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Executive Summary

This report documents our research on the conceptual framework of an integrated transportation system (PART I) with a prototype application under the framework (Part II).

The envisioned framework involves three levels of control: the global level, local level, and vehicle level. At the global level, a high-level simulation at the traffic operation center (TOC) gathers pieces of traffic information from field sensors, generates a system-wide overview, and preview system evolution in the near future, e.g. the next half to one hour, with the assistance of available traffic prediction techniques. As a result, the simulation output could assist traffic managers to identify potential problems in advance, test control strategies, and take preventive actions before the problems build up. At the local level, a roadside equipment (RSE) keeps a high resolution local map, communicates with all vehicles within range, and exchanges information with the TOC. A low-level simulation could run at the RSE to preview local traffic operation in the near future, e.g. five to ten minutes, with the assistance of short-term traffic prediction techniques. The simulation result enables the RSE to communicate with drivers and coordinate them to move in an orderly, efficient, and safe fashion. At the vehicle level, a vehicle communicates with an RSE within range as well as other surrounding vehicles. Therefore, this vehicle knows its surroundings (from other vehicles), its local context (from the RSE), and the global context (from the TOC via the RSU). A ground-level simulation could run in this vehicle to integrate information from other vehicles, the RSE, and the TOC (via the RSE). The simulation result enables the driver to preview his/her position and surroundings in the next half to one minute. In addition, the simulation could assist driving by suggesting control strategies or taking partial or full control of the vehicle.

As an application under the above framework, Part II presents the design of a prototype intersection collision warning system based on Vehicle Infrastructure Integration (VII) technologies. 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 synchronized 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.

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Part I: Conceptual Framework of an Integrated Transportation System

Introduction

The national problem. Have you imagined that a momentary lapse of attention during driving might cost your life and ruin the lives of others? Have you imagined that blindly running into a congested route could disrupt a well-planned trip or appointment? The Bureau of Transportation Statistics (BTS) [1] showed that the annual fatality rate in this country has remained over 40,000 in the past few decades, let alone the costs incurred by injury and property damage. The Texas Transportation Institute (TTI) mobility study [2] revealed that a traveler on average spent about 40% more time on the road which amounted to about 60 hours per year. At an aggregate level, congestion caused the unnecessary consumption of 2.3 billion gallons of fuel and a total cost of $63.1 billion in terms of wasteful time and fuel. In addition, many other critical issues such as energy, environment, emergencies, and security are also faced by transportation systems in the 21^{st} century. These issues are not only collecting a high toll on the economy, they are also changing the way that people live, travel, and work.

The source of the problem. Many problems in transportation can be directly or indirectly attributed to *inattention, lack of cooperation, and poor decisions*. More specifically, *at a vehicle level*, we rely on the driver to pay full attention to driving all the time watching for directions, other vehicles, pedestrians, blind spots, road conditions, signs, and signals. A momentary lapse of attention could result in an immediate crash, especially during lane changing, merging, and turning. *At a local level* such as a highway segment, an intersection, or a freeway merge, there is neither cooperation between vehicles and vehicles nor interaction between vehicles and roadside. Accidents may occur because drivers fail to see each other at intersections, accommodate at merges, or follow safely on highways. Efficiency problems arise if signals are not responsive enough at intersections, vehicles compete against each other at merges, or drivers are not warned of an accident downstream. *At a global/system level*, congestion may build up because traffic diversion is not well-planned or drivers are not well-informed of a bottleneck ahead. System gridlock may occur because incidents are not reported in time or actions are taken too late.

The envisioned solution. While no single solution can respond to all transportation problems, there is a growing demand for *integrated* solutions that could address many of the problems and could potentially lead to fundamental changes in the way that transportation systems are managed and operated in the decades to come. *The goal of this research is to formulate a framework to promote the development of an integrated transportation system using simulation and sensor technology. It is envisioned that in this framework global-level traffic control will be proactive, local-level traffic control will* *be cooperative, and vehicle-level control will be attentive. Underlying this research are sensor technology which enables ubiquitous situation-awareness and transportation simulation which assists decision-making at these three levels.* More specifically, a traffic operation center (TOC) collects traffic information from field sensors and develops global-level control strategies. Equipped with memory, computing, and communication capabilities, a roadside unit (RSE) can be one of the field sensors and the RSE develops local-level control strategies. Equipped with positioning, computing, and communication capabilities, an on-board unit (OBE) resides in a vehicle and the OBE develops vehicle-level control strategies. Two-way communications are enabled between these levels and a computer simulation system is central to the traffic control assistance at each level. *At the global level*, a high-level simulation at the TOC gathers pieces of traffic information from the field sensors, generates a system-wide overview, and preview system evolution in the near future, e.g. the next half to one hour, with the assistance of available traffic prediction techniques. As a result, the simulation output could assist traffic managers to identify potential problems in advance, test control strategies, and take preventive actions before the problems build up. *At the local level*, an RSE keeps a high resolution local map, communicates with all vehicles within range, and exchanges information with the TOC. A low-level simulation could run at the RSE to preview local traffic operation in the near future, say five to ten minutes, with the assistance of short-term traffic prediction techniques. The simulation result enables the RSE to communicate with drivers and coordinate them to move in an orderly, efficient, and safe fashion. *At the vehicle level*, a vehicle communicates with an RSE within range as well as other surrounding vehicles. Therefore, this vehicle knows its surroundings (from other vehicles), its local context (from the RSE), and the global context (from the TOC via the RSE). A ground-level simulation could run in this vehicle to integrate information from other vehicles, the RSE, and the TOC (via the RSE). The simulation result enables the driver to preview his/her position and surroundings in the next half to one minute. In addition, the simulation could assist driving by suggesting control strategies or taking partial or full control of the vehicle.

