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Contributed articles

Reducing Rear-end Crashes with Cooperative Systems

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Abstract

This paper presents an evaluation of the effectiveness of a cooperative Intelligent Transport System (C-ITS) to reduce rear-end crashes. Two complementary simulation techniques are used to demonstrate the benefits of the C-ITS. Traffic (VEINS) and sensor (SiVIC) simulations use realistic data related to traffic and roads in Brisbane's Pacific Motorway; driver's reaction time; and injury severity to evaluate benefits. The results of our simulations show that C-ITS could reduce rear-end crash risk by providing several seconds of additional warning to drivers.

Keywords

Rear-end crashes, Cooperative ITS, Traffic simulation.

Introduction

Rear-end collisions represent approximately one-third of all reported crashes in Queensland and often result in injuries which have long-standing consequences [1]. These crashes constitute the third most common type recorded by police. Between 2000 and 2009, rear-end crashes cost the Queensland community $1.7 billion. Rear-end crashes often arise from a complex set of interacting factors including the roadway, environment (such as poor weather conditions), vehicle capability and road user factors [2].

Rear-end crashes are over-represented on roads with higher speed limits (70-90 km/h) [3]. Signalised intersections are also rear-end crash-prone areas due to the variability in drivers' braking behaviours during the signal change. Post-crash analyses have shown that inattention and distraction, from in-car and external sources, and a deterioration of driver alertness are associated with an increased risk of involvement in rear-end collisions [1, 4, 5]. Unsafe following distances have been identified as a contributing factor in between 10% and 66% [2] of rear-end crashes.

Several engineering, education and enforcement approaches have been used to curb rear-end related crashes. There are a plethora of ITS in-vehicle technologies such as Forward Collision Warning (FCW), which provide warning to the driver and performs emergency braking on behalf of the driver when a crash is imminent [1]. However the use of Cooperative-ITS (C-ITS) to prevent rear-end crashes have not been comprehensively evaluated. Most of the studies do not take into account human factors issues (e.g. reaction time) and limitation of wireless network reliability. Furthermore there is a lack of naturalistic on-road benefit assessment mainly due to limited market penetration of such devices. In this paper, we use relevant variables such as real traffic network (Brisbane Highway), real traffic data and driver's reaction time, in a traffic simulator (VEINS), to assess the benefits of cooperative systems.

C-ITS intervention assessment: general methodology

We use simulation to evaluate the safety benefits of C-ITS. Simulation is chosen over on-road experimentations because the latter are time-consuming and require considerable resources. Simulation has its limits, but a well-designed simulation framework that integrates models of the road environment; virtual sensors and telecommunication devices; and vehicle dynamics, can be a good approximation to evaluate the performance of C-ITS applications. Empirical evaluation is not entirely removed from this process, as several of the models used in our simulation are based upon empirical data.

Two levels of simulation

Our approach is focused on simulation with two levels of abstraction. The first level of abstraction is microscopic simulation related to individual vehicle. The simulator we are using is the SiVIC-RTMaps™ framework as described in [6]. SiVIC was designed to support a limited number of vehicles (typically less than 10) and cannot simulate large traffic. The second level of abstraction allows us to simulate interaction between a large number of vehicles. It is a microscopic traffic simulation, linked to a wireless network simulator. We used the VEINS [7] framework that combines the open-source SUMO traffic simulator with the OMNet++ network simulator. The two approaches are complementary, as they allow for testing of the same scenario from different level of abstraction, namely individual vehicles, and vehicle's fleets.

Scenario

Our investigation focuses on a common scenario applied in both simulation scales. It features a string of vehicles driving on a freeway. At some point, the string's leader brakes suddenly because of an incident, which can trigger a series of rear-end crashes or near misses downstream. This scenario has several advantages:

- It focuses on rear-end crashes, which are a significant road safety problem as explained in the introduction.
- It focuses on freeways, which is a simple driving environment with few parameters to control in a simulation.
- It allows testing different approaches to FCW including non-cooperative and cooperative ones such as EEBL (Electronic Emergency Brake Lights).

