Crash Risk Assessment with Cooperative Systems

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Abstract

Crash risk is the statistical probability of a crash. Its assessment can be performed through ex post statistical analysis or in real-time with on-vehicle systems. These systems can be cooperative. Cooperative Vehicle-Infrastructure Systems (CVIS) are a developing research avenue in the automotive industry worldwide. This paper provides a survey of existing CVIS systems and methods to assess crash risk with them. It describes the advantages of cooperative systems versus non-cooperative systems. A sample of cooperative crash risk assessment systems is analysed to extract vulnerabilities according to three criteria: market penetration, over-reliance on GPS and broadcasting issues. It shows that cooperative risk assessment systems are still in their infancy and requires further development to provide their full benefits to road users.

Keywords

Crash risk assessment, Cooperative Vehicle-Infrastructure Systems (CVIS), GPS, Vehicle-to-Vehicle (V2V), market penetration

Introduction

Decentralised information systems based on inter-vehicular communications and cooperation have drawn increasing attention in recent years as hardware/software capacities to process and store data on large scale and fast enough to be relevant to the timescale of automotive applications have emerged. For the field of Intelligent Transportation Systems (ITS), Cooperative Vehicle-Infrastructure Systems (CVIS) present a major potential for numerous applications ranging from safety to comfort functions. Crash risk assessment is part of these applications.

This paper is divided in three sections: (1) cooperative systems; (2) analysis of selected cooperative systems; and (3) contribution of augmented maps. In the first section we will provide an introduction to CVIS and their contribution to road safety in general and crash risk assessment in particular. Then in a second section we will analyse a few selected CVIS-based risk assessment systems with three criteria related to market penetration, sensibility to GPS and communication issues. In a last third section we will outline a few improvements that augmented maps, as a possible future research avenue, can bring to CVIS according to the second section’s criteria.

Cooperative systems

Cooperative Vehicle-Infrastructure Systems (CVIS) are gathering a lot of interest in the automotive industry [1-4]. For example the European COOPERS project [5] is aimed at creating a complete integrated network between vehicles and the infrastructure through continuous wireless communication. This continuous communication enables services such as cooperative traffic management, accident and incident warning, roadwork information, variable speed limits, congestion information, etc. Historically CVIS have started as a solution to the creation and management of vehicles groups as well as automated control of these groups. This concept is called platooning, as described by Broqua et al. [6] or Tank and Linnartz [7].

One of the major contributions of CVIS is that they allow to extend the perceptive horizon of the ego-vehicle further than the driver’s natural limit, i.e. further than one’s eyesight range [8] (the ego-vehicle is defined as the vehicle on which the local referential is centred, e.g. in this context the
vehicle that performs risk assessment relatively to other vehicles and objects). This applies to pure visual
range as well as obstructions within the visual range. For example Von Arnim et al. [9] showed how
infrared and radio communication devices on a vehicle and surrounding infrastructure can be used for
road sign detection and cooperative traffic lights (the latter similarly to the work by Yoshizu et al. [10]).
Occluded signs can be detected earlier and long-range identifications by on-board sensors confirmed, as
well as the traffic lights’ state displayed to drivers in order for them to prepare for the appropriate action
as they approach without visibility. Unsurprisingly in the literature the most common contribution of
CVIS to crash risk assessment is related to this extension of the perception. In general the recognised
improvements brought on by CVIS are: (1) extension of the sensors’ field of view; (2) acquisition of valid
data on neighbouring vehicles; and (3) exchange of data that one vehicle’s sensors could not remotely
measure, such as data directly related to the driver’s state (e.g. the driver’s state of vigilance, or any
physiological data).

Crash risk is defined as the statistical probability of a crash. It can be assessed by evaluating the relative
significance of a set of contributing factors. Contributing factors are related to: (1) the driver; (2) the
vehicle; and (3) the environment. Inexperience, speed and weather conditions are, respectively, examples
for each set of the contributing factors. As of today few studies have considered these contributing factors
together [11]. Crash risk assessment can be done via statistical analysis of crashes databases or in
real-time by using in-vehicle sensors such as radars or laser scanners.

