A New Collision Warning System for Lead Vehicles in Rear-end Collisions

Adrian Cabrera, Sven Gowal and Alcherio Martinoli

***Abstract*— Collision Warning Systems (CWS) are safety systems designed to warn the driver about an imminent collision. A CWS monitors the dynamic state of the traffic in real-time by processing information from various proprioceptive and exteroceptive sensors. It assesses the potential threat level and decides whether a warning should be issued to the driver through auditory and/or visual signals. Several measures have already been defined for threat assessment and various CWS have been proposed in literature.**

In this paper, we will focus on two time-based measures that assess both front and rear collision threats. In particular, a new threat metric, the time-to-last-second-acceleration (T_{lsa}), for lead vehicles in rear-end collision is proposed and compared with its counterpart, the time-to-last-second-braking (T_{lsb}) [18]. The T_{lsa} is a novel time-based approach that focuses on the lead vehicle (as opposed to the following vehicle). It inherits the properties of the T_{lsb} and, as such, is coherent with the human judgement of urgency and severity of threats. It directly quantifies the threat level of the current dynamic situation before a required evasive action (i.e. maximum acceleration) needs to be applied. Furthermore, different warning thresholds are proposed by considering the average driver reaction time. Its effect on decreasing the severity of a rear-end collision is studied and its reliability is tested using a well-established physics-based robotics simulator, namely Webots [13].

I. Introduction

Rear-end collisions occur when the front bumper of a car strikes the back bumper of its leading car. According to the National Highway Traffic Safety Administration (NHTSA), rear-end crashes are the most frequently occurring type of collision. They account for approximately 29% of all crashes in the U.S. and result in a substantial number of injuries and fatalities each year, making them the most common type of accident [4]. In the U.S., rear-end accidents cause 950'000 injuries and 2'000 deaths each year. NHTSA also claims that 90% of rear-end accidents are caused by delay in driver recognition and could be prevented if the driver would become aware of the situation just one second earlier.

A considerable amount of research [2, 5, 6, 11, 15] has been conducted to try to prevent such accidents by integrating a CWS on-board of the rear vehicle. The equipped vehicle uses both proprioceptive sensors (to estimate its speed, acceleration or tire friction) and exteroceptive sensors (to estimate range or range rate) to compute an assessment of potential collision threats in real-time. When the CWS detects a threat, the driver is usually warned through auditory and/or visual signals.

Adrian Cabrera, Sven Gowal and Alcherio Martinoli are with the Distributed Intelligent Systems and Algorithms Laboratory, School of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Fédérale de Lausanne. adrian.cabrera@epfl.ch, svenadrian.gowal@epfl.ch, alcherio.martinoli@epfl.ch

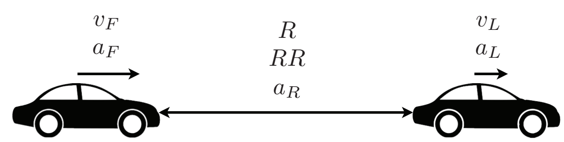


Fig. 1. Schematics for the study of a longitudinal rear-end collision: the following vehicle $\mathcal{V}_F$ traveling at velocity v_F and constant acceleration a_F is at a bumper to bumper distance R (range) from the lead vehicle $\mathcal{V}_L$, and approaching it at a closing speed RR (range rate). $\mathcal{V}_L$ is traveling at velocity v_L and acceleration a_L.

This paper aims to convey the idea that until all vehicles are equipped with such systems, it is important to not only consider threat measures for rear vehicles but also for front vehicles. To the best of our knowledge, only very few approaches have been implemented on leading (front) vehicles [3] and none focus on a time-based (rather than a distance-based) metric. Hence, we will propose a new collision warning metric (called T_{lsa}), inspired by the T_{lsb} measure [18] that informs the front vehicle's driver that he or she will be part of a rear-end collision. This warning signal may allow the driver to take an evasive action such as pressing the throttle when enough driving space is available, or, allow the vehicle to automatically honk or flash the braking lights to warn the following vehicle. In both cases the front car's belt mechanism may tighten and the headrest may move forward in a preemptive manner (mainly avoiding a whiplash - the most common rear-end collision injury).