Rear-end crash risk index

To assess the performance of C-ITS intervention, we use a crash risk metric based on the Time to Collision (TTC) and Intervehicular Time (IVT). Risk is a combination of the probability for an event to happen and its associated severity. The instantaneous crash risk is thus the probability of crash multiplied by the expected severity.

The crash probability can be computed from the TTC and IVT separately [8], as those two values express different driving conditions. The severity is obtained using the Equivalent Energy Speed (EES) [9] (see Eq. 4 below). The EES gives an indication of the kinetic energy that was dissipated by the collision. The EES value is then linked to probability of injuries experienced by the vehicle's occupant(s), based on the Maximum Abbreviated Injury Scale [10].

Let us have a string of n vehicles: $\{v_1,...,v_n\}$. We define several risk indicators. For a pair of vehicles *i* and *j*, there is $R_{j,i}$ (Eq. 1) that expresses the risk of collision between those two vehicles, as measured by vehicle *i*. $R_{j,i} \in [0,1]$. If the risk equals 1, the crash is inevitable or has already happened. Depending on the information available to each individual vehicle, we may have $R_{i,j} \neq R_{j,i}$.

$$R_{j,i} = R_{j,i,TTC} + R_{j,i,IVT} \qquad (1)$$

$$R_{j,i,TTC} = P_{j,i,TTC} \times g(V_j, V_i) \qquad (2)$$

$$R_{j,i,IVT} = P_{j,i,IVT} \times \max\left(g(V_j, V_i), g(V_j, V_i - \gamma TTC_{i,j})\right) \qquad (3)$$

with:

$$P_{j,i,TTC} = f(TTC_{j,i}) \qquad (4)$$

$$P_{j,i,IVT} = f(ITV_{j,i}) \qquad (5)$$

$$g(V_j, V_i) = G(EES_{j,i}) \qquad (6)$$

$$EES_{j,i} = (V_i - V_j)\frac{2m_i}{m_i + m_j} \qquad (7)$$

where $P_{j,i,TTC}$ (Eq. 4) and $P_{j,i,IVT}$ (Eq. 5) are the probabilities of crash as computed from the relevant TTC, resp. IVT; $g(V_j,V_i)$ (Eq. 6) represents the severity of a hypothetical crash where the two involved vehicles do not change their current speeds; $g(V_j, V_i\text{-}\gamma TTC_{i,j})$ represents the severity of the crash that would happen if vehicle i was to perform a sudden emergency braking manoeuvre with deceleration *γ*. The severity is based upon the likelihood *G* of severe injury or death, depending on the crash's EES. Eq. 7 gives the EES, with *V* and *m* the vehicles' speeds and masses.

A vehicle equipped with multiple sensors or C-ITS communications thus has an array of risks associated with each of the vehicles it can detect: $\{R_{1,i},...,R_{n,i}\}$. From there, we can create a global risk value $R_{g,i}$, which is defined as the global collision risk as perceived by a single vehicle *i*. This value becomes relevant when a vehicle has access to multiple sources of information. Importantly, another vehicle nearby might not have access to the same information. The value of $R_{g,i}$ for each vehicle will thus change depending on their situation and what they know about the overall driving context gathered from communicating vehicles. Eq. 8 shows how we compute $R_{g,i}$.

$$R_{g,i} = \max\left(R_{1,i}, \ldots, R_{n,i}\right) \qquad (8)$$

If all vehicles share their individually perceived risk of the driving situation we can then create an augmented collision risk called R_{aug} (Eq. 9). R_{aug} is the combined risk for the whole driving context. R_{aug} is most informative if its scope is limited; indeed, if there is a single dangerous event in a string of 1,000 vehicles, R_{aug} will only return a very small increase in the total risk.

$$R_{aug} = \frac{1}{n}\sum_{j=1}^{n} R_{g,j} \qquad (9)$$

Concretely, R_{aug} is a risk estimation (gathered from communicating vehicles) which will be greater than the local risk $R_{j,i}$ if a crash occurs among communicating vehicles. The knowledge of the overall risk R_{aug} will give extra time to drivers to react. Our approach is similar but simpler than the average-based risk valued computed in [11], as we do not weigh the risk values received from other vehicles.