Crash risk is often studied ex post, analyzing crash data to determine the risk at a location according to the
previous crashes at that particular location. For example Pasupathy et al. [12] created a model to predict
crash risk on highways plans prior to construction based on statistical crashes data of existing highways.
Another example can be found with Cromley [13] where contributing risk factors are extracted from
statistical analysis. The approach described by Abdel-Aty et al. [14] is half-way between prediction and
the aforementioned analytical approach: conditions that are known to increase crash risk from previous
crashes data are identified in real-time. The same approach is followed again by Abdel-Aty et al. [15] but
taken to another driving context. They are based on establishing relationships between past crashes and
current traffic data. Crash risk is determined based on the analysis of current traffic patterns measured in
real-time by induction loops.

Some of the parameters than can be used in order to assess crash risk can be found in table 1.

<table>
<thead>
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<th>Parameter</th>
<th>Related contributor(s)</th>
<th>References</th>
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<tbody>
<tr>
<td>Time to collision (TTC) with neighbouring</td>
<td>Vehicle</td>
<td>[16-18]</td>
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<tr>
<td>vehicles/infrastructure</td>
<td>Environment</td>
<td></td>
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<tr>
<td>Emergency/alert messages sent by other vehicles</td>
<td>Environment</td>
<td>[16]</td>
</tr>
<tr>
<td>Relative geographic-based risk inferred from</td>
<td>Environment</td>
<td>[13, 19]</td>
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<td>statistical data</td>
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<tr>
<td>Meteorological data</td>
<td>Environment</td>
<td>[20]</td>
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Table 1: List of parameters for crash risk assessment.

The most commonly used real-time assessment method is based on the Time to Collision (TTC) between
the ego-vehicle and other objects (vehicles or obstacles) — the TTC is usually considered along the
longitudinal axis; it can also be named the Time to Line Crossing (TLC) when considered on the
transversal axis [21]. We will consider them as equivalent — The TTC can be computed based on
sensors’ data obtained only within the ego-vehicle or augmented with data received from other vehicles or
the infrastructure as we will detail later in this paper. A probability of crash can then be computed from
the TTC and weighted according to the precise situation.

The potential benefits in term of road safety that CVIS could provide are currently assessed by a number
of researchers. It can be safely argued that they present a considerable potential. The most common
example is collision warning and prevention where CVIS are used to assess in real-time collision risk and
alert the driver in consequence. Lytrivis et al. [22] presented a path prediction system fusing inertial data
and digital map data that uses cooperation between vehicles to enhance its performance. Proprioceptive
data are exchanged between vehicles so the path prediction system would identify 92% of impending
collisions within a radius of 400 metres around the ego-vehicle. Ammoun et al. [17] described a similar
system. Tsugawa et al. [23] described a cooperative system aimed at providing assistance to elderly
drivers. In that case by cooperating with vehicles driven by elderly drivers, “average” vehicles can reduce the risk of collision introduced by elderly drivers’ different behaviours. A simple system warning drivers of traffic lights’ states as described by Yoshizu et al. [10] is enough to reduce crash rate by 96% if market penetration is maximal. Broadly, the right balance of fundamental parameters such as communication range, frequency, protocols and minimal necessary market penetration in CVIS is still an unsolved issue.

As we mentioned previously a common method to assess crash risk is based on the computation of the Time to Collision (TTC). In order to work this method requires a precise measurement of the distance between the ego-vehicle and other objects susceptible to collide with it. This measurement can be obtained single-handily by the ego-vehicle through on-vehicle sensors such as radars, laserscanners or vision-based sensors. These sensors are sensibly more precise than the human eye to measure distances and relative speeds between objects but suffer from similar limitations in terms of range or angular opening. With CVIS technologies one can bypass these limitations.

A simple method to improve the knowledge on the other objects’ position is to share position data. Typically GPS position data can be gathered and transmitted through wireless communication to other vehicles. Ammoun et al. have worked on the subject in two papers [17, 24] as an example of a fully CVIS-based risk assessment system. In their first paper [24] they describe an anti-collision system for crossroads situation based solely on the use of GPS data. It performs a probabilistic estimation of the collision risk. Vehicles are modelled as elliptically-shaped zones of probable presence in order to take into account the imprecision on GPS data. A collision is said to occur whenever two zones overlap. Trajectory prediction is based on a Kalman filter in order to take into account the vehicles’ speeds and accelerations as well as errors introduced by the GPS.

