Development of a VII-enabled prototype intersection collision warning system

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Abstract: This paper presents the design of a prototype intersection collision warning system based on Vehicle Infrastructure Integration (VII). This system involves Roadside Equipment (RSE) at an intersection and several units of On-Board Equipment (OBE), each in a moving vehicle. When an equipped vehicle approaches the intersection, its OBE queries the remaining time before the light turns red from the RSE which is synchronised with the intersection signal. Combining its own speed and position, the OBE determines the likelihood of running the red light. In case of such a hazard, the OBE warns its driver and notifies other OBEs wirelessly.

Keywords: collision warning; DSRC; dedicated short-range communications; intersection; safety; VII; vehicle infrastructure integration.

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1 Introduction

In the USA, more than 40,000 people are killed by roadway accidents every year, 21% 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% (FHWA, 2006; BTS, 2005). 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 going on for years teaching drivers and pedestrians to follow traffic rules and driving defensively. Law enforcement has attempted to prohibit Driving Under Influence (DUI), to deter red light running, and to discourage the use of cell phones during driving. Better intersection design has involved optimising signal timing and raised intersections. Whereas these efforts have been working well, safety enhancements brought about by advanced technologies have successfully complemented and supplemented the above-mentioned solutions.

The subject of intersection collision avoidance/warning system has drawn considerable attention in the past decade as technology advances. Karr (2004) 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 (Jocoy and Pirson, 1999), vision-based (Atev et al., 2005), infrastructure-based (White and Eccles, 2002; Ferlis, 2002; BMI, 2003), vehicle-based (Lee, 2004), vehicle-to-vehicle cooperative (Huang and Miller, 2004; Misener et al., 2005) and infrastructure-vehicle-cooperative (Ferlis, 2002; Misener et al., 2001; Shladover, 2005; Shladover and Tan, 2006). Other related work has been reported on dilemma zone warning system (Moon, 2002; Moon et al., 2002) and advanced prediction algorithms (White, 2004; Sun et al., 2004) 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 VII (USDOT, 2006). 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.

2 Selection of VII enabling 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 (OBU). Roadside Equipment (RSE) consisting of computing devices and telecommunication devices (RSU) will also be deployed at roadside such as intersections. As the VII initiative is 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 GPS and Dedicated Short-Range Communications (DSRCs). 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 shortlisted. 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 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 Airbornedirect 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.

3 Design of the prototype system

3.1 System requirements

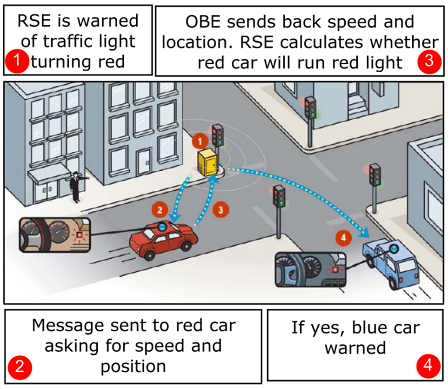
Our main concerns when designing the system are:

- *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 travelling at the same speed.
- *Warning range*: 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.

3.2 Principle of operation

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

Figure 1 Principle of operation of the prototype system (see online version for colours)



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 more likely to run red light.

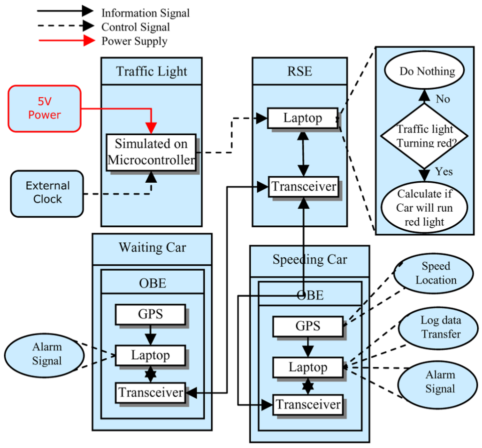
4 If yes, vehicles on the conflicting approach (such as the waiting car) will be warned of the potential danger.

