Development of a Prototype Intersection Collision Avoidance System under VII

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DEVELOPMENT OF A PROTOTYPE INTERSECTION COLLISION WARNING SYSTEM UNDER VII

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Abstract

Vehicle collisions at intersections account for a large percentage of overall traffic accidents, a good portion of which are fatal. A large number of these accidents can be avoided by a warning system which makes a driver aware of potential collisions on the road, thus allowing the driver enough time to prevent such situations. This paper presents the design of a prototype intersection collision warning system based on Vehicle Infrastructure Integration (VII). Underlying the system are wireless communications, positioning technology, and information technology that ensure accurate and timely safety information.
INTRODUCTION

In the United States, more than 40,000 people are killed by roadway accidents every year, 21 percent of which occur at intersections. Every year, more than 6.3 million road crashes are reported, of which intersection crashes account for more than 45 percent [1] [2]. For many years, improving intersection safety has been remaining on the priority list of many transportation jurisdictions all over the country.

Over the time, efforts to address intersection safety issues have been pursued in multiple dimensions including education, enforcement, better intersection design, and application of advanced technologies. Public education has been on-going for years teaching drivers and pedestrians to follow traffic rules and driving defensively. Law enforcement has attempted to prohibiting driving under influence (DUI), to deter red light running, and to discourage the use of cell phones during driving. Better intersection design has involved optimizing signal timing and raised intersections. While these efforts have been working well, safety enhancements brought about by advanced technologies have successfully complemented and supplemented the above solutions.

The subject of intersection collision avoidance/warning system has drawn considerable attention in the past decade as technology advances. Karr [3] provided an overview of the chief projects that are receiving a strong emphasis under the Intelligent Vehicle Initiative (IVI). A number of intersection collision/warning systems were reported and their underlying working principles include multi-radar [4], vision-based [5], infrastructure-based [6] [7] [8], vehicle-based [9], vehicle-to-vehicle cooperative [10] [11], and infrastructure-vehicle-cooperative [7, 12] [13] [14]. Other related work has been reported on dilemma zone warning system [15] [16] and advanced prediction algorithms [17] [18] for accidents.

This paper continues the direction of applying advanced technologies to improve intersection safety by presenting the development of a prototype intersection collision warning system under Vehicle Infrastructure Integration (VII)[19]. The paper first discusses the concept of VII and its enabling technologies. This is followed by the design of the prototype intersection collision warning system and field test results.

SELECTION OF VII EMABLING TECHNOLOGIES

Vehicle Infrastructure Integration (VII) was one of the new initiatives developed at the United States Department of Transportation (USDOT) in 2004. The VII initiative proposed the use of vehicle-to-vehicle and vehicle-to-roadside communications to innovatively address transportation safety issues. It is envisioned that future vehicles, when they come out of automobile manufacturers, are equipped with on-board equipment (OBE) consisting of computing devices, global positioning system (GPS), and telecommunication devices (on-board unit, OBU). Road-side equipment (RSE) consisting of computing devices and telecommunication devices (roadside unit, RSU) will also be deployed at roadside such as intersections. As the VII initiative rolling out, it is expected that more abundant, timely, and accurate information will be available to help address transportation issues. With VII, what we did in the past may be done better and what we were unable to do in the past may become possible.
At the core of VII are sensor and communication technologies including global positioning system (GPS) and dedicated short range communications (DSRC). Low latency and accurate data perception were the two key factors in selecting a suitable GPS receiver. For accurate positioning of the vehicle, we needed a GPS with an accuracy of about 3 m and update of the GPS should occur every second. A wide range of GPS products were considered and short-listed. We eventually choose Magellan AC12 board for our purpose because the board provides a reasonable balance between cost and accuracy. In addition to its reasonable accuracy, the board also has two bidirectional serial RS232 ports for communication with other peripheral devices. It is envisioned that, as the prototype evolves, more accurate GPS will be considered. For Dedicated Short Range Communications (DSRC), low latency, range of warning, and interface were the major concerns in selecting a suitable transceiver. Considering that an 802.11p transceiver is not commercially available at the moment, we used a surrogate 802.11b transceiver from Airborne Direct Serial Bridge Development Kit which works in a range of 100 m. It is envisioned that, once an 802.11p transceiver becomes available, the surrogate will be replaced with the true DSRC transceiver.