From few vehicles to a large fleet

Previous SiVIC simulation result using 5 vehicles

Our previous research [6] implemented the vehicles' string scenario in SiVIC with a five vehicles platoon. We recorded the local and global risks for the last vehicles of the string and then compared each risk indicator; the goal was to show whether using a C-ITS application increases the drivers' awareness of the risk. To compare both approaches, we defined a crash risk threshold of 0.4. A risk higher than the threshold would require the driver to take evasive actions otherwise the vehicle would crash.

At first, we measured the local risk ($R_{j,i}$) with a non-cooperative ITS system. The local risk could warn drivers on average five seconds before they potentially collide with the vehicle in front. However, this system gave them no information on the crash risk associated with the original emergency braking occurring several vehicles in front of them.

Table 1: Variations of *dt* over six runs

Event begins at... (s)	t_A	$t_{L,5}$	dt
47.29	51.94	58.85	6.91
57.27	60.55	67.82	7.27
50.0	53.52	59.86	6.34
97.45	101.05	108.28	7.23
96.77	99.93	107.2	7.27
379.85	383.05	390.66	7.61

Accordingly, we investigated the performance of a C-ITS system. We used dt as our main metric, where $dt = t_{L,i} - t_{A.}$ $t_{L,i}$ is the time when the local risk ($R_{j,i}$) passes the threshold for vehicle i, and t_A is the time when R_{aug} does the same. In all of the simulated runs, R_{aug} passed the threshold well before $R_{4,5}$, and shortly before $R_{3,4}$ which means that vehicles four and five have extra time to prepare for emergency actions. Table 1 shows the values obtained for six simulated runs compared to $t_{L,5}$ only. On average, vehicle five has $\overline{dt} = 7.1$ seconds extra time to react when it uses C-ITS.

Rationale for using VEINS

In the previous findings, the simulated C-ITS system showed it had the potential, for a given vehicle, to give on average seven seconds of additional warning time compared to a purely local system. Overall, R_{aug} signalled the danger three to four seconds after the initial emergency braking. This suggests that apart from the few vehicles immediately following the leader, the other vehicles in string would benefit from this system by having more time to prepare. Drivers would be alerted, slow down or engage in evasive manoeuvre, limiting the scope of the incident.

However, since we were not able to simulate more than five vehicles in SiVIC we were not able to verify whether that the benefit holds at larger scale. Additionally, an intervention that is positive in the first few vehicles might have unforeseen consequences when considering the larger string. For example, in [12] the immediate braking created additional lower severity crashes when vehicles were not all equipped with the system. This highlights the needs for larger scale simulation. In the remainder, we will do so using VEINS. However, one should note that traffic simulation is not the most appropriate medium for simulating safety-related ITS applications. Indeed, vehicle's behaviour is controlled by car-following models that rarely allow for a crash to happen. In our case, by using the risk we can still study safety C-ITS application; indeed, the risk derives from the TTC and IVT. SUMO's car-following model will still allow for plausible TTC and IVT values.

Methodology

In this new study, we implemented a 45km long section of Brisbane's Pacific Motorway in SUMO (Fig. 1). The section covers both driving directions from the Coronation Drive exit in the CBD to Ormeau, including all entry and exit ramps, interchanges and some neighbouring large roads. All lanes are accurately represented.

Instead of five vehicles, we consider a much larger number of vehicles corresponding to the actual traffic flow on the Pacific motorway. We inject into SUMO the traffic volumes recorded by induction loops along that portion of the network. The simulation runs for two minutes with a traffic volume equivalent to the one measured at 7am. About 2,500 vehicles are injected on the road. One minute into the scenario we trigger an incident by having a randomly selected vehicle (the leader) brake suddenly. Many variables are recorded during the run, but we will only need a limited subset to estimate risks:

- Position (X,Y)
- Speed
- Acceleration
- ID of the vehicle in front
- Following distance

VEINS pre-existing functions simulate the complete WAVE stack; we selected the two-ray interference propagation model as it is more realistic compared to a simple free-space propagation model and fits well with our own previous research [13]. Most of the work was centred on implementing the functions necessary for playing the emergency scenario and the C-ITS application.