4 System block diagram

The prototype system block diagram is presented in Figure 2. The block diagram consists of four components: traffic light, RSE and two OBEs (one in moving car and one 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 RSU.
- *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 colour. It is directly connected to the RSU 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 (see online version for colours)



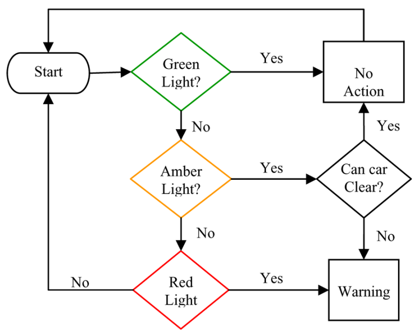
5 System algorithms

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

5.1 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 owing to human and machine.

Figure 3 Flow chart of the warning algorithm (see online version for colours)



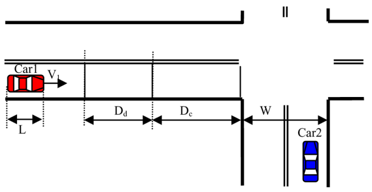
5.2 Road calculations

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.
- D_c is the length of clear zone. If a vehicle is in this zone, it is guaranteed to pass intersection safely before light turns red. D_c is the distance travelled in time left before red light less the sum of vehicle length and intersection width. $D_c = v_1 t_{\text{amber}} - L - W$.
- D_d is the length of dilemma zone where drivers have difficulty to decide whether to proceed or stop. To be clearer, if a car is present in dilemma zone, then it cannot stop in time and neither can it cross the intersection safely before the light turns red. This region is present right before the clearance zone. One of the aims of traffic light design is to reduce the dilemma zone.
- D_s is the stopping distance representing the distance travelled during the perception–reaction time (t_{PR}), and the braking distance (v_1 speed of the vehicle and a the deceleration rate).

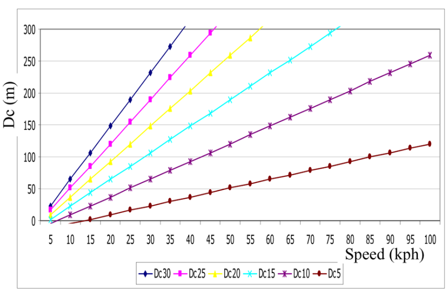
$$D_s = t_{PR} v_1 + \frac{v_1^2}{2a}.$$

Figure 4 The intersection under analysis (see online version for colours)



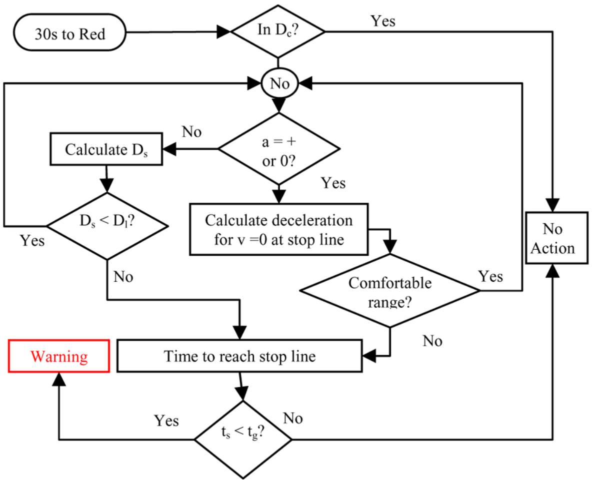
To obtain the length of clear zone, a chart is constructed showing clear zone as a function of approaching speeds, as shown in Figure 5. D_c30, D_c25, …, D_c5 represent 30 s, 25 s, …, 5 s, respectively, before light turns red. So, if we take 56 kph (35 mph), and there are 5 s before light turns red, we see car needs to be about 60 m within distance from stop line.

Figure 5 Determination of clear zone length (see online version for colours)



With the above-mentioned preparation, road calculation algorithm is presented in Figure 6 where variables are defined earlier except the following: t_s time to reach stop line, t_g time for light to turn green and D_l distance from stop line.