**DESIGN OF THE PROTOTYPE SYSTEM**

**SYSTEM REQUIREMENTS**

Our main concerns when designing the system are:

- **Low latency.** Quick real-time updates are very important to the system especially since vehicles travel large distances in very short periods of time.
- **Accurate data perception.** The accuracy with which a vehicle's location and speed can be estimated is extremely important. For example, a vehicle 500 m away approaching the intersection at 50 mph is less of a threat than a vehicle 450 m away traveling at the same speed.
- **Warning range.** In order to ensure that a driver has a reasonable amount of time to stop the vehicle once warned of potentially running the red light, we need to establish an appropriate distance at which vehicles should be warned.

**PRINCIPLE OF OPERATION**

The immediate goal of the prototype system is illustrated in Figure 1.

![Figure 1 Principle of operation of the prototype system.](image-source:technologyreview.com)

The principle of operation of the prototype system is the following:
1. When a vehicle (the moving car) approaches the intersection near the end of green interval, the signal box (RSE) is warned of traffic light turning red.
2. A message sent from RSE to the moving car (OBE), asking for speed and position of the OBE.
3. OBE responds by sending back the requested speed and location information. The RSE then calculates whether moving car is likely to run red light.
4. If yes, vehicles on the conflicting approach (such as the waiting car) will be warned of the potential danger.

SYSTEM BLOCK DIAGRAM

The prototype system block diagram is presented in Figure 2. The block diagram consists of four components: traffic light, RSE, and 2 OBEs (1 in moving car and 1 in waiting car).

- **The OBE of moving car**: The OBE consists of a GPS which constantly determines the location and speed of the car in which the unit is located. This information is logged by a laptop and sent to the transceiver, which sends it to the Roadside Unit.

- **RSE**: The RSE transceiver receives the speed and location information from the OBU of moving car. It verifies if the light is turning red anytime soon, and if it is then it calculates whether the moving car will run the red light. If it will run the red light, then a warning signal is sent to the transceivers of all OBEs. The core algorithm which takes into account all factors such as probability of a vehicle running the light and human reaction time represents the function of the RSE laptop.

- **Traffic Light**: We are simulating the traffic light on a microcontroller. The microcontroller has an external clock which helps it keep track of the period of time the light should remain a certain color. It is directly connected to the Roadside Unit laptop, to which it sends a control signal defining the point after which the RSE needs to consider all messages from the OBE as Event Messages.

- **OBE of both cars**: OBE Transceivers receive warning signal and forward warning to respective laptops. The Laptops display alarm.

![Figure 2. Prototype system block diagram](image-url)
SYSTEM ALGORITHMS

This section presents the algorithms that support the above concept of operation.

Warning Algorithm

A warning algorithm resides in the RSE which constantly monitors the state of traffic signal and OBEs within range. Figure 3 shows the flow chart of the warning algorithm which determines when to send out alarm signal. The following information is needed to determine whether a car will run red light: vehicle speed, time before light turns red, vehicle deceleration rate, delays due to human and machine.

![Flow chart of the warning algorithm](image)

**Figure 3. Flow chart of the warning algorithm**

Road Calculations

Road calculations answer the question “Can car clear?” To facilitate discussion, the intersection under analysis is sketched in Figure 4 where:

- Car1 (the subject vehicle) is approaching the intersection and Car2 is located somewhere on a conflicting approach.
- Dc is the length of clear zone. If a vehicle is in this zone, it is guaranteed to pass intersection safely before light turns red. Dc is the distance traveled in time left before red light less the sum of vehicle length and intersection width. \( D_c = v_i t_{amber} - L - W \)
- Dd is the length of dilemma zone where drivers have difficulty to decide whether to proceed or stop.
- Ds is stopping distance consisting distance traveled during perception-reaction time and braking distance. \( D_s = t_{pr} v_i + \frac{V_i^2}{2a} \)

![The intersection under analysis](image)

**Figure 4. The intersection under analysis**
To obtain the length of clear zone, a chart is constructed showing clear zone as a function of approaching speeds, as shown in Figure 5. $D_{c30}, D_{c25}...D_{c5}$ represent 30s, 25s...5s respectively before light turns red. So, if we take 56 kph (35 mph), and there are 5s before light turns red, we see car needs to be about 60m within distance from stop line.

![Figure 5. Determination of clear zone length](image)

With the above preparation, road calculation algorithm is presented in Figure 6 where variables are defined above except the following: $t_s$ time to reach stop line, $t_{tg}$ time for light to turn green, and $D_t$ distance from stop line.