The significance of the solution. The envisioned solution is expected to greatly improve mobility and safety by establishing situation-awareness throughout a transportation system and creating a mechanism to automate the system in a safe and efficient manner. In addition to the effect of mutual enhancement, improvements in mobility and safety could increase fuel efficiency and reduce vehicle emission. Under emergencies, improved situation-awareness allows shorter time-to-detection, better decision making, and quicker response which contribute to more security and less life and property loss.

Existing Work

With its high financial, social, and environmental costs, traditional solution of constructing more and larger highways is no longer considered a viable option. A consensus has been reached which proposes increasing the efficiency of existing infrastructure by means of computer and telecommunication technologies. This gives rise to *Intelligent Transportation Systems (ITS)* [3] starting in the 1990s. As the result of systematic efforts in the last 15 years, ITS have been established nation-wide with an emphasis on system-wide/global-level applications. We have been able to successfully monitor a transportation system, provide real-time traffic information, and respond to incidents once they were reported. What we have not yet done successfully is to understand how the system evolves, preview system operations, and manage the system proactively by preventing accidents from happening and congestion from building up.

With an emphasis on vehicle-level applications, recent development in *intelligent vehicle technology* [4] coupled with *automated highway systems (AHS)* [5] have enabled many driving assistance features, such as (adaptive) cruise control, forward collision warning, lane-keeping assistance, lane change assistance, pedestrian detection, road departure warning, etc. We have been successful in making vehicles easier to handle and safer to drive. What we have not yet successfully done is to relieve drivers of heavy information loads, make vehicles more attentive, and provide drivers more situation-awareness at vehicle, local, and global levels.

Concurrent with ITS and AHS in the U.S. were similar efforts in the world, such as VICS [6], AHSRA [7], and VERTIS (now ITS Japan) [8] in Japan and DRIVE, PROMETHEUS, and ERTICO in Europe [9]. The above efforts have shown a clear trend of integration of traffic control at the global, local, and vehicle levels. It appears that the local-level control is relatively weak in the spectrum. In response, The *Vehicle Infrastructure Integration (VII)* [10] has emerged as one of the United States Department of Transportation (USDOT)'s new initiatives. It is expected that the VII initiative will help bridge the gap between the global and vehicle levels by means of vehicle to vehicle, vehicle to roadside, and roadside to system communications.

So far, the VII initiative has been in its beginning stage with an emphasis on high-level planning and architecture development [11] [12]. The National VII Coalition has been established, followed by a few VII programs at the State level. Some 113 use cases of VII have been identified and their implementation has been prioritized [13]. Meanwhile, many agencies and institutions have already taken initial steps toward proof-of-concept studies and experimental implementation. These efforts include data use [14], vehicles probes [15], collision avoidance [16], weather [17], pedestrians [18], testbed [19, 20] [21] [22], just to name a few. As will become clear soon, the research proposed herein is centered on the integration of simulation, sensor technology, and transportation systems – an approach that integrates traffic control at the three levels yet complementing and augmenting existing VII efforts.

The Framework of an Integrated Transportation System

The framework of the integrated transportation system proposed in this research distinguishes itself from the existing work by (a) applying simulation in the loop of traffic control at the global, local, and vehicle levels, (b) integrating traffic control at these levels by means of two-way communication between these levels and establishing situation-awareness throughout the system, and (c) creating a mechanism to automate the system in a safe and efficient manner.

The following paragraphs summarize the framework which addresses traffic control at three levels, as illustrated in Figure 1. At the global level, the TOC functions as the central processing unit which receives traffic information from traffic sensors and RSEs. A simulation system at the TOC is able to link piecewise, disjoint observations in the field and generate a full picture of the system. Traffic data are loaded into the simulation system which allows preview of traffic operation in the near term. To be helpful for decision-making, the simulation needs to be able to work on-line and allows the insertion of new data [23]. This will enable traffic managers to keep track of traffic evolution, identify potential problems, test control strategies, and resolve the problems before they build up. Considering the scale of the problem and the timeliness requirement in decision-making, a high-level, low-fidelity (e.g. macroscopic) simulation is appropriate at the TOC.