Figure 6 Road calculation algorithm (see online version for colours)



The algorithm works as follows:

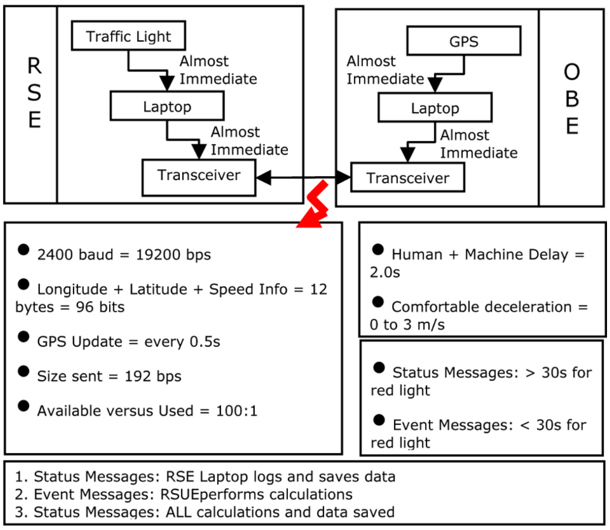
- Start calculations at 30 s before light turns red – the number is arbitrarily chosen, which is early enough to begin useful calculations.
- Check if a car is in its clearance zone.
- If it is, then no action because in clearance zone, car is guaranteed to cross intersection safely before light turns 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 $D_s < D_l$ (actual distance of car from stop line), then safe. So, go back and check for latest update on car speed and location.
- Example: car needs 200 m to come to a complete stop at its deceleration rate. Car is actually 300 m away from stop line. Thus, 100 m buffer. Safe
- Example: car needs 200 m to come to a complete stop at its deceleration rate. Car is actually 100 m 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 = 5 s. Time for light to turn green again = 7 s. So, in 5 s the light is still red. Alarm!

- Example: time to reach stop line = 5s. Time for light to turn green again = 3 s. So, in 5 s 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 = 5 s. Time for light to turn green again = 7 s. So, in 5 s the light is still red. Alarm!
  - Example: time to reach stop line = 5 s. Time for light to turn green again = 3 s. So, in 5 s the light is still green. No action

5.3 *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 summarised in Figure 7.

Figure 7 Calculation of system latencies (see online version for colours)



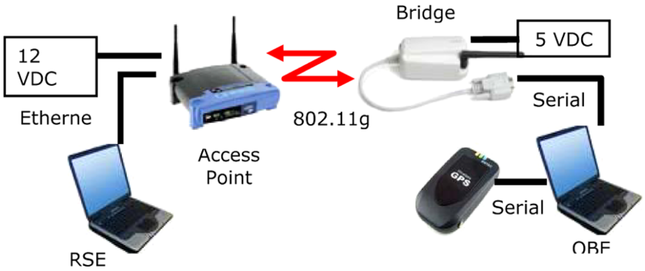
Analysis of the design based on the figure shows the following:

- 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.
- Two types of messages are 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/s^2. Human and machine delay taken from human factor analysis.

5.4 *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 (Airbornedirect Serial Bridge). Data transmission uses 802.11 g protocol.

Figure 8 Connectivity of the prototype system (see online version for colours)



6 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 three small side pictures illustrate how the prototype system was set up. This set-up restricted us to the 100 m 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.

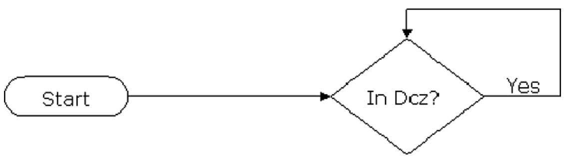
Figure 9 Test site and test equipment (see online version for colours)

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 here. The purpose of these tests was to check the system under various conditions to detect if there was any flaw in the system design, which could lead to the failure of the system.

6.1 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 flow chart we tested is shown in Figure 10 (shows for light currently green).

Figure 10 Clearance zone check in flow chart



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 1 Field test data for clearance test

Speed (m/s)	*Traffic light* (s)	*To*	*Distance* (m)	*Clearance zone distance* (m)	*Alarm*
13.55	45	R	118.99	591.08	0
15.50	43	R	89.76	647.53	0
17.06	41	R	57.57	680.93	0
18.57	39	R	24.42	705.57	0
19.55	37	R	14.44	704.39	0

6.2 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 flow chart under test is shown in Figure 11 (shows for light currently green).

