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Coordinated Braking Strategies Supporting Mixed Autonomous and Conventional Vehicles

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Abstract

Autonomous driving vehicles are becoming popular as a solution to reach safe, efficient and comfortable mobility. However, at early market penetration, autonomous vehicles based on Cooperative ACC (C-ACC) policies will have to co-exist in mixed traffic conditions with less autonomous vehicles, such as Adaptive Cruise Control (ACC) or conventional vehicles. In this paper, we introduce a simple concept by which vehicles with such advanced technology would help avoid not only possible collisions onto other vehicles in front (front end collisions) but also collisions of conventionally driven following vehicles onto itself (rear end collision), and this under non ideal circumstances, where vehicle gets informed about an obstacle later than usual due to communication or sensing limitations. We show a superior performance of our approach against a baseline ACC strategy, and our results encourage the possibility of keeping low inter vehicular spacing between conventional and autonomous vehicles without fearing collisions.

Index Terms

Coordinated braking, coexistence, autonomous vehicle, conventional vehicle, connected vehicle, V2X

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1 Introduction

An intelligent vehicle in our terminology is any vehicle which is able to take smart decisions based on the geometry of the traffic, this vehicle which might be required to be equipped with sensing technologies involving cameras, radars, lidars, etc for ACC and/or Vehicle to Vehicle (V2V) communication technology for CACC. CACC based driving would involve communication between vehicles for traffic flow where as ACC based driving would involve local decision making based on distance and velocity as measured of immediate neighbors. CACC and ACC equipped intelligent vehicles categorize under different levels of automation, from 0: completely manually controlled conventional vehicle to 4: maximum complete automation [1]. Current day CACC is categorized as level 2 automation. Such intelligent vehicles with a sense of automation might solve a lot of issues related to safety and traffic throughput.

Ideally, a full scale acceptance and adaptation of CACC based vehicles with perfect automation (level 4), coordinating and cooperating within themselves to drive would be desired. Platoons of such autonomous vehicles enabled with CACC could provide even better results, but this could be foreseen not before a few decades. At this early stage of deployment of autonomous vehicles, a mix of intelligent vehicles with different levels of automation and conventional manually driven vehicles is seen. Thus we thus choose to work on this present day mixed traffic scenario.

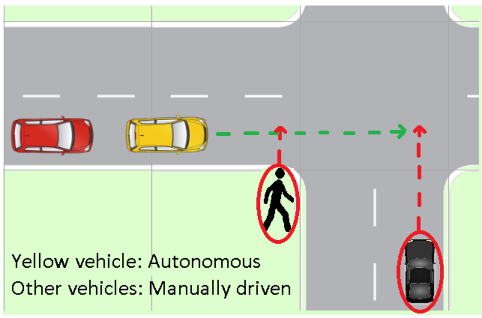


Figure 1: Mixed vehicular traffic scenario

From a controller perspective, behavior and control tasks for CACC in longitudinal direction, (some also applicable to ACC) can be profiled into:
Profile 1. Speed control: when there are no vehicles in front
Profile 2. Vehicle following with gap maintaining strategies: when there is a vehicle in front
Profile 3. Platoon related: forming or dissolution of a platoon

Due to the high ratio of manually driven vehicles to intelligent vehicles, it is more probable that an intelligent vehicle would have a manually driven vehicle as its neighbor. Thus, either the autonomous vehicle would be travelling with no vehicle in front(Profile 1.) and it may have a manually driven vehicle following it or the autonomous vehicle would be behind a manually driven vehicle(Profile 2) as depicted in fig.1. We focus on a scenario close to Profile 1 in this paper.

Statistics show around 25% of accidents happen with vehicle in front or with the vehicle following [2]. Considering longitudinal motion, humans driving a vehicle tend to react based on the vehicle in front and thus only care about preventing accidents with the vehicle in front (front-end accident avoidance). The effect of the behavior of the subject vehicle onto the following vehicle is not considered by humans, leading to rear-end collisions. On the other hand, an intelligent vehicle could consider vehicles at both ends and make an educated decision. Although intelligent vehicle can not force the following vehicle to act according to its wishes, it can modify its own movement based on the actions of the following vehicle. How can an intelligent vehicle avoid colliding with vehicle in front and play its part in ensuring collision avoidance of the following vehicle onto itself even when the following vehicle doesn't have ACC/CACC or AD is answered by us in the following sections.