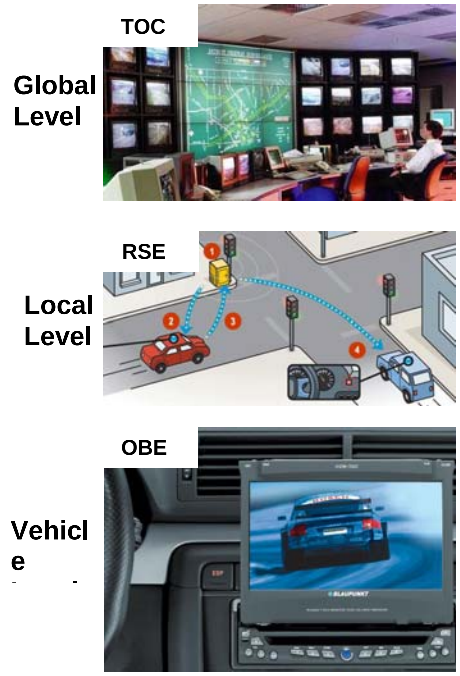

Figure 1 The initial framework

At the local level such as a highway segment, an intersection, or a freeway merge, the processing unit is an RSE which coordinates traffic movement in a cooperative manner. All vehicles within range transmit their identities, locations, speeds, and destinations to the RSE. A simulation system at the RSE previews traffic movement, optimizes local control strategy, sends messages to each vehicle, and directs the vehicle to proceed cooperatively. Significant improvements in safety and mobility can be expected, especially at potential bottlenecks such as intersections and freeway merges. In addition, the RSE also reports local traffic conditions to the TOC and receives information from the TOC such as system-wide traffic conditions and control strategy. This information can be made readily available to vehicles within range. Considering the limited scope of a local area and the details required to enable cooperative control, a low-level, high-fidelity simulation such as the microscopic type is appropriate at the RSE.

At the vehicle level, the processing unit is the OBE which not only monitors the position and movement of the vehicle by means of Global/Local Positioning System (GPS/LPS) but also those of the surrounding vehicles by means of vehicle-vehicle communication. An on-board simulation system serves as an ever-vigilant co-pilot, integrating pieces of information, previewing what will happen next, notifying the driver when necessary, and executing control as appropriate. By communicating with the RSE, the OBE extends its situation-awareness from its surroundings to the local area and to the global system. Considering the very limited scope which involves only a few vehicles and the great details needed to assist vehicle control, a ground-level, very high-fidelity simulation such as the nanoscopic type is appropriate at the OBE. The above discussion on the initial framework is summarized in Table 1.

Table 1. Summary of the initial framework

Level	Proc. unit	Coverage	Sensor/Comm.	Simulation	Objective	Control strategy
Global	TOC	An entire transportation system	Loop detectors Video cameras Other sensors	Macroscopic	Mobility	Proactive system control to improve mobility
Local	RSE	A highway segment An intersection A freeway merge	GPS/LPS DSRC Others	Microscopic	Mobility Safety	Cooperative local control to improve mobility and safety
Vehicle	OBE	A vehicle and its surrounding	GPS/LPS DSRC Others	Nanoscopic	Safety	Attentive vehicle control to improve safety

Keys TOC – traffic operation center; GPS – global positioning system; RSE – roadside equipment; LPS – local positioning system; OBE – on-board equipment; DSRC – dedicated short range communications

The simulation system at TOC to assist proactive decision making

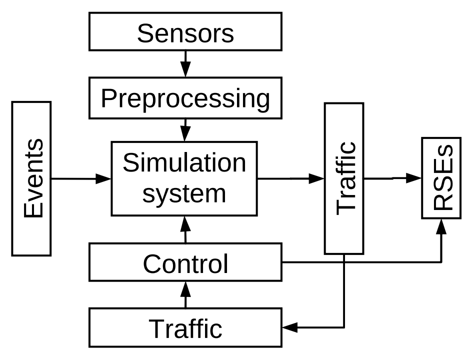

Figure 2 Simulation at TOC

This simulation system at the TOC assists proactive decision making. The simulation process is functionally sketched in Figure 2. Information from traffic sensors are preprocessed and fed into the simulation system. Other sources of input include traffic events such as conventions and pre-scheduled maintenance. With these sources of information, the simulation system loads traffic demands into the transportation network and outputs traffic states (e.g. flow, speed, density, bottleneck, travel time, delay, etc.). Traffic managers, based on the simulation output, develop control strategies if necessary and feed them into the simulation system to preview their effects. Once an appropriate control strategy is determined, it is executed and sent to RSUs to serve travelers.

Several challenges are identified in order for the simulation system to better serve its purpose. First, the simulation system should be fast and efficient because the simulation at this level typically involves a regional transportation network. Second, the simulation system should be able to work on-line because demand pattern changes dynamically and off-line simulation would be slow to incorporate the dynamic changes. Third, the simulation system needs to allow insertion of new data which is frequently required when testing control strategies.

The simulation system at RSE to facilitate cooperative traffic operation

The simulation system at an RSE level assists cooperative traffic operation at a local area in a transportation system such as a highway segment, an intersection, or a freeway merge. Efficiency and safety problems frequently arise at such a locality because its local control mechanism lacks the ability to account for dynamic changes in traffic volume (for signalized intersections and ramps with meters) or lacks the ability to encourage cooperation among vehicles and roadside (for unsignalized intersections, ramps without meters, and highway segments). The simulation system is functionally sketched in Figure 3. Vehicles/OBEs within range continually transmit their identities, locations, speeds, and destinations to the RSE. Hosting a high resolution local map, The RSE receives global control strategy from the TOC, develops local control strategy, and feeds the above information into the simulation system. The simulation system synthesizes above information, performs simulation, and preview local traffic condition in the near term. Based on the simulation result, the RSE refines local control strategy and invokes the simulation system again. At the end of the iterative process, an optimized local control strategy is developed. Then RSE could communicate with each vehicle/OBE, directing it to proceed or stop in a cooperative manner.