A. Problem Formulation

As shown in Figure 1, our study considers longitudinal rear-end collisions consisting of two vehicles traveling behind one another on a straight road. In order to assess the collision threat, we need to take into account the dynamics of the situation and the measures that describe it. In other words, we have a leading vehicle $\mathcal{V}_L$ and a following vehicle $\mathcal{V}_F$. Both travel on a straight line and, as such, our dynamical system can be represented as a state $\mathbf{x}$ that includes the gap R between the vehicles (range), the speed of both vehicles v_L and v_F and their current acceleration a_L and a_F. The equipped vehicle ($\mathcal{V}_L$ for T_{lsa} and $\mathcal{V}_F$ for T_{lsb}) can also estimate its current maximum acceleration a_H^{max} and deceleration a_H^{min} knowing its current engine torque and using a tire-road friction coefficient monitor, as reviewed in [12]. Hence we have $\mathbf{x} = [R, v_L, v_F, a_L, a_F, a_H^{\text{max}}, a_H^{\text{min}}]^\mathsf{T}$. All the value of $\mathbf{x}$ (except a_H^{max} for $\mathcal{V}_F$ and a_H^{min} for $\mathcal{V}_L$) are directly measurable by either vehicle and may be affected by noise. Finally, we will use the following notation to denote the gap closing speed $RR = v_L - v_F$ (range rate) and the gap closing acceleration $a_R = a_L - a_F$.

II. Background

In this section, we summarize two important concepts: the driver reaction time and the assessment of the impact severity.

A. Driver Reaction Time

In order to correctly assess the threat of a potential collision, we need to take into account, not only the dynamics of the current situation but also the driver reaction time. The driver reaction time is a major parameter in CWS and much research is performed on measuring human driver reaction times to different stimuli under various situations. It has been shown that driver reaction times can be approximated with a lognormal probability distribution with parameters μ and σ^2 [2, 17].

Most research focus on reaction times involved when pressing the brake pedal due to an imminent frontal threat. Two main situations are analyzed. One is the normal driver reaction time towards common unexpected canonical traffic signals (e.g., lead vehicle brake lights or the amber traffic light). The other is the driver reaction time to unexpected artificial warning signals (e.g., red icon appearing in the front of the driver or auditory warning signals). Research experiments on artificial visual warning systems by means of sudden appearance of a red square reported an approximate 1.13s reaction time average [14]. The driver reaction time to an unexpected auditory signal is estimated to be 0.99s on average [9]. The driver reaction time to both visual and auditory signals is the shortest with a 0.9s on average [10]. Table I (reported and corrected here from [18]) reviews the driver reaction times in response to different types of unexpected stimuli (visual and/or auditory).

Note that, for simplicity, we will consider the reaction time of pressing the throttle pedal after receiving a visual or auditory warning the same as when pressing the brake pedal.

B. Severity assessment

Human drivers do not always react quickly enough or apply sufficient evasive action (brake or acceleration) after receiving the warning signals. To assess the severity of a collision, the Acceleration Severity Index (ASI), which has been proposed in [7, 16], is defined as follows:

$$ASI(t) = \left[\left(\frac{\bar{a}_x}{\hat{a}_x}\right)^2 + \left(\frac{\bar{a}_y}{\hat{a}_y}\right)^2 + \left(\frac{\bar{a}_z}{\hat{a}_z}\right)^2 \right]^{1/2} \quad (1)$$

where $\bar{a}_x$, $\bar{a}_y$ and $\bar{a}_z$ are the averaged component vehicle accelerations over a moving time interval of $\delta = 50$ms:

$$\bar{a}_x = \frac{1}{\delta}\int_t^{t+\delta} a_x \, \mathrm{d}t, \quad \bar{a}_y = \frac{1}{\delta}\int_t^{t+\delta} a_y \, \mathrm{d}t, \quad \bar{a}_z = \frac{1}{\delta}\int_t^{t+\delta} a_z \, \mathrm{d}t$$

and $\hat{a}_x$, $\hat{a}_y$ and $\hat{a}_z$ are corresponding threshold accelerations for each component direction. They are interpreted as the threshold values below which the driver's death risk is negligible: $\hat{a}_x = 12g$, $\hat{a}_y = 9g$ and $\hat{a}_z = 10g$ with $g = 9.81\text{ms}^{-2}$.

The ASI is a dimensionless positive quantity and is a scalar function of time. The maximum ASI value over the duration of the vehicle acceleration pulse provides a single measure of collision severity that is assumed to be proportional to the occupant risk. To provide an assessment of the occupant risk, the ASI value for a given collision acceleration pulse is compared to the established threshold values: if the ASI is over unity, the likelihood of death becomes significant. Note that values below one may still result in life-long injuries.

TABLE I

Estimates of Driver Reaction Time in seconds.