Figure 11 Acceleration test in flow chart (see online version for colours)

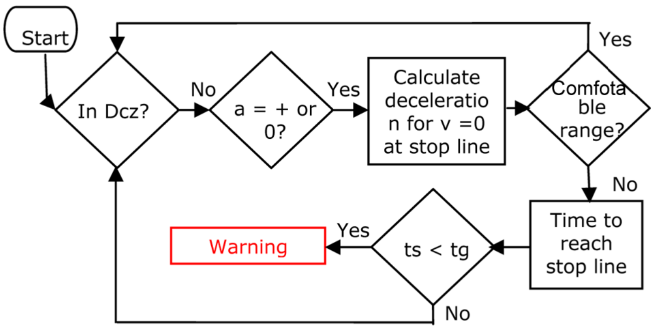


Table 2 shows that we are always outside the clearance zone during green light and inside the clearance zone during red light, which is unwanted and branches the flow of control to check the acceleration rate of the vehicle. The predicted deceleration rate is within comfortable range till the speed reaches 19.222 m/s. At that point, the predicted deceleration range becomes −3.464 m/s^2, which is greater than 1.5 m/s^2. We then check the time for the vehicle to reach the stop line −2.883 s, whereas the time left for the light to turn green is 19 s. Thus, the alarm is set off. The predicted deceleration rate continues to be outside of comfortable range and the time to reach the stop line reduces at a rate faster than the countdown of the traffic light, therefore the alarm keeps being triggered.

Table 2 Field test data for acceleration test

Speed (m/s)	*Traffic light* (s)	*To*	*Distance* (m)	*Clearance* (m)	*Predict acc* (m/s^2)	*Time stop* (s)	*Alarm*
15.34	2	R	190.55	11.84	–0.62		0
17.06	25	G	158.79	407.74	–0.92		0
18.09	23	G	124.88	397.21	–1.31		0
18.79	21	G	89.30	375.77	–1.97		0
19.22	19	G	53.33	346.40	–3.46	2.88	1
19.38	17	G	16.59	310.71	–11.33	0.86	1
19.55	15	G	20.55	274.37	–9.30	1.06	1

6.3 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 flow chart being tested (shows for light currently green).

Figure 12 Deceleration test flow chart (see online version for colours)

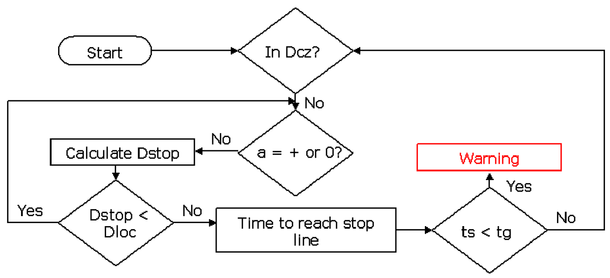


Table 3 shows one of the field test data for this test. We are always inside the clearance zone during a green light, thus sending the flow of control to check the vehicle's acceleration rate. The first set of data seems to indicate the vehicle accelerated because the predicted deceleration column is filled. The distance of the vehicle at that point is greater than 30 m so the comfortable deceleration range is 0–1.5 m/s^2. 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 s whereas the time left for the traffic light to turn green is 33 s. Thus, the alarm is set off. The vehicle continues to be seen to run the red light, and thus, the alarm is set off repeatedly.