2 Problem Formulation

2.1 Mixed Traffic Scenario

Without loss of generality, we simplify the braking maneuver described in Figure 1 in a 1-D domain, consisting of an potential obstacle L, a C-ACC autonomous vehicle A and a following regular vehicle B. d_e represents the distance to L requiring an emergency braking by vehicle A in Fig. 2. $d_{la} \geq d_e$ represents the distance at which vehicle A becomes aware of the potential danger by object L over V2X communication. Assuming an WiFi-based ITS-G5/DSRC technology communicating over a 5.9GHz frequency band, d_{la} is strictly bigger than the detecting range of vehicle A own sensors. However, harsh communication conditions (i.e. Non-Line-of-Sight, channel congestion…) limit d_{la} to a few hundred of meters. In [3], An et al. investigated such typical emergency notification distance, and notably considered that $d_{la} = 95.9m$ could be reached with 99.5% probability[1]. Obviously, the longer d_{la}, the lower is the probability for vehicle A to actually be notified of the danger. We consider in this paper d_{la} to be strictly bigger than d_e ($d_{la} > d_e$), so that vehicle A may use the distance $d_s = d_{la} - d_e$ to adjust its braking strategy. D_{AB} is the distance between vehicle A and vehicle B, which cannot

[1]Being notified of a danger by V2X technology at a distance D means receiving *at least* one Emergency message before reaching distance D.

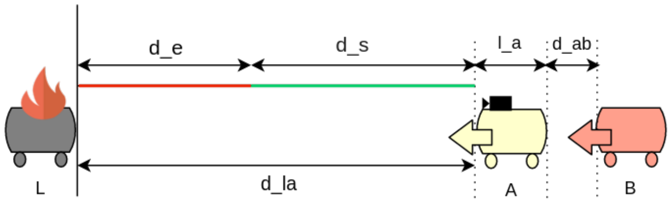


Figure 2: Mixed traffic scenario considered in this paper, where autonomous vehicle A detects an obstacle L via V2X communication.

be adjusted by vehicle A as in full C-ACC scenario, and only depend on vehicle B. Finally, both vehicle A and vehicle B are assumed to drive at a similar speed V.

Considering the scenario previously described, vehicle A will be notified of a danger and its C-ACC controller will initiate a braking maneuver. This paper will investigate the capability of this maneuver to avoid an impact with the obstacle L and also with the following vehicle B.

2.2 Braking Policy

The C-ACC vehicle A being isolated in mixed traffic with regular vehicle, its maneuvering strategy will resemble that of baseline ACC. The Intelligent Driver Model (IDM) [4], is a typical driving strategy implemented by industrial ACC [5]. The IDM is originally a microscopic traffic flow model falling in the case of *Follow-the-Leader* models, and which therefore adjust a vehicle acceleration according to the driving dynamics of the vehicle immediately following it. IDM has been shown to not only avoid creating accident with preceding vehicles, and through subsequent extensions (IIDM, IDM+) [6, 7] managed to optimize traffic capacity and flow. We consider in this paper that vehicle A uses the IDM as part of its ACC. Without loss of generality, the IDM may be modeled as follows:

$$a_\alpha = a * (1 - (\frac{v_\alpha}{v_0})^\delta - (\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha})^2) \tag{1}$$

where

$$s^*(v_\alpha, \Delta v_\alpha) = s_0 + v_\alpha * T + \frac{v_\alpha \Delta v_\alpha}{2 * \sqrt{ab}} \tag{2}$$

and

$$s_\alpha = x_{\alpha-1} - x_\alpha - l_{\alpha-1} \tag{3}$$

$$\Delta v_\alpha = v_\alpha - v_{\alpha-1} \tag{4}$$

where α is the vehicle being considered, α -1 is the vehicle in front and so on. $a_\alpha, v_\alpha, x_\alpha$ is the acceleration, velocity and the location of α. [2]. A Perception

[2]For emergency situations like the one considered here, limitations on jerks or comfort are not considered.