Alert Type	mean	std	μ	σ	75%	90%
none	1.25	0.6	0.12	0.46	1.53	2.02
Visual	1.13	0.52	0.03	0.44	1.38	1.80
Auditory	0.99	0.44	-0.1	0.43	1.20	1.55
Vis. + Aud	0.90	0.34	-0.17	0.37	1.08	1.35

III. Time-to-last-second-braking

In [18], a threat assessment measure, the time-to-last-second-braking (T_{lsb}), was introduced. T_{lsb} is implemented on the following vehicle $\mathcal{V}_F$ and directly quantifies the threat level when the required evasive action involves braking at the maximum possible deceleration. The authors claim, with justification (i.e. comparison with measurements made in the Crash Avoidance Metrics Partnership experiments), that the T_{lsb} is better suited to assess threats than many other CWS measures because it matches the human natural judgement. Indeed, the T_{lsb} is a time-based measure, and, as such, is more meaningful to quantify the urgency of a threat.

Two different cases are considered to estimate the T_{lsb} depending on whether the lead vehicle is expected to stop first or not. To know which situation applies, the leading vehicle stopping time t_{LS} and the following vehicle stopping time t_{FS} are estimated with

$$t_{LS} = -\frac{v_L}{a_L} \quad (2)$$

$$t_{FS} = T_{\text{lsb}} - \frac{v_F + a_F T_{\text{lsb}}}{a_H^{\text{min}}} \text{ with } v_F + a_F T_{\text{lsb}} > 0. \quad (3)$$

Generally, the condition $v_F + a_F T_{\text{lsb}} > 0$ is assumed to be true, otherwise the following vehicle is already decelerating hard enough and, therefore, no evasive action is needed. The T_{lsb} can be found through Newton's dynamics equations by assuming that both rear and front vehicles continue on their course at their current speed and acceleration for T_{lsb} seconds, after which, the following vehicle brakes at a maximum deceleration a_H^{min}. Two different cases exist, the first case, described by Equation (4), occurs when the lead vehicle gets to a full stop before the following vehicle does, the second case, described by Equation (5), occurs if the following vehicle needs to reach a full stop before the lead vehicle does.

For $t_{LS} \le t_{FS}$ we have

$$R = v_F T_{\text{lsb}} + \frac{a_F}{2} T_{\text{lsb}}^2 - \frac{(v_F + a_F T_{\text{lsb}})^2}{2a_H^{\text{min}}} + \frac{v_L^2}{2a_L} + R_{\text{min}} \quad (4)$$

and for $t_{LS} > t_{FS}$

$$R = -RR \cdot T_{\text{lsb}} - \frac{a_R}{2} T_{\text{lsb}}^2 + \frac{(RR + a_R T_{\text{lsb}})^2}{2(a_L - a_H^{\text{min}})} + R_{\text{min}} \quad (5)$$

where R_{min} is a safety range. In order to estimate T_{lsb}, it is first assumed that $t_{LS} \le t_{FS}$ and, thus, T_{lsb} can be found from Equation (4). t_{FS} is then computed with the newly estimated T_{lsb}, and we can verify whether the initial assumption $t_{LS} \le t_{FS}$ holds. If it holds, the computation of T_{lsb} is complete, otherwise T_{lsb} is calculated using Equation (5).

Zhang et al. finally propose a CWS based on three warning levels. Those are designed as follows:

- 1.5 s $\le T_{\text{lsb}} <$ 2.5 s: Visual signal
- 0.5 s $\le T_{\text{lsb}} <$ 1.5 s: Visual and auditory signal
- $T_{\text{lsb}} <$ 0.5 s: Overriding (automatic braking)

IV. New criterion proposal

Like the T_{lsb}, many threat measures used in automotive CWS focus on the rear vehicle and use braking as the evasive action to avoid rear-end collisions. However, very little research has been conducted on either warning the driver of the front vehicle or having the front vehicle warn the following vehicle. The time-to-last-second-acceleration (T_{lsa}) measure, proposed in this paper, assesses the threat level for the front vehicle. It computes the time left before an extreme evasive maneuver (i.e. full throttle acceleration) needs to be taken by the lead driver in order to avoid the collision.

A. Time-to-last-second-acceleration T_{lsa} Measure

The time-to-last-second-acceleration T_{lsa} is a time-based avoidance criterion implemented on the lead vehicle $\mathcal{V}_L$. It is inspired by the T_{lsb} measure and defines the time left for the driver before the maximum acceleration has to be applied to avoid the rear-end collision. As in [18], we assume that the following vehicle $\mathcal{V}_F$ is approaching the lead vehicle $\mathcal{V}_L$ with constant acceleration.

The new criterion directly depends on six state parameters: the current speed v_L and acceleration a_L, as well as the gap size R, closing speed RR and closing acceleration a_R and the maximum acceleration possible a_H^{max}. The vehicle proprioceptive sensors can measure v_L and a_L precisely. R and RR can be observed through exteroceptive sensors such as cameras, lidars and/or radars and a_R can be calculated with the history of the acquired RR measures. The maximum acceleration on the other hand needs the knowledge of the maximum traction of the wheels as well as the vehicle state [12].