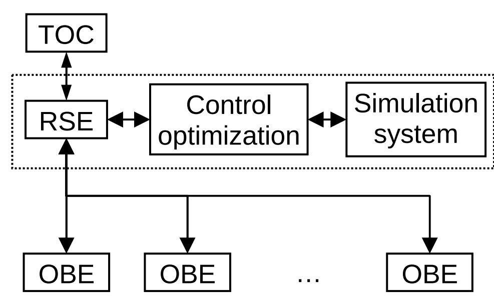

Figure 3 Simulation system at an RSE

Several challenges are identified for the simulation system to serve its purpose. First, the simulation needs to model vehicle movements in the local area with high fidelity. Second, the simulation needs to be computationally efficient so that the simulation system can support control strategy optimization faster than real time. Third, an algorithm needs to be formulated to perform the optimization using the simulation results.

The simulation system at OBE to provide attentive driving assistance

The simulation system at an OBE level assists attentive vehicle control in a small context involving the vehicle and its surroundings. Safety problems frequently arise in this context because accidents may occur if drivers fail to see conflicting vehicles, to accommodate at merges, or to follow safely on highways. This is so because we rely on drivers to pay full attention to driving all the time, watching for directions, other vehicles, pedestrians, blind spots, road conditions, signs, and signals. The result of a momentary lapse of attention could be disastrous. Recent advancements in vehicle technology has enabled many driving assistance features, such as (adaptive) cruise control, forward collision warning, lane-keeping assistance, lane change assistance, pedestrian detection, road departure warning, etc. These

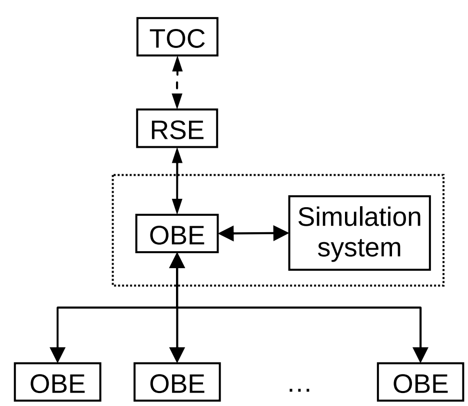

Figure 4 Simulation system at an OBE

advancements have successfully solved part of the problem. What have yet to be addressed are the following. One, these earlier, incremental advancements might demand more driver attention and, as a result, the added information load tend to render driving even more energy-consuming. Two, these advancements aim to make a “perfect” vehicle which can only achieve a limited goal when driving in a mix of “not-so-perfect” vehicles because there is no cooperation or communication between vehicles. Three, vehicle to vehicle communication has the potential to enhance the vehicle's awareness about its surroundings and, as a consequence, the value of such awareness could be maximized if local and global awareness are enabled as well.

With these challenges, a simulation system at an OBE level is functionally sketched in Figure 4. In addition to exchanging information with RSEs and TOC, an OBE communicates with other OBEs within its surroundings. With the high-resolution local map obtained from the RSE within range as well as precise locations, speeds, and accelerations of other vehicles, the OBE invokes its simulation system and previews what is going to happen in the immediate future, say the next half to one minute. In response to the challenges identified above, the simulation system will be attentive, cooperative, and connected. To be attentive, the simulation should provide a one-stop solution for the driver by facilitating the processing of all required information related to navigation, longitudinal and lateral movements, relative distances and speeds to other vehicles, hidden objects, signs and signals, and other important factors. To be cooperative, two-way communication should be enabled between this vehicle and other vehicles so that, when an emergency happens, other vehicles could receive notice in advance and could take preventive actions accordingly. To be connected, two-way communication should be enabled between this OBE and RSEs so that the OBE could receive live updates of local and global traffic conditions as well as control strategies.

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Part II: A Prototype of VII-Enabled Intersection Collision Warning System

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 research 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 report 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 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.

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.

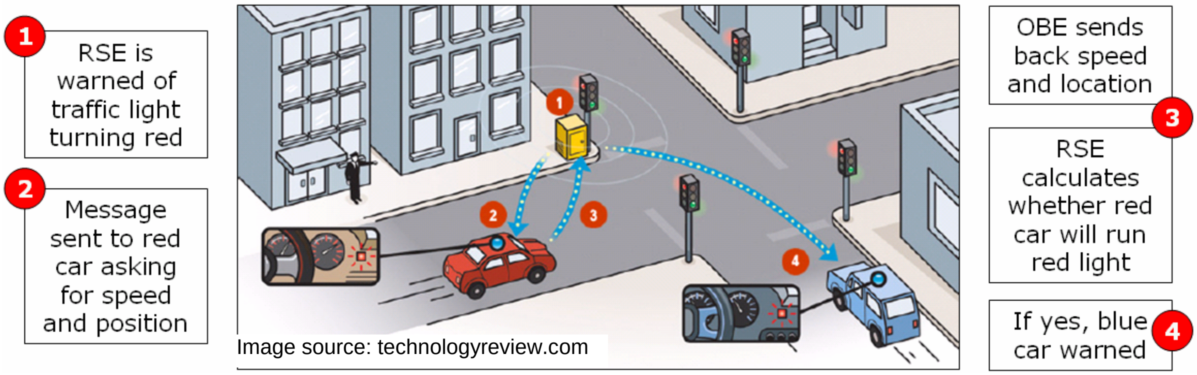

Figure 1 Principle of operation of the prototype system.