Parameter description	symbol	value
Desired speed	v_0	96kmph
Free acceleration exponent	δ	4
Desired time gap	T	0.1s
maximum acceleration	a	1.4 m/s^2
Deceleration	b	0.6*g m/s^2
Length of vehicle	l_a	4 m
Desired minimum distance	s_0	5 m

Table 1: IDM constants and their values

response time(t_{prt}) of 1.3 sec is thus set for vehicle B [8], and we that both vehicles A and B can support a maximum deceleration of 0.6*g [9].

Considering the mixed traffic scenario described in Sec.2.1, we evaluate the reaction of the IDM to not only avoid collision with the obstacle L, but also with preceding vehicle B. We implemented the IDM on Matlab, considering the scenario parameters described on Table 1. Figure 3 illustrates the impact of the braking manoeuver of vehicle A on the inter-distance between vehicle A and B. As it can be seen, the IDM braking strategy brakes too strong and although it can avoid collision with obstacle L, it cannot avoid a rear-collision with vehicle B. Although this behavior strongly depend on the distance D_{AB}, the IDM not considering rear-traffic for its braking maneuver, and convention vehicle not adjusting their distance to such cases, this is expected to happen, unless C-ACC/ACC consider coordinated braking strategies.This is the objective of this paper.

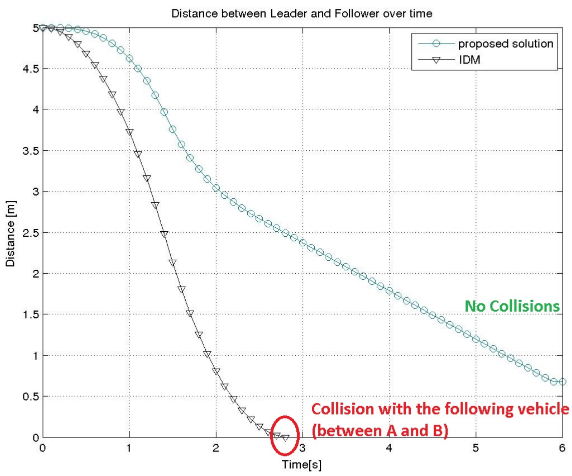


Figure 3: Inter-distance between vehicle A and B, considering an IDM braking strategy.

2.3 Related Work

The car following models like Psycho-physical model by Wiedemann implemented in VISSIM simulator [10,11], defines a decision making behavior of a manually driven vehicle approaching the one in front. The approaching vehicle would continue at the same velocity until it enters as deceleration perceptual threshold which stimulates the driver to brake. Whereas Intelligent Driver's Model(IDM) [4], or a modified version of IDM is assumed to be a good basis for implementation of ACC/CACC systems [5]. But it comes as a bit of a surprise that the calculated deceleration at any moment based on IDM's depends on the vehicle's acceleration capacity. IDM based ACC in vehicles take decisions locally and thus the presence of following vehicles is not considered, similar is the case with the psycho-physical model. According to our understanding IDM is designed to only avoid front-end accidents and can not guarantee rear-end accident avoidance where as we in our approach focus on front and rear end accident avoidance. We later prove in section 4 that indeed this is the case. Some reports doubt if responding to emergency situations would ever be a part of CACC/ACC [12] but we think they need to be for full scale level 4 automation.

The rest of the work can be classified into a domain different than the above mentioned three profiles mentioned in the introduction, in general under *collision avoidance* algorithms. Specific collision avoidance algorithms are designed for specific scenarios. Most of the work till date has been on collision avoidance between subject vehicle and vehicle in front and comparatively little on the influence of actions of subject vehicle onto following vehicle. In [13, 14] authors discuss collision avoidance for autonomous vehicles based on steering rather than braking, where as an innovative approach based on elastic band theory is proposed involving non linear algebraic equations for collision avoidance systems in [15]. In [16] authors focus on collision avoidance based on predicting intent of nearby vehicles. Other application area is collision avoidance during automated lane changing where an approach is presented in [17].