B. Estimation of the T_{lsa} Measure

A rear-end collision occurs when the bumper to bumper gap R is less than zero ($R \le 0$). Therefore, it is clear that, from any valid state $\mathbf{x}$ ($R > 0$), a collision may only occur when the gap is closing, that is $RR < 0$. Before the T_{lsa} can be computed, those two conditions need to be satisfied, otherwise no collision is detected.

The minimum condition to avoid the collision is that the lead vehicle needs to reach the velocity of the following vehicle before the bumper gap goes to zero. That is $v_L(T) = v_F(T)$ or $RR(T) = 0$ such that $T > 0$ and $R(t) > 0$ for all $t \in [0, T]$. Therefore, assuming that both vehicles travel at their own speed and acceleration until $t = T_{\text{lsa}}$ and that,

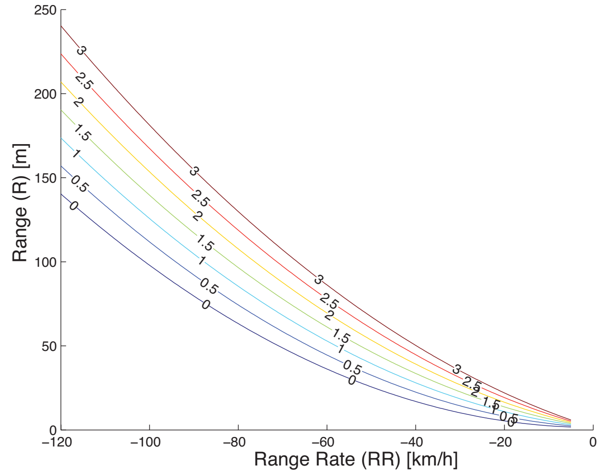


Fig. 2. T_{lsa} curves in seconds. The following vehicle $\mathcal{V}_F$ approaches a fully stopped lead vehicle $\mathcal{V}_L$ at constant speed ($a_L = a_F = 0, a_H^{\text{max}} = 4\text{m/s}^2$) for different ranges ($R$) and range rates ($RR$).

when $t \ge T_{\text{lsa}}$, the lead vehicle undergoes an evasive action ($a_L = a_H^{\text{max}}$), we have:

$$R = \underbrace{\underbrace{-RR \cdot T_{\text{lsa}} - \frac{a_R}{2} T_{\text{lsa}}^2}_{R_1} + \frac{(RR + a_R T_{\text{lsa}})^2}{2(a_H^{\text{max}} - a_F)}}_{R_2} + R_{\text{min}} \qquad (6)$$

where R_1 is the additional gap at time T_{lsa}, R_2 is additional gap when both vehicles speed are equal ($RR(T) = 0$) and R_{min} is a safety minimum range obtained at time T. The smallest root of Equation (6) gives the T_{lsa}. In Figure 2, we can observe that the new T_{lsa} follows a similar behavior than the one observed for the T_{lsb} in [18] which were well aligned with the human drivers' last-second "normal" and "hard" braking onset data recorded in CAMP experiments [10]. Thus, the proposed T_{lsa} appears to be a good candidate for threat assessment analysis.

C. Estimation of a_H^{max}

To the contrary of the maximum deceleration, which can be considered constant throughout the evasive maneuver (as done in [18]), the maximum acceleration cannot: it depends on the acceleration curves of the lead vehicle. The maximum acceleration a_H^{max} actually represents the effective acceleration of the lead vehicle as a function of its estimated engine state at time $t = T_{\text{lsa}}$ and the final matching speed $v_L(T) = v_F(T)$ at time T. The final matching speed $v_{\text{fin}} = v_L(T) = v_F(T)$ is simply given by

$$v_{\text{fin}} = \frac{a_L^{\text{max}}(v_F + a_F T_{lsa}) - a_F(v_L + a_L T_{lsa})}{a_L^{\text{max}} - a_F} \qquad (7)$$

and T is then

$$T = T_{\text{lsa}} + \frac{v_{\text{fin}} - v_L - a_L T_{\text{lsa}}}{a_H^{\text{max}}} \qquad (8)$$

By sequentially choosing a valid a_H^{max} (i.e. agreeing with the vehicle's acceleration curves), one can pick the a_H^{max} resulting in the highest T_{lsa} for which v_{fin} is attainable. As an example, let us assume we are driving a Hyundai

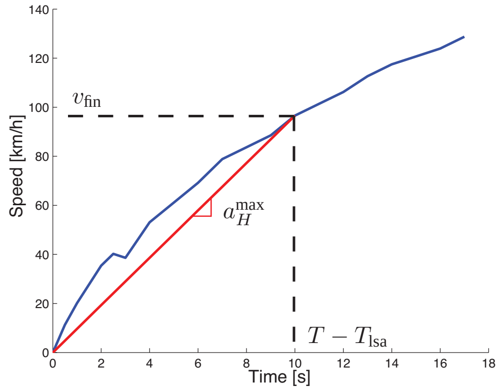


Fig. 3. Hyundai Tiburon 2.0L CVVT speed profile when applying maximum acceleration from a full stop. The estimation of $a_H^{\max}$ is achieved by evaluating the slope of the red line.