Table 3 Field test data for deceleration test

Speed (m/s)	*Traffic light* (s)	*To*	*Distance* (m)	*Clearance* (m)	*Predict acc* (m/s^2)	*Time stop* (s)	*Alarm*
17.82	35	G	107.64	604.82	–1.48		0
16.77	33	G	75.03	528.20		6.137	1
14.15	31	G	46.65	419.72		4.512	1
11.45	29	G	23.34	313.14		2.602	1
8.96	27	G	8.94	223.18		0.613	1

6.4 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 4 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 Dstop > Dloc because to prevent premature alarms, we have set the system to only alarm in the case of a decelerating vehicle, when it is within 40 m of the stop line. When the vehicle enters the 40 m range, we see that v2 (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 4 Field test data for system test

Speed (m/s)	*TL* (s)..	..*To*	*Distance* (m)	*Clearance* (m)	*Distance stop* (m)	*Acceleration* (m/s^2)	*Pred a* (m/s^2)	v^2 (m/s^2)^2	*Time stop* (s)	*Alarm*
0	83	G	258.30932	–18.83				0		0
1.13391	81	G	254.51458	73.016464				0		0
1.13391	79	G	248.16889	70.74865				0		0
1.13391	77	G	234.19495	58.480836				0		0
11.0691	75	G	215.97701	811.35167		9.935182	–0.28365	0		0
15.1188	71	G	163.01699	1054.6016		0.91792393	–0.70108	0		0
16.1987	59	G	131.6624	1098.8781		0.37796974	–0.99648	0		0
15.7127	67	G	100.74404	1033.9213	317.20061	–0.43196392		59.109532		0

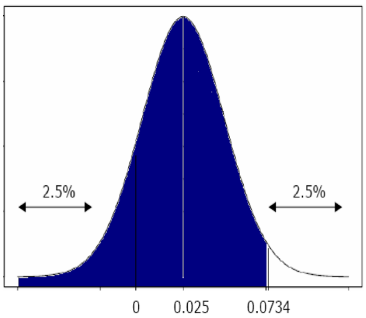
Table 4 Field test data for system test (continued)

Speed (m/s)	*TL* (s)..	..*To*	*Distance* (m)	*Clearance* (m)	*Distance stop* (m)	*Acceleration* (m/s^2)	*Pred a* (m/s^2)	v^2 (m/s^2)^2	*Time stop* (s)	*Alarm*
13.6609	55	G	73.213617	869.1269	113.72678	–1.0799112		–44.722516		0
11.3391	63	G	50.364935	695.53125	76.796448	–1.1879015		–41.447647		0
9.23724	51	G	31.357819	547.69135	60.611406	–1.0259161		–9.446062		0
6.64145	59	G	17.054967	373.01571	29.620873	–1.3498893		–18.990707		0
3.56371	57	G	8.833942	184.30131	10.921039	–1.6738617		–25.707529		0
0.59395	55	G	6.4468891	13.837304	1.3185711	–1.349889		–25.707529		0
0	53	G	6.0611208	–18.83		–1.349889		–25.707529		0
0	51	G	6.0611208	–18.83		–1.349889		–25.707529		0
0.75594	49	G	4.5847315	18.210962		0.43196499	–0.06232	–25.707529		0
1.61987	47	G	3.0057653	57.303747		0.37796903	–0.43649	1.8903761	2.0073387	1
2.69978	45	G	5.1872723	102.66001		0.70194209	–0.70257	9.3838589	1.8001716	1
3.83368	43	G	11.932819	146.01841		0.48596001	–0.61583	14.362059	3.1305707	1

6.5 *False alarm probability*

To derive the probability of false alarm for the proposed system, we carried out 40 individual tests to specifically determine with 95% confidence the probability of a false alarm. Noting that probability is always positive, we observe through Figure 13 that with 97.5% confidence, the probability of a premature/false alarm is less than 7.34%. The shaded region represents the confidence interval.

Figure 13 Normal distribution of false alarm (see online version for colours)



7 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 signalisation. 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 the 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 if 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 as summarised here.

- *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 m Range Router*. Replace the 100 m router with a 300 m router. Since the 300 m range is theoretical and the signal degrades as one approaches 300 m, use the 100 m router as an Access Point to boost the signal across 300 m. 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 vs. the current system where it works in black and white – above 1.5 m/s^2: 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

Atev, S., Arumugam, H., Masoud, O., Janardan, R. and Papanikolopoulos, N.P. (2005) ‘A vision-based approach to collision prediction at traffic intersections’, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 6, pp.416–423.

BMI (2003) *Final Report: Intersection Collision Avoidance Study*, Bellomo-McGee Incorporated, Silver Spring, MD, USA, Available on-line at: http://www.itsdocs.fhwa.dot.gov//JPODOCS/REPTS_TE//14105.htm, Accessed in June 2006.