![Figure 6. Road calculation algorithm](image)

The algorithm works as follows:

- Start calculations at 30s before light turns red – the number is arbitrarily chosen which is early enough to begin useful calculations,
- Check if a car is in its clearance zone,
- If it is, then no action because in clearance zone, car is guaranteed to cross intersection safely before light turns red,
- If not, check if car is accelerating positively or approaching intersection at constant velocity,
- If neither (then decelerating obviously), calculate D_s, the distance for car to come to stop at present deceleration rate.
- If D_s < actual distance of car from stop line (D_l), then safe. So go back and check for latest update on car speed and location.
- Example: car needs 200m to come to a complete stop at its deceleration rate. Car is actually 300m away from stop line. Thus, 100m buffer. Safe
- Example: car needs 200m to come to a complete stop at its deceleration rate. Car is actually 100m away from stop line. Not enough distance left. Alarm!!
- If D_s < D_l: Alarm!
- Then, check time left for car to reach stop line,
- If time for car to reach stop line is less than time for the light to turn green again, alarm!
- Example: time to reach stop line = 5s. Time for light to turn green again = 7s. So, in 5s the light is still red. Alarm!
- Example: time to reach stop line = 5s. Time for light to turn green again = 3s. So, in 5s the light is still green. No action
- Go back to where we checked for whether car is accelerating positively or cruising
- If doing those, then calculate the deceleration rate required for car to come to a stop at stop line
- If calculated deceleration rate is in comfortable range, no action
- If not in comfortable range, check for time to reach stop line. Once again:
  - Example: time to reach stop line = 5s. Time for light to turn green again = 7s. So, in 5s the light is still red. Alarm!
  - Example: time to reach stop line = 5s. Time for light to turn green again = 3s. So, in 5s the light is still green. No action

**System Latencies**

Considering that safety applications require very low latency, it is important to check system latencies of the proposed design. Calculation of system latencies is summarized in Figure 7.
Analysis of the design based on the figure shows the following:

- There is no latency between wired equipments, e.g. traffic light (or GPS)-laptop and laptop-transceiver.
- There is only slight latency between transceivers. The payload consists of vehicle position (longitude and latitude) and speed information which totals to 12 bytes or 96 bits. Such a payload needs to be sent twice per second. Therefore, the bandwidth required is 192 bps (bit per second). The total available bandwidth is 19,200 bps. The supply to demand ratio is 100:1. Very safe.
- 2 types of messages sent between transceivers: Status (lots of time left for light to turn red) and event (light turning red very soon)
- In status message stage: RSE saves data
- In event message stage: RSE does calculations to determine if car will run red light
- When back to status message stage: RSE saves all calculations and data and reverts to stage 1 of status message
- Main delay is only car and human delay (not delays between equipment)
- Comfortable deceleration rate number taken from US DOT publication: nominal deceleration rate is 3 m/s². Human and machine delay taken from human factor analysis.

**System Connectivity**

Figure 8 shows the connectivity of the prototype system. The RSE resides at roadside (e.g. in signal controller cabinet) and the RSE is simulated using a laptop and an access point. The OBE sits in a moving vehicle and the OBE is simulated with a laptop, a GPS receiver, and a transceiver (Airboredirect Serial Bridge). Data transmission uses 802.11g protocol.

![Figure 8. Connectivity of the prototype system](image)

**FIELD TEST RESULTS**

Field test of the prototype system has been conducted in the Spring 2007. The key objective of the field test was to ensure successful operation of the prototype involving a moving car and a car waiting at the intersection. If the moving car is about to run red light, a warning should alarm in both cars. Otherwise, no action should be taken. Other objectives included reality check of system latency and identification of potential problems that could fail the system.

Figure 9 illustrates the test site and test equipment. The test site was a straight section of the ring road at UMass Amherst football stadium. The 3 small side pictures illustrate how the prototype system was set up. This set-up restricted us to the 100 meter range of the router as the connectivity when we approached from out-of-range to in-range was not very quick.
This is due to our using an 802.11b/g transceiver which is not built for use in time-valued systems like these. Thus, as the RSE longitude and latitude can be fed into the road calculation code as a 'hard number'; i.e. constant, we can have the RSE along with the OBE within the vehicle, since according to the road calculations, the system would always detect the RSE to be at the intersection. Thus, we could test the system from distances as large as we needed.

![Test site and test equipment](image)

The following tests were conducted in the field test: a clearance zone test, an acceleration test, a deceleration test, and a system test. These tests are detailed below. The purpose of these tests was to check the system under various conditions in order to detect if there was any flaw in the system design which could lead to the failure of the system.