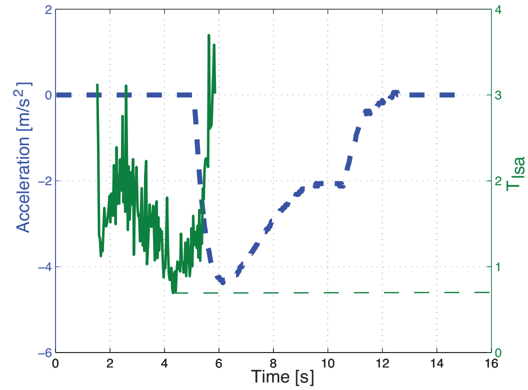


Fig. 4. Estimation of the T_{lsa} measure over time. The following vehicle $\mathcal{V}_F$ approaches at constant velocity $v_F = 60$km/h and performs an aggressive, yet realistic, stop behind a resting lead vehicle.

Tiburon 2.0L CVVT. Figure 3 shows a cut of its speed profile as a function of time when maximum acceleration is applied and the initial velocity is zero. We denote by $f(t)$ this speed profile. In a situation where we are stopped ($v_L = a_L = 0$), this speed profile is valid and thus $a_H^{\max}$ is the slope of the line drawn in red and can be calculated by $f(T - T_{\text{lsa}})/(T - T_{\text{lsa}})$. Notice that given an $a_H^{\max}$, the T_{lsa} and the final velocity v_{fin} can be computed. Hence, we can verify whether $v_{\text{fin}} \leq f(T - T_{\text{lsa}})$. If it is the case, there is the possibility to increase $a_H^{\max}$ and continue until we find the $a_H^{\max}$ resulting in the highest T_{lsa} value. In other words, we need to solve the following optimization problem:

$$\begin{aligned} \text{maximize} \quad & T_{\text{lsa}}(a_H^{\max}) && (9) \\ \text{subject to} \quad & \text{Equation (6)} && (10) \\ & v_{\text{fin}} \leq f(T - T_{\text{lsa}}) && (11) \end{aligned}$$

D. Warning Criteria in terms of T_{lsa}

The T_{lsa} provides a quantitative threat of the current dynamic situation. The rear-end collision can be avoided if the evasive action is taken while T_{lsa} is positive. As already mentioned in Section I, we propose two different warning systems based on the T_{lsa} measure:

1) **Self Warning (CWS1):** The lead vehicle warns its driver that a rear-end collision will happen. It assumes that enough driving space is available to the driver to move forward at the maximum possible acceleration.
2) **Follower Warning (CWS2):** The lead vehicle, by flashing its braking lights or honking, warns the driver of the following car that he/she should brake at the maximum possible deceleration. The motivation for using T_{lsa} rather than T_{lsb} is that the following car is not equipped with neither the sensory system nor a CWS capable of computing the T_{lsb}. Such measure is better than taking no action, but inferior to a CWS based on T_{lsb} on the rear vehicle.

In both cases the front car's belt mechanism may tighten and the headrest may move forward in a preemptive manner.

Both systems require the knowledge of the driver reaction time. As reviewed in Table I, under normal driving scenarios, 90% of all drivers reaction times are under 2 seconds. Drivers improve their reaction time to 1.8 seconds when a visual warning signal is used, 1.55 for an auditory signal and 1.35 for a visual plus auditory signal. It is also important that warning signals do not appear too often, becoming a nuisance to the driver. Therefore, the importance of choosing an appropriate warning time, so that signals are not emitted too early to reduce the frequency of appearance, but not too late to give enough time to all drivers to react, is primordial.