On the other end, to avoid rear end collisions, traditional mindset was to have larger inter vehicular distances [18] states the recommended headway in Germany is 1.8 s. where as authors in [19] suggest increasing communication range. In order to avoid such collisions, either the following vehicle should be informed as to when by latest it should start braking [20] or alternately leading vehicle can accelerate at the last moment [21]. The use of infrared sensors in place of Dedicated Short Range Communications(DSRC) is suggested in [22] to transfer certain information. All of these ideas revolve around the concept of V2V communications. What happens when the following vehicle doesn't have neither any V2V communication technology nor sensors, cameras, etc? Are rear end collisions inevitable?

3 Modeling

In order to avoid vehicle B hitting vehicle A upon strong braking maneuvers, we propose in this work to decompose the braking strategy of vehicle A in a *smooth* and *hard* braking phases. We illustrate this concept on Figure 4, where we represent the distances in Figure 2 in a *Time* domain. Vehicle A will need to come to a full halt at time T, which corresponds to moving a distance d_{la} on Figure 4. Conceptually speaking, vehicle A braking strategy includes a *weak* braking time interval $T_{weak}(\Delta t)$, during which it will perform a smooth braking, and a *hard* braking time interval $T - T_{weak}(\Delta t)$ during which it will brake harder. The challenge is to determine the braking duration Δt corresponding to the *weak* braking maneuver. Δt is not unique and can take multiple values within a time interval $T_{range}(t_{up}; t_{low})$, corresponding to an upper bound to avoid collision with obstacle O and a lower bound to avoid collision with vehicle B.

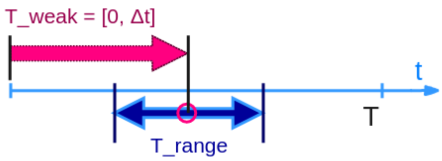


Figure 4: Relation between Δt and T_{range}

To determine the t_{up} and t_{low}, we model the deceleration curves between vehicle A and vehicle B on Figure 5. Vehicle B is assumed to perform a hard braking maneuver after a fixed reaction time T_{PRT}, while vehicle A will perform a linear braking maneuver, without reaction time. The benefit of a smooth deceleration may be illustrated by decomposing the braking maneuvers of both vehicles in four phases: Phase A, correspond to vehicle B's reaction time, and where only vehicle A brakes. Phase B, corresponds to both vehicles braking, A smoothly and B hard. Phase C corresponds to both vehicles braking hard, while phase D is when both vehicles come to a halt (collision or not).

Now, to ensure collision-free ride, the following conditions need to be ensured:

#1 – Upper bound of T_{range} $(t_{up}) : d_{la} > 0$ to avoid front end collision

#2 – Lower bound of T_{range} $(t_{low}) : d_{ab} > 0$ to avoid rear end collision

Ensuring **#1**: Total distance covered by A before halting must be smaller than initial distance $d_{la}(t = 0)$. (L is stationary in longitudinal direction). Simplifying kinematic equations to obtain conditions for #1 we get:

$$\Delta t^2(\frac{dece_{max}}{24}) + \Delta t(\frac{v}{2}) + (\frac{v^2}{2 * dece_{max}} - d_{la}) < 0 \quad (5)$$

Ensuring **#2**: As A and B behave differently in different time intervals, calculation for **#2** need to be split into the four phases previously described. Within