1. Clearance Zone Test

This test was to check if the system correctly detected whether a vehicle is in the clearance zone. Thus, the part of the flowchart we tested is shown in Figure 47 (shows for light currently green).

![Figure 10 Clearance zone check in flowchart](image)
As explained earlier, if the light is currently green, we want the vehicle to be inside the clearance zone; otherwise if the light is red, the vehicle should be outside the clearance zone. Table 1 shows one of the field test data for this test. We have replaced the To... data from 1 (to red. currently green) and 2 (to green. currently red) to R and G for easier understanding. As the light is currently green, we want the vehicle to be within the clearance zone, which it is throughout the test, thus no alarm was generated.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Traffic Light (s)</th>
<th>To...</th>
<th>Distance (m)</th>
<th>Clearance Zone Distance (m)</th>
<th>Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5528</td>
<td>45</td>
<td>R</td>
<td>118.992</td>
<td>591.08</td>
<td>0</td>
</tr>
<tr>
<td>15.497</td>
<td>43</td>
<td>R</td>
<td>89.761</td>
<td>647.529</td>
<td>0</td>
</tr>
<tr>
<td>17.062</td>
<td>41</td>
<td>R</td>
<td>57.571</td>
<td>680.93</td>
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<td>18.574</td>
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<td>R</td>
<td>24.42</td>
<td>705.57</td>
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<td>37</td>
<td>R</td>
<td>14.44</td>
<td>704.386</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1 Field test data for clearance test

2. Acceleration Test

This test was for a vehicle accelerating towards the intersection. Thus, if the light is red when the vehicle crosses the intersection, the alarm should be set-off. The portion of the flowchart under test is shown in Figure 11 (shows for light currently green).

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Traffic Light (s)</th>
<th>To Distance (m)</th>
<th>Clearance Zone Distance (m)</th>
<th>Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.335</td>
<td>2</td>
<td>R</td>
<td>190.554</td>
<td>11.839</td>
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<tr>
<td>17.062</td>
<td>25</td>
<td>G</td>
<td>158.786</td>
<td>407.735</td>
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<tr>
<td>18.0885</td>
<td>23</td>
<td>G</td>
<td>124.882</td>
<td>397.206</td>
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<tr>
<td>18.790</td>
<td>21</td>
<td>G</td>
<td>89.304</td>
<td>375.770</td>
</tr>
<tr>
<td>19.222</td>
<td>19</td>
<td>G</td>
<td>53.827</td>
<td>346.396</td>
</tr>
<tr>
<td>19.384</td>
<td>17</td>
<td>G</td>
<td>16.587</td>
<td>310.705</td>
</tr>
</tbody>
</table>

Table 2 Field test data for acceleration test
3. Deceleration Test

The deceleration test is where a vehicle decelerates until it comes to a complete stop at the stop line. Figure 12 shows the portion of the system flowchart being tested (shows for light currently green).

![Figure 12 Deceleration test flowchart](image)

Table 3 shows one of the field test data for this test. We are always inside the clearance zone during a green light, thus sending the flow of control to check the vehicle's acceleration rate. The first set of data seems to indicate the vehicle accelerated because the predicted deceleration column is filled. The distance of the vehicle at that point is greater than 30 meters so the comfortable deceleration range is 0 to 1.5 m/s². Since the predicted deceleration rate is within the range, no alarm is set off. In the second set of data, we see that the vehicle has decelerated, and Dstop > Dloc as time to reach stop line (time stop) has been calculated. This time is 6.137 seconds while the time left for the traffic light to turn green is 33 seconds. Thus, the alarm is set-off. The vehicle continues to seen to break the red light, and thus, the alarm is set off repeatedly.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Traffic Light (s)</th>
<th>To Distance (m)</th>
<th>Clearance (m)</th>
<th>Predict acc (m/s²)</th>
<th>Time Stop (s)</th>
<th>Alarm</th>
</tr>
</thead>
<tbody>
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<td>17.8185</td>
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<td>16.766</td>
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</table>

Table 3 Field test data for deceleration test

4. System Test

This test begins at the vehicle a long distance away from the intersection. The vehicle accelerates, then decelerates until it comes to a stop at the intersection. Then it slowly creeps up and crosses the intersection. The test takes place under red light, and thus the alarm should finally be triggered. This test validates the entire system shown in Figure 6.