Issuing warning signals for CWS1 is difficult as we have no information about the future deceleration of the following vehicle. Figure 4 illustrates a common situation where the lead vehicle is stopped at a red light. The following vehicle approaches with a speed of 60km/h and starts braking with an aggressive, yet realistic behavior (dashed blue line). The following vehicle was driven by a human using a joystick within our simulation framework (see Section V). The T_{lsa} values computed over time by the lead vehicle are reported in this figure (solid green line) when Equation (9) gives a solution with $R_{\min} = 1.0$m. We observe that the T_{lsa} barely drops under the second. Hence, to avoid nuisance, we should put the initial warning threshold at about one second. However, if the following vehicle does not brake, only 70% of all drivers would avoid the collision given a visual and auditory signal. Note that about 90% of all drivers will react before the T_{lsa} drops below -0.35 seconds (i.e., 0.35s later than the last collision-free opportunity to accelerate). Figure 5 shows recorded ASI values for a similar scenario where the following vehicle does not brake and the lead driver performs the evasive action at different T_{lsa} values. It shows indirectly that 90% of the drivers reduce the collision severity by a factor of at least six, resulting in only minor injuries. In view of these, the following warning criterion based on the T_{lsa} measure for CWS1 is proposed:

- $T_{\text{lsa}} < 1$ s: Visual and auditory signal
- $T_{\text{lsa}} < 0$ s: Automatic acceleration (overriding) and/or automatic belt and headrest motion

For CWS2, we directly inspire ourselves from [18] and propose:

- $1 \text{ s} \leq T_{\text{lsa}} < 2.5$ s: Visual (blinking braking lights)
- $T_{\text{lsa}} < 1$ s: Visual and auditory (activation of the horn)
- $T_{\text{lsa}} < 0$ s: Automatic belt and headrest motion

Unless the lead vehicle is equipped with a full reasoning system capable of assessing whether an automatic acceler-

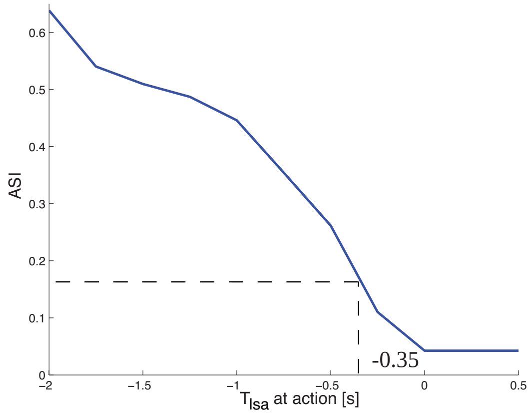


Fig. 5. Estimation of the severity of a collision (estimated with the ASI) analyzed when the evasive action is taken at different times. The following vehicle $\mathcal{V}_F$ approaches at constant velocity $v_F = 60$km/h the lead vehicle $\mathcal{V}_L$ at full stop $v_L = 0$km/h.

Fig. 6. Screen shot of the dynamic embodied vehicles. Each vehicle is equipped with four laser range finders allowing it to monitor the environment.

ation is feasible, we recommend that no overriding criteria (i.e. automatic acceleration) is used for T_{lsa}. The concern is that an automatic system can not assess with full reliability the danger that can be caused by applying full throttle acceleration on the environment in front of the car. We prefer to focus on warning the human driver who can best assess the environment.

V. Experiments

A. Setup

Experiments are conducted in Webots [13], a realistic modular mobile robotic simulator and for which we have developed a realistic car simulator plugin [8]. Webots uses the Open Dynamic Engine (ODE) [1] library and is able to simulate rigid body dynamics with high performance. Our car model (visible on Figure 6) is composed of the vehicle body and four wheels. It is able to move freely in all six degrees of freedom (DOF) in 3D space, the wheels can all spin and move vertically relative to the body, and the steering wheels can also yaw. Thus the whole vehicle has 16 DOF in total. Built in Webots based on ODE, this model already incorporates basic rigid dynamics properties including typical steering dynamics response. Additionally, we have equipped our vehicle model with four simulated SICK LMS 291 sensors (also visible on Figure 6) as to cover a $360°$ field of view. The SICK LMS 291 is a laser rangefinder, which scans at 75 Hz over $180°$ with a $0.25°$ angular resolution. Its sensing range can go up to 80m with an error of about 1cm at 30m. Note that Webots includes both nonlinear response (including delay) in sensing and actuating and models sensor noise realistically.

In our experiments, we test three CWS:

CWS0: The rear vehicle monitors the environment and applies full brake when the T_{lsb} drops below 0.25s (to account for actuation delay). The state variables are estimated by integrating over the range R measured by the laser rangefinders ($RR = \dot{R}$ and $a_R = \dot{RR}$). R_{min} is set to 1m and a_H^{min} to -5m/s^2. Note that we extend, here, the work of Zhang et al. on the T_{lsb} by providing simulation results gathered with Webots using more realistic vehicle and range sensor models.

CWS1: The lead vehicle monitors the environment and applies full throttle when the T_{lsa} drops to 0.25s. R_{min} is set to 1m and the acceleration curves of our simulated vehicles are used to compute a_H^{max}.