BTS (2005) *National Transportation Statistics*, Available at: http://www.bts.gov/publications/national_transportation_statistics/2005/, Accessed in June 2006.

Ferlis, R.A. (2002) *Infrastructure Collision-Avoidance Concept for Straight-Crossing-Path Crashes at Signalized Intersections*, Transportation Research Record No. 1800, pp.85–91.

FHWA (2006) *Facts, Statistics and Data*, Available at: http://safety.fhwa.dot.gov/facts/index.htm, Accessed in June 2006.

Huang, Q. and Miller, R. (2004) ‘An improved precrash warning system with an impact energy-based estimator’, Presented at the *Crossroads: Integrating Mobility Safety and Security. ITS America 2004*, *14th Annual Meeting and Exposition*, San Antonio, Texas, USA, April.

Jocoy, E.H. and Pirson, H.A. (1999) ‘Threat detection system for intersection collision avoidance: real-time system performance’, *IV: Vehicle Navigation Systems and Advanced Controls*, pp.87–97.

Karr, A. (2004) ‘Test smarties: new accident prevention technology in development stage’, *Transportation Management + Engineering*, Vol. 9, pp.29–31.

Lee, S.E., Knipling, R.R., DeHart, M.C., Perez, M.A., Holbrook, G.T., Brown, S.B., Stone, S.R. and Olson, R.L. (2004) *Vehicle-Based Countermeasures for Signal and Stop Sign Violations, Task 1: Intersection Control Violation Crash Analyses, Task 2: Top-Level System and Human Factors Requirements (DOT-HS-809-716)*, National Highway Traffic Safety Administration, Washington, DC.

Misener, J.A., Sengupta, R. and Krishnan, H. (2005) ‘Cooperative collision warning: enabling crash avoidance with wireless technology’, Presented at *12th World Congress on Intelligent Transport Systems*, Paper #1960. San Francisco, CA, USA, November.

Misener, J.A., Thorpe, C., Ferlis, R., Hearne, R., Siegal, M. and Perkowski, J. (2001) *Sensor-Friendly Vehicle and Roadway Cooperative Safety Systems: Benefits Estimation*, Transportation Research Record No. 1746, pp.22–29.

Moon, Y., Lee, J.J. and Park, Y. (2002) ‘System integration and field tests for developing in-vehicle dilemma zone warning system’, Presented at *9th World Congress on Intelligent Transport Systems*, Chicago, Illinois, USA. October, pp.53–59.

Moon, Y.J. (2002) ‘Functional requirements for in-vehicle dilemma zone warning system at signalized intersections’, *Transportation Research Record*, pp.62–68.

Shladover, S.E. (2005) *Effects of Traffic Density on Communication Requirements for Cooperative Intersection Collision Avoidance Systems (CICAS)*, Partners for Advanced Transit and Highways (PATH) UCB-ITS-PWP-2005-1.

Shladover, S.E. and Tan, S-K. (2006) ‘Analysis of vehicle positioning accuracy requirements for communication-based cooperative collision warning’, *Journal of Intelligent Transportation Systems*, Vol. 10, pp.131–140.

Sun, D., Ukkusuri, S., Benekohal, R.F., Waller, S.T. and Liu, B. (2004) ‘Fuzzy logic based online collision prediction system for signalized intersections’, *Advances in Transportation Studies: An International Journal, Section A & B*, Vol. 3, pp.71–86.

USDOT (2006) *Vehicle Infrastructure Integration (VII)*, United States Department of Transportation, http://www.its.dot.gov/vii/, Accessed on June 6, 2006.

White, B. and Eccles, K.A. (2002) *Inexpensive, Infrastructure Based, Intersection Collision-Avoidance System to Prevent Left-Turn Crashes with Opposite-Direction Traffic*, Transportation Research Record No. 1800, pp.92–99.

White, B.F. (2004) *Algorithm for Predicting Inattentive Signal Violators in an Infrastructure-based Intelligent System*, Transportation Research Record No. 1886, pp.85–91.