Results

We run the scenario as described in the previous section and extract the risks, specifically the estimated augmented risk R_{aug} and the local risks Rj,i. We define a danger threshold of 0.4, when the risk has reached a value high enough to warrant intervention by the driver or an ITS system. We select this value based on the specific methodological limitations of VEINS, compared to SiVIC.

In Fig. 2, we show the evolution of the risks depending on the number of vehicles considered when computing R_{aug}. Indeed, the number of vehicles considered when computing R_{aug} will influence its value. In our simulation, despite the heavy traffic injected into the highway, there were only about a dozen vehicles within a 500 metres (on the same lane) radius around the incident (crashing vehicle). Thus, we show R_{aug} computed with three, four and five vehicles (plus the leader). The 'A' curve is R_{aug}, while the other curves represent the local risk estimated by each vehicle in the vicinity: $R_{1,2}$ is 'D', $R_{2,3}$ is 'B', $R_{3,4}$ is 'C', $R_{4,5}$ is 'E', and $R_{5,6}$ is 'F'. The horizontal line is the risk threshold previously defined.

Table 2 summarises the results extracted from those curves in terms of extra time gained by using R_{aug} to warn the drivers instead of just their local $R_{j,i}$. Those results are in line with our previous findings in SiVIC, which shown no benefits for the first couple of vehicles (Vehicles 2 and 3 never benefit from R_{aug}), but increasing benefits further upstream. However, if too many vehicles are taken into account when computing R_{aug}, the useful additional warning time does not realise (R_{aug} remains under the threshold, not warning drivers). It is important to note that without crashes in VEINS, we can never have R=1.