CWS2: The lead vehicle monitors the environment and warns the following vehicle when the T_{lsa} drops to 0.25s. The following vehicle then applies full brake.

For both CWS0 and CWS2, we consider two scenarios:

S1: The following vehicle is approaching the lead vehicle at a constant speed $v_F = 60$km/h while the lead vehicle is at a full stop $v_L = 0$km/h.

S2: Both vehicles travel at $v_L = v_F = 60$km/h and, at time $t = 5$s, the lead vehicle suddenly brakes with full deceleration.

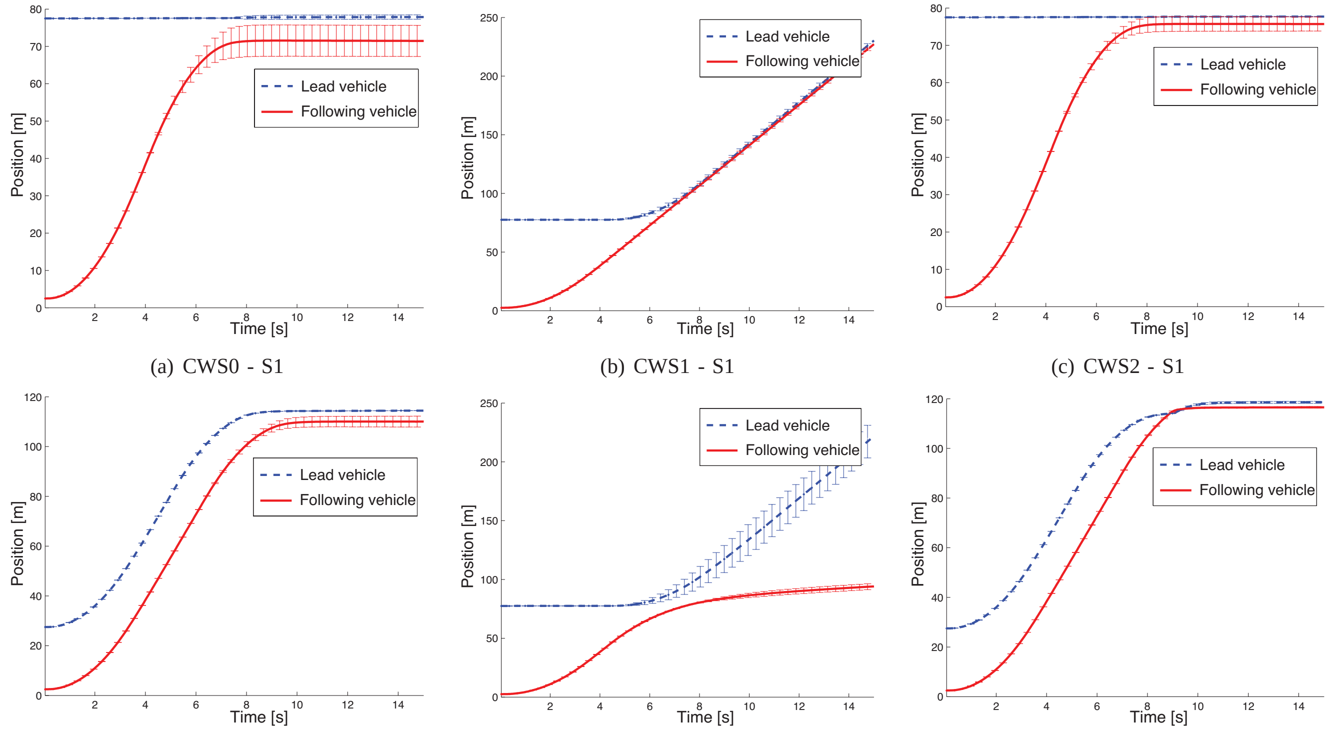
For CWS1, we consider S1 and

S3: The following vehicle is approaching the lead vehicle at a constant speed $v_F = 60$km/h and, at time $t = 4$s, applies the brake pedal at a constant deceleration (not sufficient to avoid the collision by itself).

B. Results

For each combination of scenarios and CWS, a thousand experimental runs are conducted. The mean position of the front bumper of the following vehicle and the rear bumper of leading vehicle and their corresponding standard deviation are gathered and reported in Figure 7.