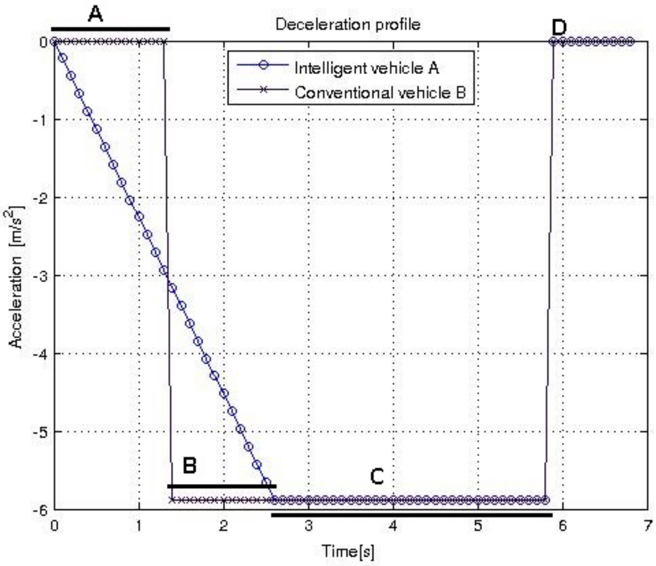


Figure 5: Deceleration profile of vehicles

each phase, the deceleration profile of both vehicles A and B remains constant. We therefore decompose the **#2** for each of the four phases below:

- Interval A: $t \in [0, t_{prt})$

$$d_{ab}(t) = d_{ab,(t=0)} + \frac{dece_{max} * t^3}{6\Delta t} > 0 \tag{6}$$

- Interval B: $t \in [t_{prt}, \Delta t)$

$$d_{ab}(t) = d_{ab,(t=0)} + \frac{dece_{max} * t^3}{6\Delta t} - \frac{dece_{max} * (t - t_{prt})^2}{2} > 0 \tag{7}$$

- Interval C: $t \in [\Delta t, T = min(T_a, T_b)$ or $T = T_a = T_b]$

$$d_{ab}(t) = d_{ab,(t=0)} + \frac{dece_{max} * (\Delta t^2 - 3 * t * \Delta t - 3 * t_{prt}^2 + 6 * t * t_{prt})}{6} > 0 \tag{8}$$

- Interval D: $t \in [T_a, T_b]$ ... for $T_b > T_a$:

$$d_{ab}(t) = d_{ab,(t=T)} + (\frac{(v + dece_{max} * (T_a - t_{prt}))^2}{2 * dece_{max}}) \tag{9}$$

or interval $t \in [T_b, T_a]$... for $T_b < T_a$:

$$d_{ab}(t) = d_{ab,(t=T)} - (\frac{(v + dece_{max} * (T_b - 0.5 * \Delta t))^2}{2 * dece_{max}}) \tag{10}$$

Equations corresponding to #1 and #2 return a set of possible values defining the time interval T_{range}. The specific value Δt that vehicle B takes depends on its adopted driving strategy, the mean $\Delta t = (t_{up} - t_{low})/2$ being taken by default.

4 Evaluation

We evaluated on Matlab our coordinated braking strategy first alone and then against the IDM ACC strategy. In order to illustrate the parameters influencing T_{range}, consider three cases: (i) we fix all parameters and draw the attention on choosing the right parameters value of Δt; (ii) we then keep the same parameters as before, but adjust the speed v; (iii) finally, we consider the road conditions (ice, rain, etc..).

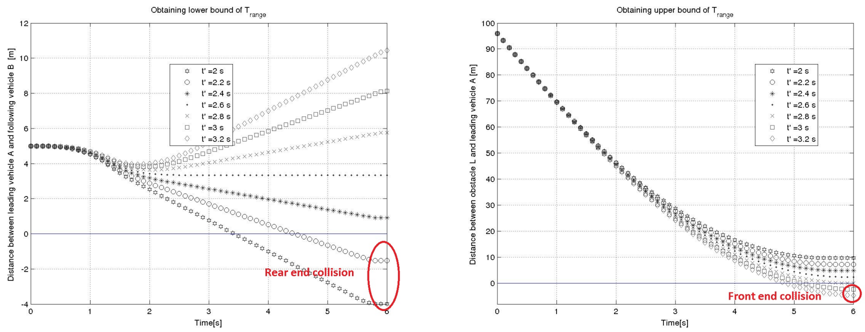
d_{ab} [m]	5	8	10	15	20
T_{range} [s]	2.4 to 2.8	2.1 to 2.8	2.0 to 2.8	1.6 to 2.8	1.2 to 2.8

Table 2: Distance between autonomous and conventional vehicle and corresponding time to reach maximum deceleration for v = 96kmph; $d_{la}(t = 0) = 95.9m$; highway scenario