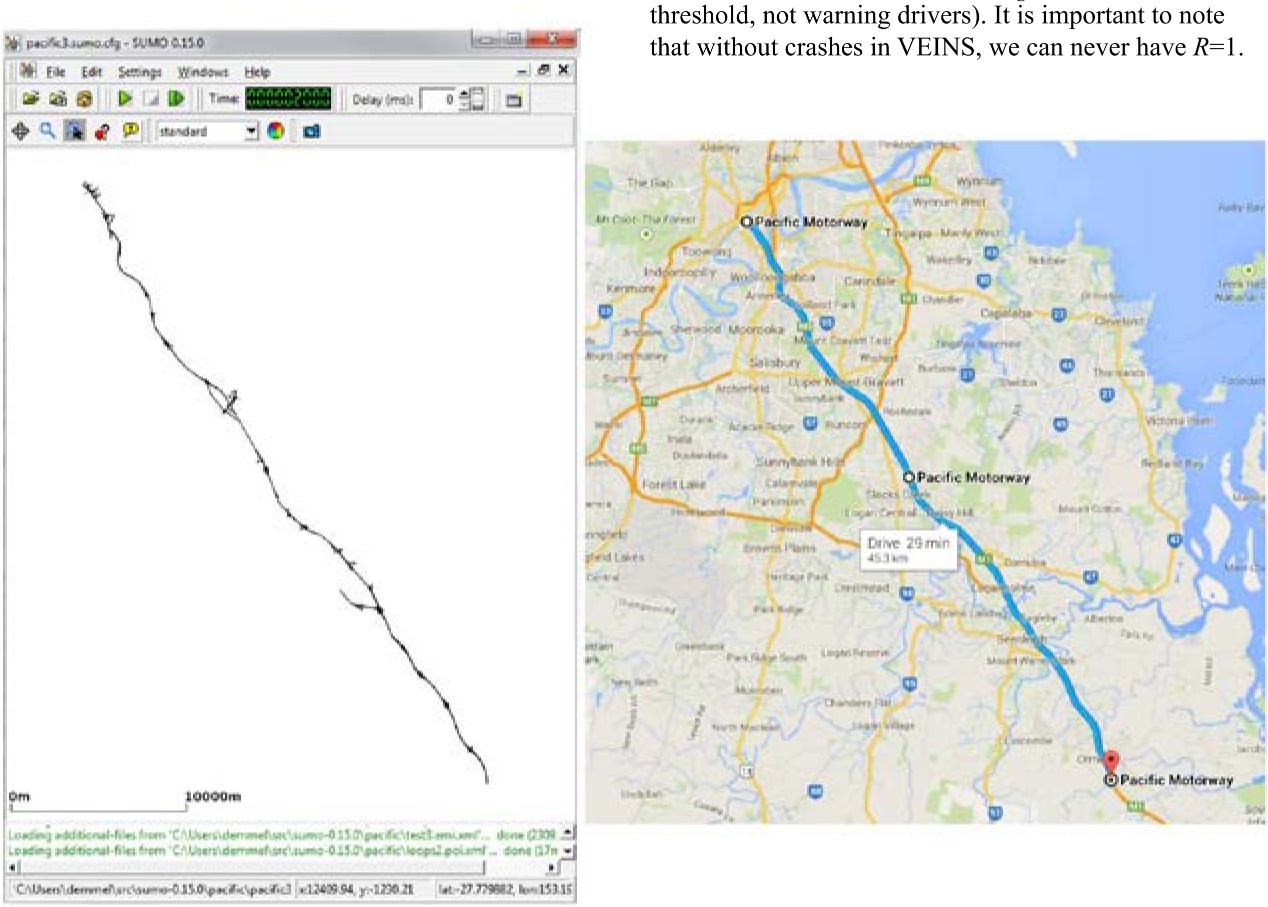

Figure 1. Map of the SUMO scenario (left) and its location in Brisbane

Otherwise, this would have allowed R_{aug} to rise higher whenever the first crash took place.

In Fig. 3 we force the second vehicle ('D' curve) to crash six seconds after the initial event. We can see that R_{aug} immediately reflects this increased danger (a crash *did* happen) for the whole group, and crosses the threshold at 6.3 seconds into the event. As a result, the following vehicles benefit from additional warnings of 0.7, 3.1, and 6.4 seconds, respectively for vehicles 4, 5 and 6 (also shown in Table 2). This scenario is perfectly in line with our previous results in SiVIC. Compared with the benefits seen in Table 2's second-to-last row, one can see how R_{aug} is useful to describe the total risk of the driving situation, especially if a very risky event has already happened such as a crash or a near-miss.

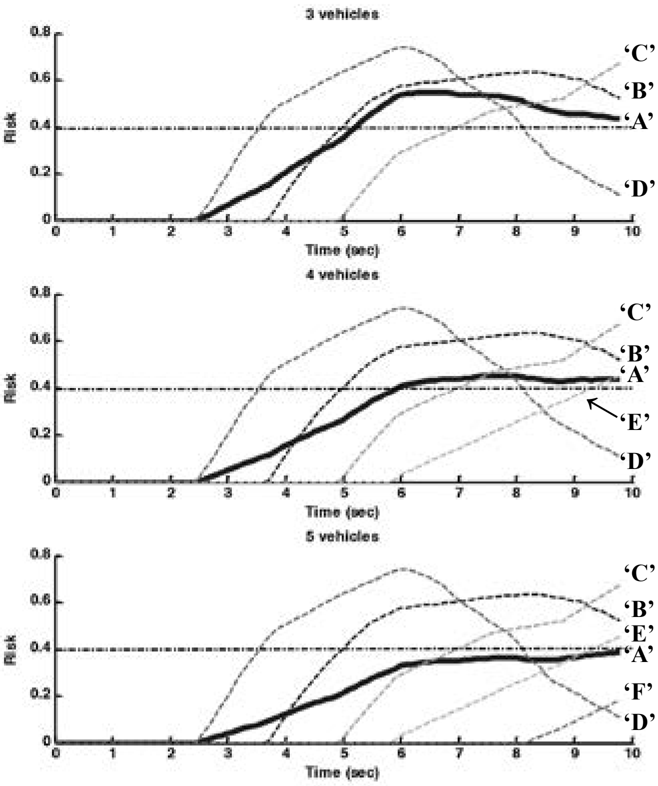

Figure 2. Augmented and local risks for 3, 4 and 5 vehicles (plus leader) following the leader – R_{aug} is the 'A' curve