The principle of operation of the prototype system is the following:

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.

A message sent from RSE to the moving car (OBE), asking for speed and position of the OBE.

OBE responds by sending back the requested speed and location information. The RSE then calculates whether moving car is likely to run red light.

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.

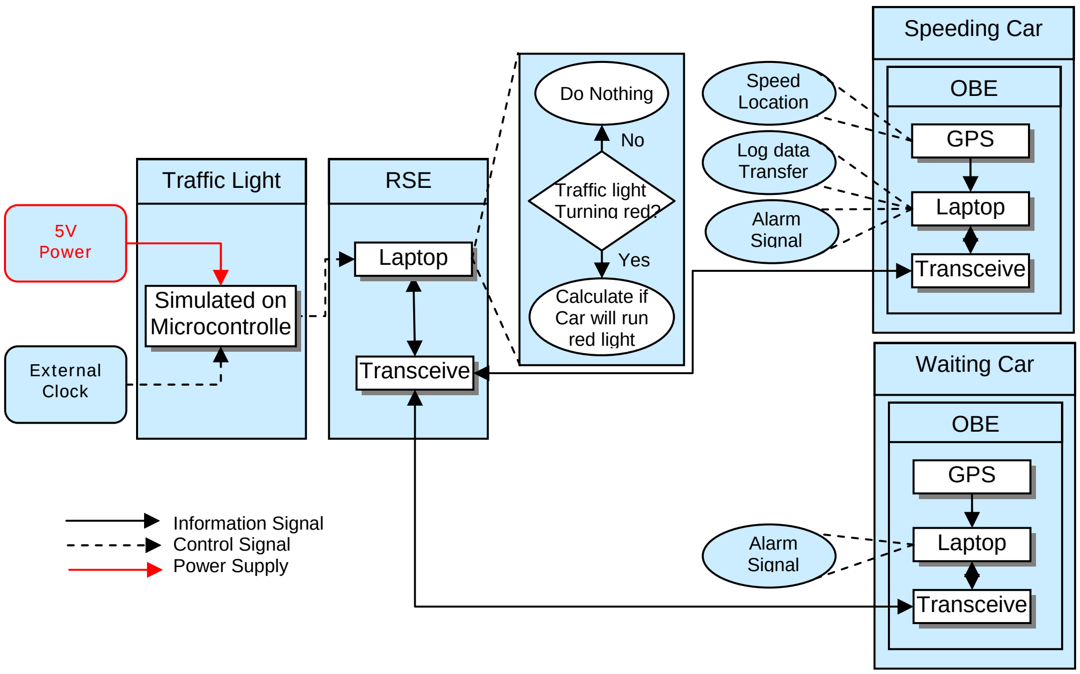

Figure 2. Prototype system block diagram

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.

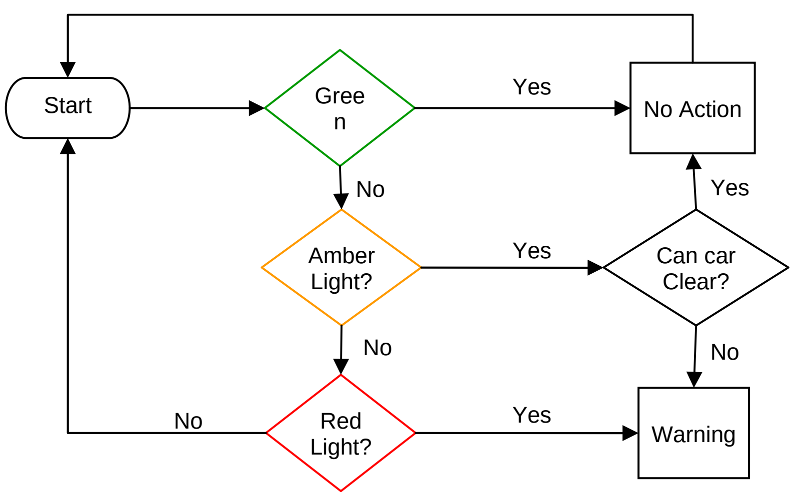

Figure 3. Flow chart of the warning algorithm

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.
- 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. Dc is the distance traveled in time left before red light less the sum of vehicle length and intersection width. $D_c = v_1 t_{amber} - L - W$
- D_d is the length of dilemma zone where drivers have difficulty to decide whether to proceed or stop.
- D_s is stopping distance consisting distance traveled during perception-reaction time and braking distance. $D_s = t_{PR} v_1 + \frac{v_1^2}{2a}$

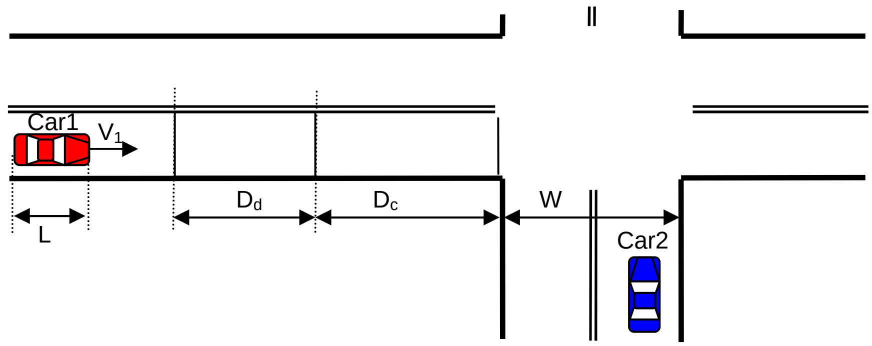

Figure 4. The intersection under analysis

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.