**Analysis of selected cooperative systems**

CVIS offer numbers of benefits as illustrated in the previous section; however, no such thing as a perfect system exists. Our aim is to show some of the vulnerabilities of CVIS-based systems: to do so we have selected three criteria that apply to the current CVIS-based systems. These criteria are: (1) the influence of the system’s market penetration; (2) the system’s over-reliance on GPS as its main sensor and thus its sensibility to GPS imprecision; and (3) the system’s sensibility to broadcasting issues. A system is deemed “vulnerable” if any of these criteria applies to it. We selected these three particular criteria as they form a common trend of issues encountered in the literature with most of the CVIS-based systems; they should be taken into account when designing CVIS-based systems in order for them to provide the full array of their benefits to road users.

The first criterion is related to market penetration. Market penetration is an important issue as some systems that offer considerable theoretical benefits can be made irrelevant by an absence of usage by the main public or a slow rate of market penetration: it is called the “network effect syndrome” [18]. The initial users of a system usually cannot benefit completely from this system because the market penetration is too limited to be relevant. A well-designed CVIS-based system would take into account this effect and insure that the service it provides is not completely dependant on the level of market penetration. Some researchers have taken market penetration in account. For example the improvement in response time by communication-enabled vehicles as shown by Liu and Ozguner [25] did not become significant until a market penetration of 20% was taken into account.

The anti-collision systems by Ammoun et al. (lane-change manoeuvre [17] and crossroads [24]) are good examples of systems vulnerable according to our first criterion. These two systems are based on the exchange of GPS position information between vehicles (further explanation and their vulnerability according to our second criterion are provided below). An equipped vehicle cannot communicate with a non-equipped vehicle — or even be aware of its presence — which makes the system inefficient until a large number of vehicles are equipped. This shortcoming is acknowledged by Sengupta et al. [26]: “The principal limitation of the concept is that effectiveness depends on the neighboring vehicles being [communication] equipped. There is an ongoing effort to find alternative communication-based active safety concepts able to deliver safety benefits at low or moderate market penetrations”. Sengupta et al. have developed a similar system to Ammoun et al. based on the exchange of GPS information to provide collision warning to the drivers. The main difference between these systems is that Sengupta et al. system has a broader scope of situations in which it can provide warning. It includes lane change and crossroads.
collision warning but also blind spots and forward collision warning which have not been considered by Ammoun et al.

On the other hand it must be acknowledged that several researches have tackled this vulnerability. Mourllion [16] studied the effect on crashes of a automatic braking system. This system uses V2V to disseminate an alert message to other vehicles when an on-board sensor detects a crash (e.g. an accelerometer). Some vehicles are equipped to receive this alert message; whenever they do so an automatic system triggers a braking response bringing the vehicle to a stop. Mourllion studied the impact of market penetration on this system’s efficiency at reducing rear-end crashes severity. Crashes’ severity, i.e. the crash’s impact on drivers’ health, instead of the number of crashes is considered in this study; a large number of crashes leading to a few injuries is better than a small number of crashes leading to important, life-threatening injuries or outright fatalities. The study shown that this automatic braking response while increasing the number of crashes (due to vehicles braking automatically far away from the initial crash) actually reduces the severity of rear-end crashes by 25% when only 5% of the vehicles are equipped with this system.

The second criterion is the over-reliance on GPS and thus the sensibility to GPS imprecision and outage. A system is vulnerable based on this criterion if it is reliant on GPS as its sole/main sensor or if GPS is susceptible to introduce major errors into the system’s assessment. Most of commercially available GPS have a positioning error that can reach as much as 3 metres. Differential GPS or Carrier-Phase Enhanced GPS are more precise (sub-metric error) but sensibly more expensive or requiring specific infrastructure so they are not considered as reasonable sensors for mainstream vehicles. Some systems aim at reducing the cost of sensors and use only GPS and, in the case of cooperative systems, commercially available IEEE 802.11 (Wi-Fi) radios. This for example is the case with Dao et al. [27] where simple GPS and Wi-Fi are used to measure the vehicles’ positions at the lane-level on multi-lane roads. Such a precise localisation is normally not possible with commercially available GPS; cooperation between vehicles allows reducing the positioning error on GPS measurements to bring their accuracy within the lanes’ dimensions.