Conclusion

This paper used simulation techniques to demonstrate the safety benefits of C-ITS on a motorway. Our simulation scenario consists of generating a crash and observing how following vehicles react to crash risks and avoid pileups with and without C-ITS. We used realistic data such as traffic flow and road geometry of the Pacific Motorway. The crash risk estimation is based on solid theories. We showed that the use of C-ITS to transmit crash risk (warning), gathered from communicating vehicles, before a driver could actually perceive it locally, gives drivers extra time to react and mitigate multi-car pileups. C-ITS is a disruptive technology and there is a need to understand the effects of introducing such technology on human factor issues.

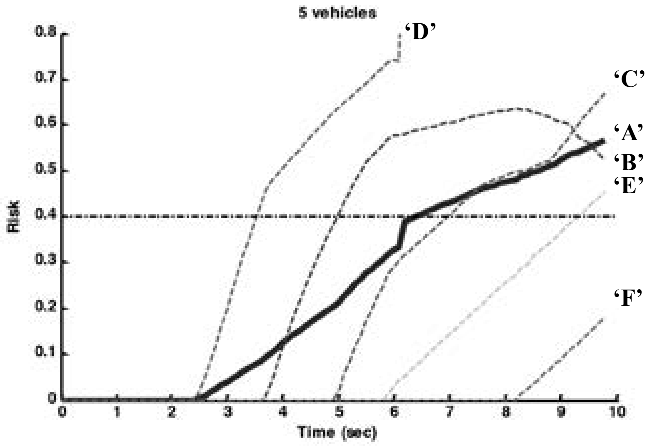

Figure 3. Risks for five vehicles with vehicle two forced to crash

Table 2: Additional warning time offered by C-ITS over local sensors for each vehicles

Number of vehicles accounted in R_{aug}	R_{aug} passes threshold at... (s)	Benefit for vehicle 2 (s)	Benefit for vehicle 3 (s)	Benefit for vehicle 4 (s)	Benefit for vehicle 5 (s)	Benefit for vehicle 6 (s)
3	5.2	None	None	+1.7		
4	6.0	None	None	+1.0	+3.3	
5	10.0	None	None	None	None	+2.7
5 + *crash*	*6.3*	None	None	*+0.7*	*+3.1*	*+6.4*

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Autonomous emergency braking – the next seat belt?

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Introduction

Autonomous Emergency Braking or AEB is a safety technology which monitors the traffic conditions ahead and automatically brakes the car if the driver fails to respond to an emergency situation. It is one of the most significant developments in vehicle safety since the advent of the seat belt or the airbag. As technology improves, the numbers of fatal and serious injuries on UK roads are reducing. With improved vehicle structures, improvements to the road infrastructure and consumer test programmes such as Euro NAP, the number of fatalities has continued to fall, from over 7,000 in the 1970s to just 1,754 in 2012 in the UK alone [1].

However, some types of injury have been proportionally increasing in recent years - in particular injuries to vulnerable road users and pedestrians. We have also seen a significant rise in whiplash and associated personal injury claims. Auto braking technologies, such as AEB, can help to reduce the kind of incidents that result in these significant injuries by preventing the crash from happening at all.

Some of the reduction in casualties we have seen on UK roads is due to improvements in commonly recognised safety systems, such as seat belts and airbags; defined as passive safety systems that aim to prevent or reduce injury in a crash. However, AEB can be defined as an active safety system, operating before the crash happens and aiming to prevent the crash from occurring in the first place, or to reduce its severity. With the increasing technological complexity and computing power accessible from a modern vehicle's control systems, the availability and performance of these active safety systems are improving rapidly. Human error accounts for 90% of crashes, so it is easy to understand how driver intervention systems can help to substantially reduce the likelihood of a crash.