Table 9 shows the field test data. We see that the vehicle is at rest at the beginning. Once it starts moving, the light is currently red, and it is outside the clearance zone which means it is safe. However, at the speed of 11.0691 m/s, it moves within the clearance zone,
thus branching the flow of control to check the acceleration rate of the vehicle. We see that the car is accelerating until its speed reaches 16.1987 and during the entire time its predicted deceleration rate is within the comfortable range, thus not triggering the alarm. Once it starts decelerating, we see that the alarm is not triggered despite $D_{stop} > D_{loc}$ because in order to prevent premature alarms, we have set the system to only alarm in the case of a decelerating vehicle, when it is within 40 meters of the stop line. When the vehicle enters the 40 meter range, we see that $v_2$ (from Section 4.6) is negative, which means that the vehicle can stop before the stop line at its present deceleration rate. The vehicle comes to a complete stop with no alarm having been triggered off so far. But the vehicle starts accelerating again to cross the intersection during a red light and this time when detected that the vehicle is inside the clearance zone, and is moving, the alarm is triggered.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>TL. (s)</th>
<th>Distance (m)</th>
<th>Clearance (m)</th>
<th>Distance Stop (m)</th>
<th>Acceleration (m/s²)</th>
<th>Pred. a (m/s²)</th>
<th>$v_2$ (m/s²)</th>
<th>Time Stop (s)</th>
<th>Alarm</th>
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Table 4 Field test data for system test

**SUMMARY AND FUTURE WORK**

Intersections frequently act as limiting points in a transportation network. Two goals compete at intersections: safety and mobility. Traditionally there are levels of intersection control: basic rules, stop/yield sign, and signalization. It is interesting to note that sometimes an intersection controlled by human/police may achieve these goals better. This is because every driver receives explicit instruction whether to proceed or stop (which ensures safety) and the police can adjust control based on the dynamics of the demands. After VII has been fully deployed and vehicle-vehicle and vehicle-roadside communications enabled, it is possible to develop the fourth level of intersection control - an “electronic policeman” – which sits at the intersection and dynamically directs traffic. It is envisioned that the prototype system developed in this paper can be integrated into the fourth level of intersection control.

Taking a broader perspective, the abundant, accurate, and timely information enabled by vehicle-vehicle and vehicle-roadside communications can be fully leveraged at global level (concerning an entire transportation system), local level (concerning a local area such as an intersection), and vehicle level (concerning a vehicle and its surroundings). At the global level, proactive traffic control will be possible to deploy resources in advance to prevent accidents and congestion from occurring; at the local level, cooperative traffic control is possible by encouraging vehicle-vehicle and vehicle-roadside cooperation; at the vehicle
level, attentive driving assistance is feasible by using inter-vehicle communication to deploy in-vehicle control.

In this study, we developed a prototype intersection collision warning system under VII. The study included selection of VII enabling technologies, design of the prototype system including system requirements, principle of operation, system block diagram, and system algorithms. We also conducted field test and presented the test results. We conclude that all specifications have been met. The system passed all tests and performs within suitable parameters.

It is understood that the development of an intersection collision warning system involves many issues. For example, a technical issue can be “what is GPS signal is blocked in urban canyon?” and a liability issue can be “who should be responsible if the safety message gets lost or the system malfunctions?” Though these issues are very important for a complete intersection collision warning system, our attention is limited to the proof-of-concept study in the beginning phase with the understanding that these issues will be progressively addressed as the system evolves into the full-blown version.

In terms of future work, several directions of improvement have been identified and summarized below.

- GPS Inaccuracy Correction. This study used a low accuracy GPS receiver as part of the OBE which may affect the calculation of vehicle speed and position to certain degree. A high accuracy GPS receiver will serve the purpose better in future development.
- 300 Meter Range Router. Replace the 100 meter router with a 300 meter router. Since the 300 meter range is theoretical and the signal degrades as one approaches 300 meters, use the 100 meter router as an Access Point to boost the signal across 300 meters. The best alternative is to use DSRC transceivers, which unfortunately are only available in 2008.
- All Road Calculations on OBE. To avoid institutional problems such as who is responsible for malfunction of RSE, all road calculations can be done at the OBE side. Thus, the RSE acts only to broadcast all messages received by it, which makes it an economically replaceable unit.
- Robustness of Road Calculations. As noticed, our system at times gives out premature alarms. The current system finds it difficult to accommodate sudden braking. Thus, the road calculations pertaining to comfortable deceleration range and different speeds need to be taken into account. The system needs to be “transient” in nature versus the current system where it works in black and white - above 1.5 m/s² : alarm. Else: No alarm.
- Improve Code Efficiency. A major improvement would be to abolish the necessity of HyperTerminal in attaining GPS data. Other improvements include editing the current code into a more compact version.
REFERENCES