For the first set of evaluation, we fixed the parameters of $d_{la} = 95.9m$, $d_{ab} = 5m$, $v = 96km/h$. Accordingly, the set of equations 5- 10 provides T_{range} between [2.4,2.8], which can be verified from table 2. For different Δt values, Fig. 4 illustrates the variation of d_{ab} vs time where as Fig. 4 illustrates the variation of d_{la}. Intersection of a plot with x-axis indicates zero distance between A and B which implies a rear-end collision. Thus, a value of Δt should be chosen such that the plot doesn't intersect x-axis in both the sub-plots or Fig. 6. The Upper bound t_{up} can be determined graphically from Figure 4 (thus **#1** resolved), while the Lower bound t_{low} can be determined graphically from Figure 4 (thus**#2** is resolved). Now, a value Δt can be chosen from T_{range} according to different driving policies or parameters configured by the vehicle owner. In our simulations, we took the default value (mean of T_{range}, i.e. $\Delta t = (t_{up} - t_{down})/2$).

To further illustrate the consequences of an inaccurate Δt, we consider three different cases in Figure 7. The first case corresponds to conditions on Δt are not respected, and Δt is chosen smaller than the acceptable T_{range}. In this case, it can be seen that A collides with B (i.e. rear end collision for ($\Delta t < t_{low}$)).The second case corresponds to the desired scenario where conditions on Δt are observed. Δt is chosen from the calculated T_{range}, and collisions are avoided (i.e. $\Delta t \in T_{range}$). The third case correspond to the case, where Δt is too big and A fails to brake and collides into L (i.e. front end collision for $\Delta t > t_{up}$).

For the second set of evaluation, we focus changing the velocity v of the vehicles, yet keeping on having a constant $d_{ab} = 5m$. The objective is to find the



(a) Calculating lower bound for T_{range} (b) Calculating upper bound for T_{range}

Figure 6: Getting vales for T_{range}

minimum d_{la} and the corresponding T_{range} for Δt to be used by vehicle A to avoid any collision. Results are summarized in the following Table 3.[3]

Velocity $[m/s^2]$	d_{la}(t=0)$[m]$	T_{range} $[s]$
v = 30 kmph; low speed limit scenario	10	x
	15	1.6 to 2.5
	20	1.6 to 4.6
v = 50 kmph; urban city with stricter speed limits	20	x
	30	2.1 only
	35	2.1 to 2.9
	40	2.1 to 3.9
v = 70 kmph; urban city scenario	50	x
	55	2.3 to 2.5
	60	2.3 to 3.1
	70	2.3 to 4.3
v = 96 kmph; highway scenario	90	x
	95.9	2.4 to 2.8
	100	2.4 to 3.1
	110	2.4 to 4
	120	2.4 to 4.9

Table 3: T_{range} corresponding to braking strategies for different vehicular speed.

First and second approaches assume decent road conditions. If a road surface with some oil or sand spill (roads considered dirty) is considered, maximum deceleration is physically restricted to $4m/s^2$ [23]. In this third set of evaluation, we limit deceleration accordingly. Simulations show no matter what if the vehicles are

[3]In the following tables, x means either rear-end or front-end collision is bound to take place

