e.g., lead vehicle stopped at a junction in preparation to make a turn), it would propbably be safest to not perform any intervention.

As mentioned in Section 1.3, it may not always be possible to detect if it is safe to accelerate due to difficulty in detecting cross traffic or even liability issues. One way to get around these issues is to warn the driver of an impending rear-end collision and use the driver's response as input to the system. Since typically, autonomous interventions are also preceded by a warning phase wherein the driver has an opportunity to intervene, the detection needs to be done equally early (approximately) in both cases. However, when the system has to just detect and warn the driver and not perform any autonomous intervention, the sensor requirements may be reduced as it offloads part of the liability to the driver.

One could envision simpler versions of the AEA which use the driver response to determine the required response. For e.g., similar to the Emergency Brake Assist (EBA) and Forward Collision Warning (FCW) functions (collectively called the brake assist functions along with the AEB), Emergency Acceleration Assist (EAA) and Rear-end Collision Warning (RCW) functions (collectively called the acceleration assist functions along with the AEA) could be devised. EAA would warn the driver and if the driver tries to accelerate would amplify their input and deliver maximum acceleration that it can achieve. RCW warning on the other hand would simply warn the driver and let the driver perform any intervention.

In Kusano and Gabler (2012), a study comparing the effectiveness of collision warning, brake assist and autonomous braking, it was found that up to 70 % and 50 % effectiveness of a fully autonomous system can be expected with assistance and warning systems respectively. With acceleration systems, similar or potentially even higher benefits can be expected compared to their brake-based counterparts due to the much shorter delays and much quicker response of electric drives.

Furthermore, if a rear-end collision can be detected, it would be easy to warn the following vehicle of an imminent collision by flashing the brake lights of the lead and thereby serve as a rudimentary "collision warning" system as has been speculated in Anderson and Baldock (2008). Additionally, in a cooperative environment the FCW and AEB of a following vehicle could be used to issue RCW and AEA or vice versa.

However, the design of an EAA or a RCW is not as straightforward as the design of EBA and FCW and presents new challenges from a human factors, engineering, and liability standpoint. Accelerating is not an obvious reaction or a standard evasive manoeuvre in rear-end collision scenarios. As a consequence, a warning to trigger such reaction may not be intuitive and require a driver to be trained to appropriately react. FCW guides a driver's attention to the threat (forward roadway), it may be harder for a RCW to guide a driver's attention to the rear-view mirror and, while looking at the rear-view mirror, it could be hard for a driver to deem whether it is safe to accelerate. EAA may surprise the driver who may react in an impulsive way, which may be unsafe. Further, when the acceleration of the lead vehicle is fully autonomous, the transition back to manual driving may be a concern. In fact, it may not be acceptable to assume that the driver is in the loop and able to control a vehicle that is suddenly moving at 15 km/h, and if any collision would happen shortly after the intervention of the AEA the vehicle manufacturer may still be liable. It might therefore be necessary to have supporting functions that bring the vehicle to a safe halt or state after an AEA intervention.

Although in this paper, the AEA activation timings are such that if brake assist functions were to be present on the following vehicle, they would always be activated before the AEA, ensuring a synergetic interaction between the two is still a crucial challenge. In fact, the brake assist algorithms are influenced by TTC and a sudden acceleration of the lead vehicle may abort the brake assist interventions and potentially aggravate the rear-end collision. In a non-cooperative environment, the AEA system would need to perfectly predict the behavior of the brake assist systems in the following vehicle and vice versa to have a safety impact. The potential interaction between autonomous systems in the lead and following vehicle also creates new liability challenges. Even if the AEA and AEB system activity would be logged, the lack of synchronization may prevent from reconstructing the actual crash dynamics.

5. CONCLUSION

An analysis on the potential of AEA in an electrified lead vehicle to mitigate rear-end collisions is presented. It is found that when used in conjunction with AEB, even collisions with high relative speed (up to 75 km/h) can be prevented with low increases in lead vehicle speed and distance travelled (on average ≈15 km/h and ≈2 m respectively). An brief investigation into the injury reduction potential offered by such a system shows that it can have a large safety benefit.

Further development of the AEA concept presented in this paper should address several human factors issues (such as acceptance and the extent of driver in the loop required at different times of intervention), engineering challenges (such as potential interaction between AEA and FCW/AEB in a following vehicle), and liability issues.

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