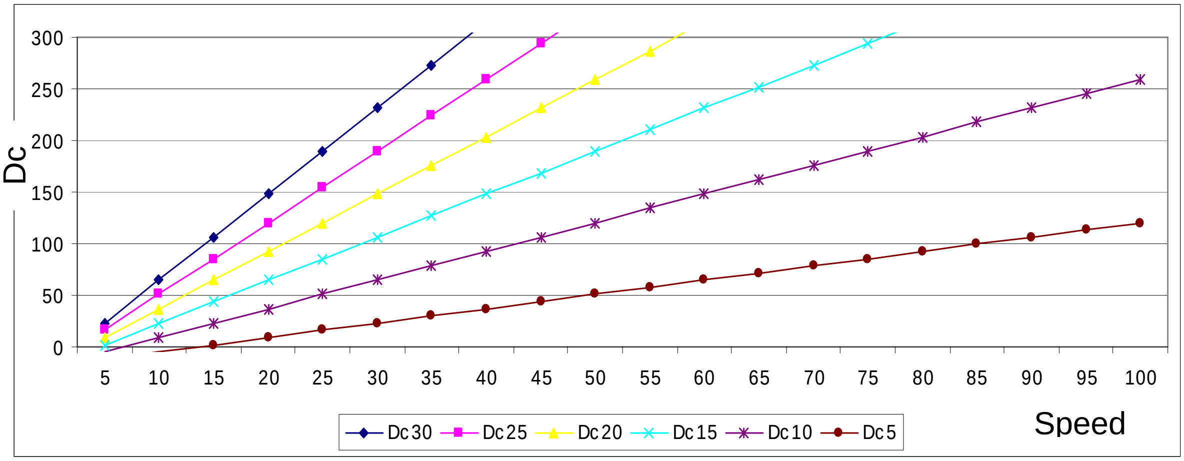

Figure 5. Determination of clear zone length

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_g time for light to turn green, and D_l distance from stop line.

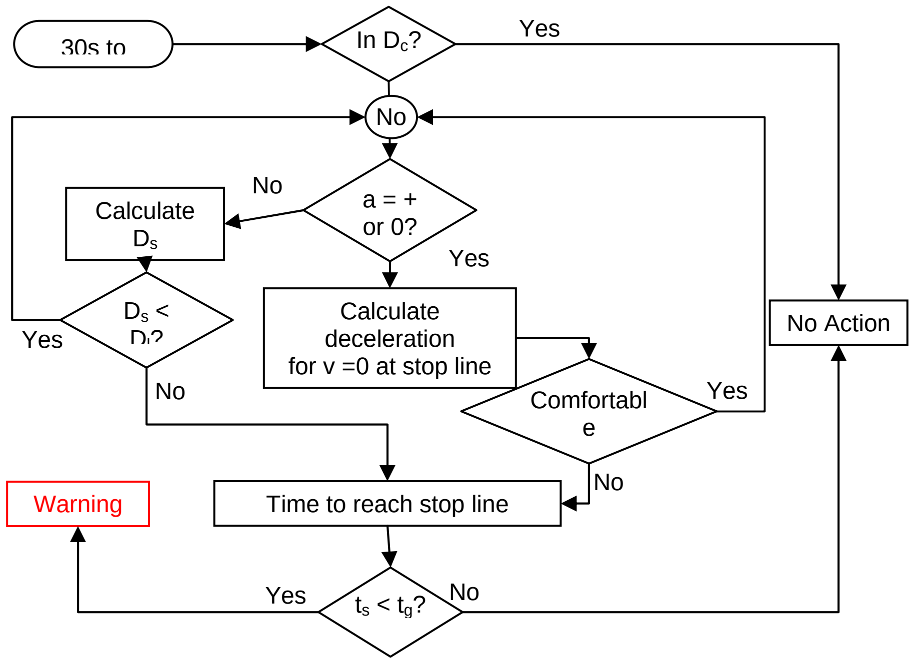

Figure 6. Road calculation algorithm

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:

- o Example: time to reach stop line = 5s. Time for light to turn green again = 7s. So, in 5s the light is still red. Alarm!
- o 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.