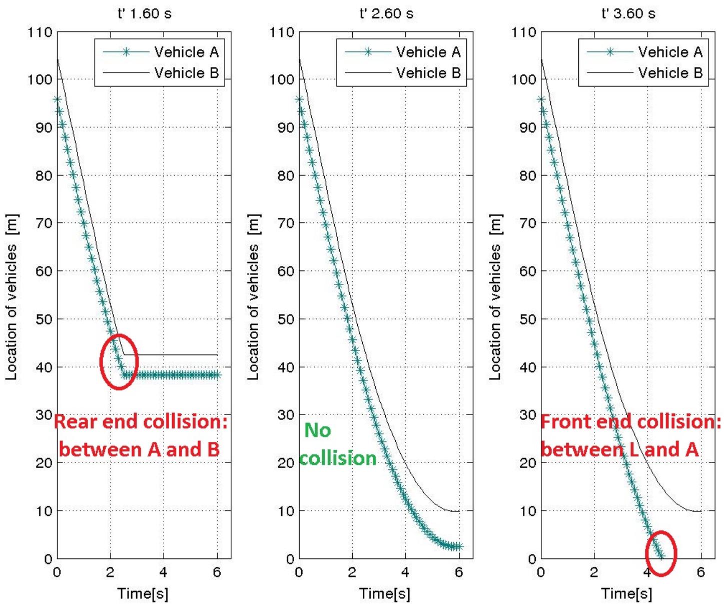


Figure 7: Three cases - rear end collision, no collision, front end collision

travelling at $96km/h$ with d_{ab}= 5 m, and $d_{la} = 95.9m$ collision can not be averted (i.e. A will collide with either B or L). For these reasons, the maximum speed limit should be capped, say to $80km/h$ (50mph) which in turn returns T_{range} of [2.3 s; 3.2 s]. Alternately, under optimal road conditions which allows braking up to $8m/s^2$, maximum velocity permitted can be increased up to $110km/h$ (68mph) such that with Δt values [2.3s;2.4s] collisions could be avoided.

We complete our evaluation through a comparison against the IDM ACC mechanism. IDM [4], among other car following models aim to follow the vehicle in front and avoid accidents with it. Let A follow IDM and B be manually driven. A upon notification of an object in front(L) will try to follow it, according to the acceleration value given by IDM. As soon as it realises that L is not moving longitudinally and d_{la} is decreasing it would result into a warning or an emergency scenario. IDM under normal conditions observes a comfortable level of say below 2 m/s^2, but to consider its response to an emergency, the deceleration capacity has been raised to the mean value of maximum deceleration, 0.6*g (5.88) m/s^2. IDM parameters are the same as Table 1. We illustrate on Figure 8, Figure 10 and Figure 10 the performance enhancement from our coordinated braking maneuver against IDM.

The plots on the right of Figures[8, 9, 10] showcases the performance of our algorithm compared to IDM's shown on the left. Acceleration profile of our algorithm (on right) is compared to one with IDM applied on vehicle A is shown

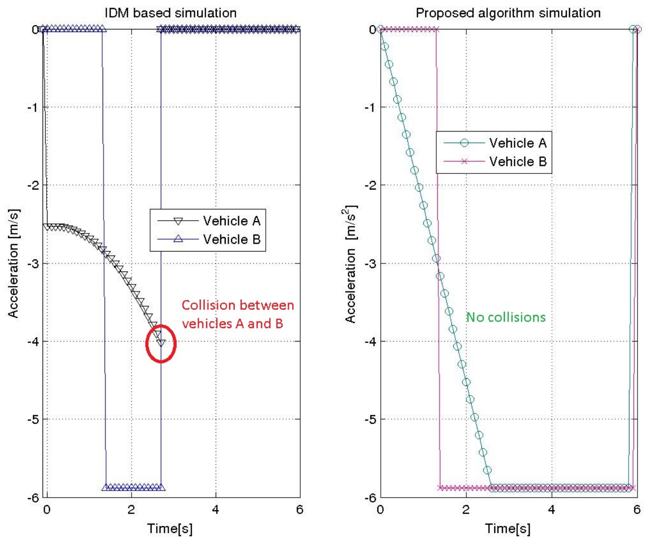


Figure 8: Acceleration profile of vehicles; vehicle A following:IDM(left) proposed algorithm(right)

in fig. 8. Considering this is an emergency maneuver, restrictions related to the implementation delay are not considered for IDM model, but the maximum possible deceleration is capped to the mean of the maximum deceleration of vehicles (around 5.88 m/s^2). At 2.8 seconds, the acceleration jumps from around -4 to 0 m/s^2 which is due to rear end collision of vehicle A with B. Same is the interpretation of Figure 9 which shows sudden fall of velocity to zero after the accident between A and B. Figure 10 shows the vehicles maintaining their position after collision at 2.8 sec, where as Figure 3 shows distance between vehicles A and B over time for two different algorithms. These figures clearly supports our claim that IDM indeed couldn't assure collision avoidance of the following vehicle onto itself where as our proposed algorithm does.