The work by Ammoun et al. [17] is also a good example of vulnerability according to our second criterion. The anti-collision system is relying solely on GPS. As it is an anti-collision system for lane changes, the situation present no particular risk in terms of view obstruction, negating the specific advantages of cooperation. If the GPS is unavailable or fails, the anti-collision application will be lost. Similarly if the imprecision on GPS becomes too important the system will see its performances degrading quickly. Ammoun et al. other work on crossroads anti-collision [24] presents the same problem. The system uses a Kalman filter to filter and to predict vehicles’ trajectories; however, a Kalman filter is also vulnerable to a large imprecision on GPS data and might diverge significantly. Kalman filtering does not protect the system from GPS unavailability either, though it can be significantly enhanced if inertial data are available. This in not the case in Ammoun et al. crossroads anti-collision system; the Kalman filter is only reducing GPS noise error. In their lane manoeuvres anti-collision system inertial data are available but are not exchanged between vehicles; inertial data are only used for computing the lane change trajectory. Lytrivis et al. [22] on the other hand do take into account inertial data, thus reducing their vulnerability to over-reliance on GPS.

The third criterion is the vulnerability to broadcasting issues, especially the so-called “broadcast storm”. CVIS-based systems function within large wireless networks incorporating potentially hundreds of vehicles within communication range of each other (typically 500 metres). Several information dissemination techniques exist for these type of networks: flooding (a-periodic and periodic), epidemic, proximity, opportunistic and highway-specific [28]. CVIS-based systems have to be designed taking in account the relevance of information exchanged on the network. A broadcast storm will happen if too many messages are exchanged. This is typically the case when flooding dissemination is used; irrelevant messages are conveyed all over the network without discrimination and clutter relevant messages [29]. We have found that most of the systems described in the literature do not take into account broadcasting issues. Some authors acknowledge this issue, such as Sengupta et al. [26], but others make no mention of it. In all instance, these systems are thus vulnerable to the broadcasting issues criterion.

A summary of vulnerabilities for some systems described previously in this paper can be found in table 2....
Contribution of augmented maps

Any CVIS-based application must take into account the three criteria we have outlined in the previous section. Otherwise their promised benefits might be undermined to the point cooperation does not offer any significant advantage compared to non-cooperative systems. We have seen in the previous section that current systems do not systematically take into account these criteria or, at least, one of them. Researchers should consider these aspects while designing their systems as a system can be rendered inefficient by vulnerabilities according to our criteria if not weighted in during the design phase.

It is also important to take into account the outcome of a system when designing it. Some passive advanced driving assistance systems (ADAS) — cooperative or not — do not need a considerable precision or stability of their sensory inputs. For example a navigation application or an application that warns the driver of road works, changed infrastructure, congestions or crashes ahead does not need a sub-metric precision in its ego-vehicle’s GPS localisation. The market penetration is not either a problem for these systems and their users can benefit more completely from them even with low penetration rates.

Other passive and active ADAS have more stringent needs. A cooperative anti-collision application or a crash risk assessment application need application to know precisely where the vehicles are located, which is why they are vulnerable to GPS imprecision. At the highest level of requirements we found active applications such as collision avoidance/mitigation (via automated braking for example) and autonomous driving.

CVIS-based systems can take advantage of techniques such as augmented maps. There are four actors on the road that sensors can provide information on, and thus that can be used by a cooperative system: (1) the driver; (2) the vehicle; (3) the environment/infrastructure; and (4) obstacles. Information on each of these actors provides for a complete local map. As we explained in the first section, CVIS typically extend the perceptive horizon. Augmented maps push this logic to its extreme. Augmented maps centralise information gathered on all the four actors from various sources. They thus provide redundant information when comparing information gathered directly by the ego-vehicle to information received from other sources. Different sensors can augment information on one object: an obstacle detected by a laserscanner can be identified as a vehicle ahead by a vision-based sensor or via an exchange of information with the said vehicle. The typical information transfer concerns vehicular, environmental and obstacles-related information.

With these techniques the general vulnerability to CVIS can be reduced. Vulnerability to our second criterion — over-reliance on GPS — can be reduced. Vulnerability to our first criterion — market penetration — can also be reduced if vehicles are equipped with their own sensors and do not rely solely on communication to get information on their surroundings. Augmented maps cannot influence vulnerability according to our third criterion; separate measures must be taken to do so.

Conclusion

In this paper we have provided an outlook at the rapidly developing field of the cooperative systems for ITS applications. While they show a considerable potential, they still require thorough design process and
cost benefit assessment. We have shown that current CVIS are vulnerable to three simple criteria related to market penetration, over-reliance on GPS and broadcasting issues. Future crash risk assessment systems using CVIS must tackle these vulnerabilities in order to provide their full benefits to their users. We have mentioned augmented maps as a possible research avenue for solving at least two vulnerabilities.

References