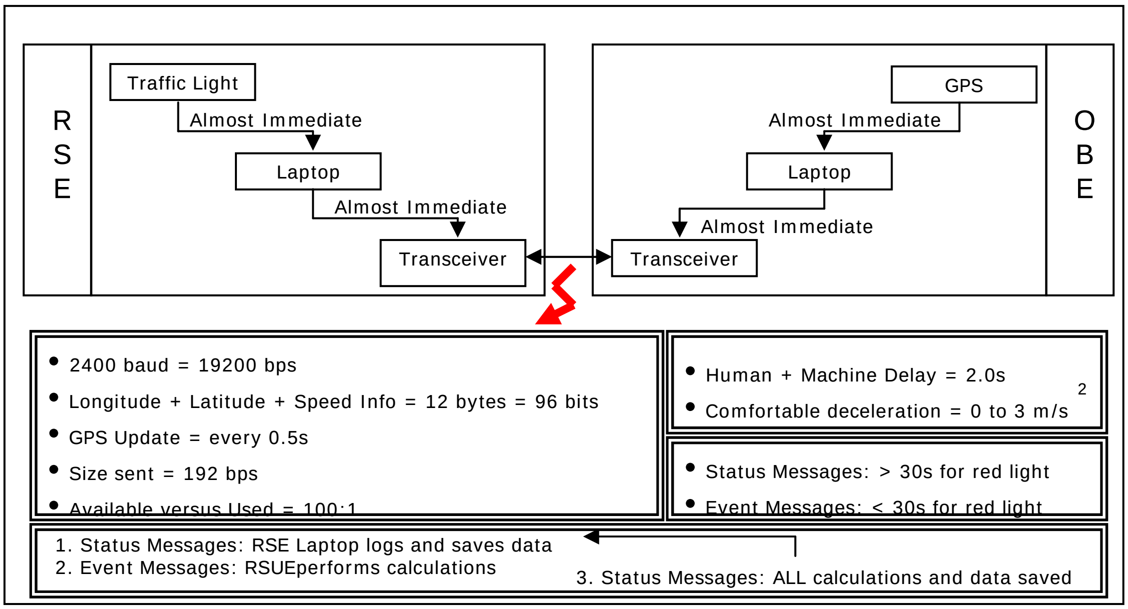

Figure 7. Calculation of system latencies

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 12bytes 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/s^2. 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 (Airbornedirect Serial Bridge). Data transmission uses 802.11g protocol.

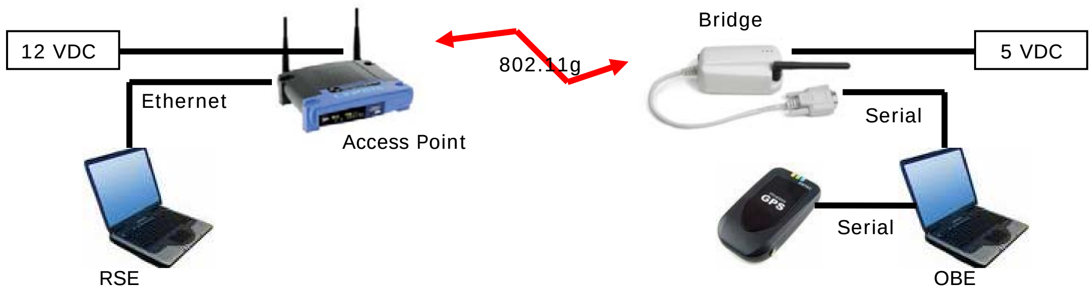

Figure 8. Connectivity of the prototype system

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.

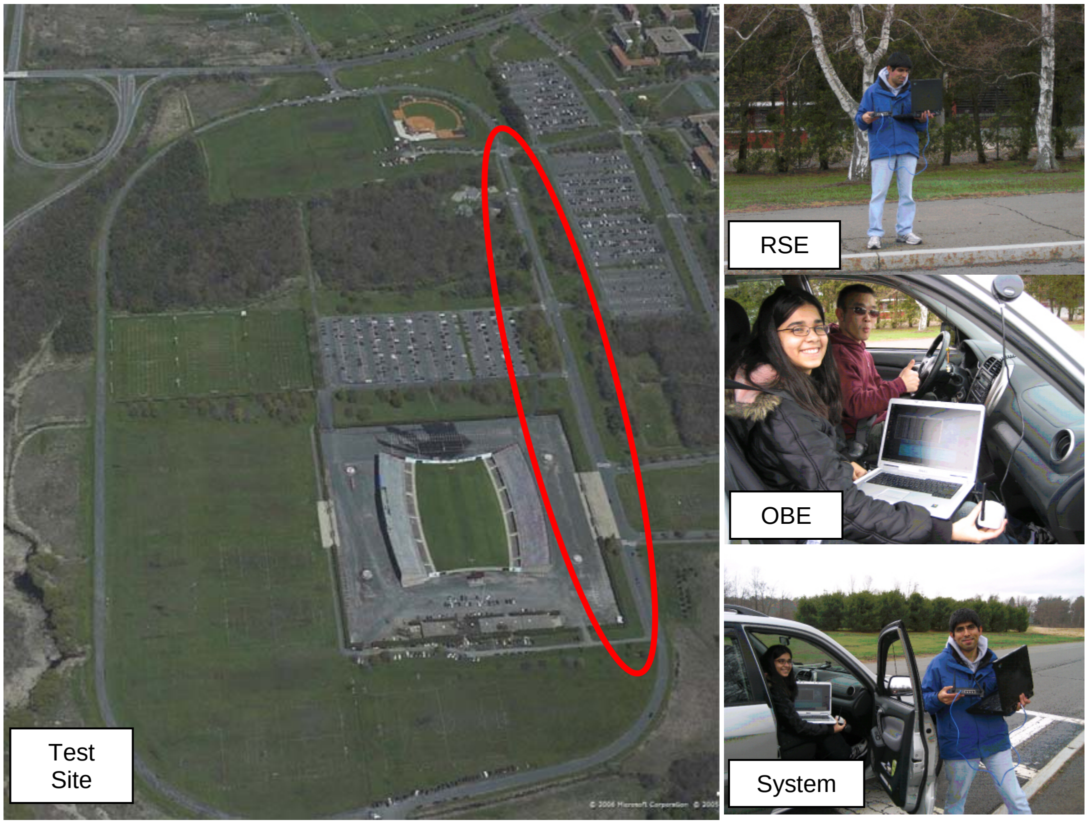

Figure 9. Test site and test equipment

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).