5 Conclusions

In this paper, we investigated coordinated braking strategies for autonomous vehicles driving among conventionally driven vehicles. In such conditions, autonomous vehicles are not able to synchronize with preceding vehicles to adjust their maneuver, which can lead to read-collision in case of too harsh braking maneuvers. we propose in this work a dynamic braking strategy, where a first phase avoids strong brake to mitigate read-collision, and a second phase perform a conventional brake to avoid forward collision.

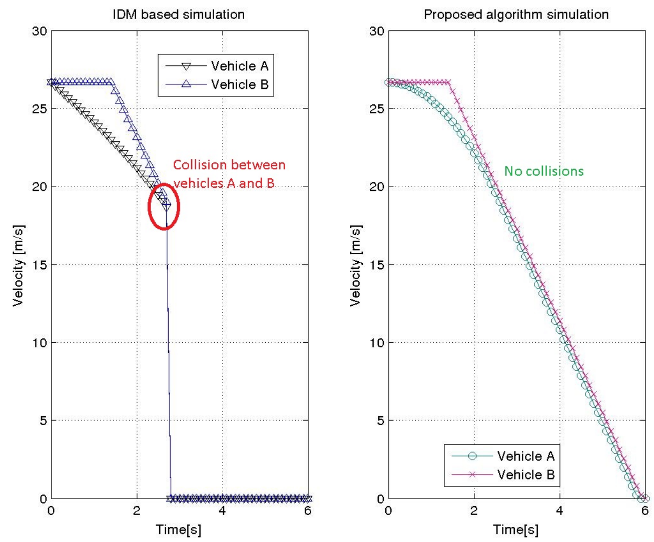


Figure 9: Velocity profile of vehicles; leading vehicle following:IDM(left) proposed algorithm(right)

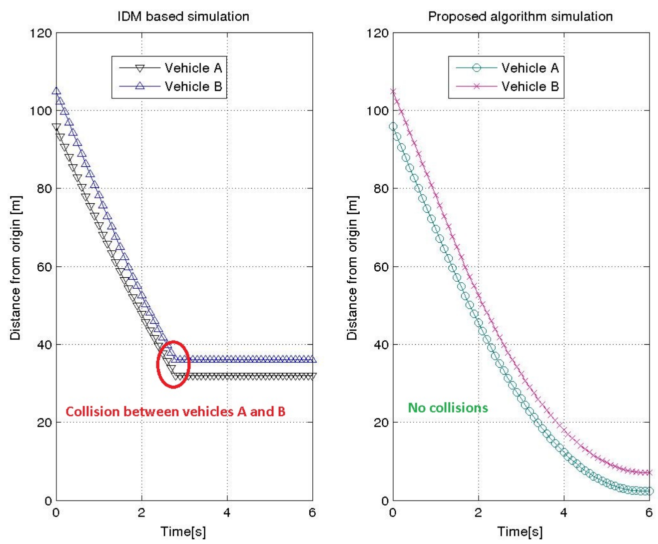


Figure 10: Locations of vehicles; leading vehicle following:IDM(left) proposed algorithm(right)

Via simulation, we show the superiority of the proposed algorithm over ACC/C-ACC algorithms like IDM, which manage to avoid forward collision at the cost of a read-collision. Although tested only on IDM, we believe our approach may be generalized to other ACC strategies, as they usually do not consider their preceding vehicles.

The proposed approach also proves that even at high velocities (96kmph) and low inter vehicular distance(5m), safety is not compromised provided the leading vehicle brakes smoothly and increases the braking strength to its maximum over Δt seconds. This split of time between gradual increase and maintaining maximum deceleration needs to be from a range (T_{range}) such that there are no collisions neither with the vehicle in front nor with the one behind. Obviously collisions can not be avoided if the distance between subject vehicle and the obstacle is too low for it to brake at even the maximum strength.

This concept of collision avoidance doesn't require constant V2V communication for CACC(or sensing for ACC), rather just once to inform about(or sense) an obstacle. Thus, chances of failure leading to a collision are pretty low. Obviously probability of accidents would be considerably reduced if range of communication systems or sensing technologies improve, but it would inturn have an impact on the communication network. The current scenario thus encourages us to look into alternate collision avoidance techniques similar to the one proposed here.

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