All scenarios show successful collision avoidance maneuvers (except for CWS2 in S2) in more than 90% of the runs, as indicated by the standard deviation bars. Due to noise in the measurements, some collisions remain unavoidable but such experiments clearly show the validity of both the T_{lsa} and T_{lsb} measures implemented in CWS0 and CWS1. As one might expect collision happen more frequently in CWS2 as this collision warning system monitors the time of the potential collision from the point of view that the lead vehicle will accelerate (and not that the follower will brake). However, we believe that CWS2 in a more practical implementation of the T_{lsa} as it does not require the front vehicle to accelerate (which may or may not be feasible). Note that in the extreme case of scenario S2, where the lead vehicle fully brakes and T_{lsa} assumes as an evasive maneuver its acceleration, the collision severity is still drastically



(a) CWS0 - S1
(b) CWS1 - S1
(c) CWS2 - S1
(d) CWS0 - S2
(e) CWS1 - S3
(f) CWS2 - S2

Fig. 7. The mean position of the front bumper of the following vehicle and the rear bumper of leading vehicle and their corresponding standard deviation recorded for 1000 experimental runs for each scenario and CWS combination. Note that although the curves in Figure (c) seem to overlap, the cars keep a consistent 10m gap between each other.

reduced as the speed of the rear vehicle is divided by a factor two at impact (30km/h instead of 60km/h).

VI. Conclusion

A new collision avoidance warning system T_{lsa} for lead vehicles in rear-end collision is proposed and discussed throughout the paper. It is a time-based approach and, as such, is coherent with the human judgement of urgency and severity of threats. It directly quantifies the threat level of the current dynamic situation assuming that the required evasive action involves accelerating. Furthermore, warning criteria were proposed considering driver reaction times to artificial warning signals under two possible implementation of CWS using the T_{lsa}. Their effect on decreasing the severity of the accident was studied and the reliability of the system was tested in a realistic simulation framework. Future work include the integration of a complete deceleration model to make better estimates of the T_{lsa} and better warn the driver. Additional tuning of the warning criteria based on real world data still needs to be performed.

References

[1] Open dynamic engine. `http://www.ode.org/`.

[2] S. Brunson, E. Kyle, N. Phamdo, and G. Preziotti. Alert algorithm development program. *NHTSA Rear-End Collision Alert Algorithm. Final Report. DOT HS*, 809:526, 2002.

[3] T.-H. Chang and C.-J. Chou. Rear-end collision warning system on account of a rear-end monitoring camera. In *Intelligent Vehicles Symposium, 2009 IEEE*, pages 913–917, 2009.

[4] M. Distner, M. Bengtsson, T. Broberg, , and L. Jakobsson. City safety - a system addressing rear-end collisions at low speeds. In *Enhanced Safety Vehicles Conference, 21st*, 2009.

[5] A. Doi et al. Development of a rear-end collision avoidance system with automatic braking control. *JSAE Review*, 15(4):335–340, 1994.

[6] Y. Fujita, K. Akuzawa, and M. Sato. Radar brake system. *JSAE Review*, 16(2):219–219, 1995.

[7] D. Gabauer and H. Gabler. Evaluation of threshold values of acceleration severity index by using event data recorder technology. *Transportation Research Record: Journal of the Transportation Research Board*, 1904(1):37–45, 2005.

[8] S. Gowal, Y. Zhang, and A. Martinoli. A realistic simulator for the design and evaluation of intelligent vehicles. In *Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*, pages 1039–1044, 2010.

[9] G. Johansson and K. Rumar. Drivers brake reaction times. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 13(1):23–27, 1971.

[10] R. Keifer et al. Development and validation of functional definitions and evaluation procedures for collision warning/avoidance systems (final report dot hs 808 964). *Washington, DC: US Department of Transportation*, 1999.

[11] K. Lee and H. Peng. Evaluation of automotive forward collision warning and collision avoidance algorithms. *Vehicle System Dynamics*, 43(10):735–751, 2005.

[12] L. Li, F.-Y. Wang, and Q. Zhou. Integrated longitudinal and lateral tire/road friction modeling and monitoring for vehicle motion control. *Intelligent Transportation Systems, IEEE Transactions on*, 7(1):1–19, 2006.

[13] O. Michel. Webots: Professional mobile robot simulation. *Journal of Advanced Robotic Systems*, 1(1):39–42, 2004.

[14] L. Nilsson et al. Changes in driver behaviour as a function of handsfree mobile phones–a simulator study. *Accident Analysis & Prevention*, 26 (4):441–451, 1994.

[15] P. Seiler, B. Song, and J. Hedrick. Development of a collision avoidance system. *Development*, 98:417, 1998.

[16] M. Shojaati. Correlation between injury risk and impact severity index asi. *ETH Zurich*, 2003.

[17] G. Taoka. Break reaction times of unalerted drivers. *ITE Journal*, 59 (3), 1989.

[18] Y. Zhang, E. Antonsson, and K. Grote. A new threat assessment measure for collision avoidance systems. In *Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE*, pages 968–975, 2006.