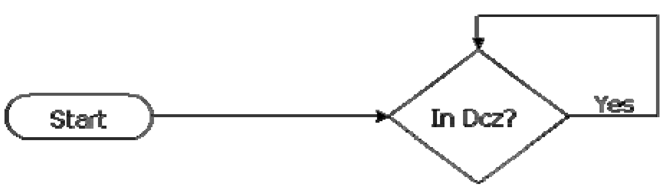

Figure 10 Clearance zone check in flowchart

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

2. Acceleration Test

Speed (m/s)	Traffic Light (s)	To...	Distance (m)	Clearance Zone Distance (m)	Alarm
13.5528	45	R	118.992	591.08	0
15.497	43	R	89.761	647.529	0
17.062	41	R	57.571	680.93	0
18.574	39	R	24.42	705.57	0
19.546	37	R	14.44	704.386	0

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).

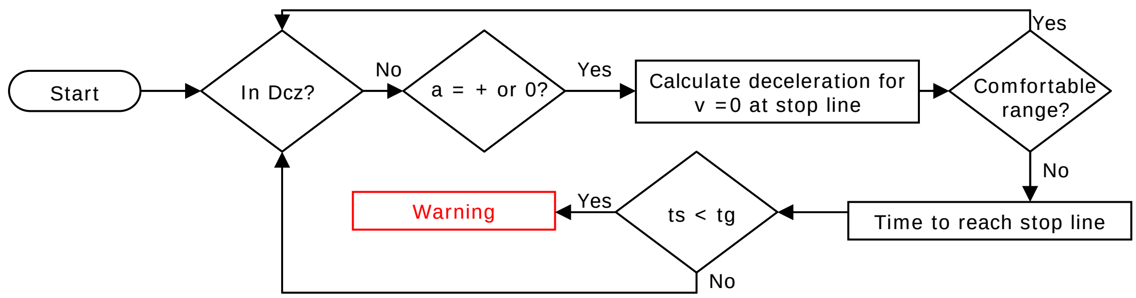

Figure 11 Acceleration test in flowchart

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/s2, which is greater than 1.5 m/s2. We then check the time for the vehicle to reach the stop line - 2.883 seconds, while the time left for the light to turn green 19 seconds. 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/s2)	Time Stop (s)	Alarm
15.335	2	R	190.554	11.839	-0.617		0
17.062	25	G	158.786	407.735	-0.916		0
18.0885	23	G	124.882	397.206	-1.31		0
18.790	21	G	89.304	375.770	-1.97		0
19.222	19	G	53.327	346.396	-3.464	2.883	1
19.384	17	G	16.587	310.705	-11.327	0.863	1
19.546	15	G	20.547	274.366	-9.296	1.062	1

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).

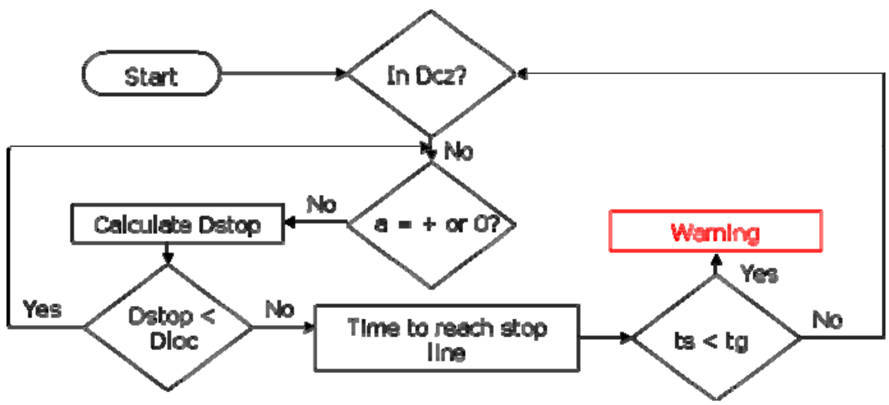

Figure 12 Deceleration test flowchart

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/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 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 3 Field test data for deceleration test

Speed (m/s)	Traffic Light (s)	To	Distance (m)	Clearance (m)	Predict acc (m/s2)	Time Stop (s)	Alarm
17.8185	35	G	107.641	604.8186	-1.475		0
16.766	33	G	75.030	528.199		6.137	1
14.146	31	G	46.65	419.722		4.512	1
11.4471	29	G	23.342	313.135		2.602	1
8.96326	27	G	8.936	223.178		0.613	1

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 Dstop > Dloc 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 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/s2)	Pred a (m/s2)	v2 (m/s2)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	68.480836				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	69	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
13.6609	65	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
9.28724	61	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

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 research 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 emabling 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 ans 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.

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