Vehicular-to-Infrastructure Traffic Information System for the Work Zone Based on Dedicated Short-Range Communication Development and Field Demonstration

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Dedicated short-range communication (DSRC) is a 75-MHz spectrum in the 5.9-GHz band assigned for automotive use by the U.S. Federal Communications Commission to increase traffic safety and efficiency (1). In its 5-year intelligent transportation systems strategic plan, the U.S. Department of Transportation (U.S. DOT) is committing to the use of DSRC technologies for active safety in both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications (2). U.S. DOT’s commitment to DSRC highlights two critical points:

1. Safety is the highest priority for U.S. DOT and will form the central focus for its IntelliDrive program, formerly known as vehicle–infrastructure integration.

2. The analysis illustrates that DSRC is the only viable technology in the near term that offers the latency, accuracy, and reliability needed for active safety.

The preceding critical points have motivated a lot of interest in developing applications with DSRC technology to improve safety and mobility of traffic on U.S. highways (3–11). Recently, a remote collision avoidance system using DSRC-based V2V communication was verified (8). Similarly, a DSRC-based secure communication protocol for a vehicle ad hoc network has been proposed by exchanging warning messages using both V2I and V2V communication (9). The Integrated Vehicle-Based Safety System program of the University of Michigan aims to integrate several collision warning systems into one vehicle in a way that alerts drivers to potential collision threats with an effective driver–vehicle interface, while minimizing the number of excessive warnings presented to the driver (J0). Furthermore, ongoing work by the California Partners for Advanced Transportation Technology program is in many areas, some of which include sending travel time (TT) data to vehicles; sending incident information to vehicles; and having work zone safety, intersection collision, and curve overspeed warnings (J1).

An area where there is a need for such applications is the work-zone environment, which can cause severe congestion on U.S. roadways and a potential hazard to driver safety. Work-zone-related congestion can grow very quickly, especially during peak hours. In this paper, this application area has been targeted and a system has been developed that can estimate and periodically broadcast the start of congestion (SoC) location and the TT through the congestion by using DSRC-based V2I communication. Traffic efficiency can be improved by letting drivers know the TT through a congested area, which allows them to make informed decisions about whether to seek an alternate route. The driver’s safety can be improved by communicating how far the SoC is from the current location of the driver so that he or she can be prepared for a sudden breaking situation ahead.

The system that has been developed for a work zone is fully portable and can be easily installed at any work-zone site. In addition to the
work-zone application, this system can also be used for a road temporarily congested due to partial blockage of lanes resulting from an accident. A field demonstration of the proof of concept was performed for the newly developed system. In the remainder of this paper, the system overview is described first, followed by system functionality, and V2I protocol. Then the field demonstration results and discussion are presented, followed by a discussion of future work and conclusions.

**SYSTEM ARCHITECTURE OVERVIEW**

The conceptual diagram of the portable work-zone traffic safety information system is shown in Figure 1. This system is portable because it can be used for any work-zone or accident-related congestion site by installing a roadside unit (RSU) on one side of a congested road or work-zone area. Once the RSU is installed, the RSU software will control the back-and-forth DSRC communication with all vehicles containing the onboard units (OBUs) to acquire TT and SoC location information from vehicles passing through the congestion. The OBU software is designed so that no user input is required and it can be seamlessly engaged with the portable RSU by means of V2I communication. OBU hardware must have Global Positioning System (GPS) capability in addition to the DSRC technology as compared with RSU, which needs only DSRC technology. In a developed system, RSU communicates with OBU without knowing or keeping any identity information about the OBU or the corresponding vehicle to preserve privacy. After powering up, RSU requires user input to initialize a set of parameters (shown in Table 1) for adapting to a particular work-zone or congested road environment.

As shown in Figure 1, the SoC location can vary with growing or shrinking congestion in real time, depending on traffic influx, and so can the TT. The RSU software is designed so that it can estimate the varying TT and SoC location periodically. In parallel, RSU also periodically broadcasts the TT and SoC location parameters to approaching vehicles by using DSRC communication. The OBUs of approaching vehicles can then calculate the distance to the SoC location because their location is known to them. The TT and the distance to the SoC location are then communicated to the driver by a text message to a Bluetooth (BT)-enabled cell phone in the vehicle. This BT-enabled cell phone interface is just an example of

![Conceptual diagram of developed system using V2I DSRC communication to estimate TT and SoC, which are then broadcast to approaching vehicles.](image)

**TABLE 1 RSU Input Parameters**

<table>
<thead>
<tr>
<th>RSU Parameter</th>
<th>Units</th>
<th>Description and Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal road speed limit</td>
<td>mph</td>
<td>This is the maximum speed permissible on the road. It is used to estimate SoC location.</td>
</tr>
<tr>
<td>Road direction</td>
<td>Degrees</td>
<td>This is relative to north increasing clockwise direction. It is used for the direction check in the OBU to eliminate vehicles going away from the congestion on the same or other roads.</td>
</tr>
<tr>
<td>End of congestion location</td>
<td>Longitude, latitude</td>
<td>This is the location where the work zone or congestion ends and the lanes are opened up again. It is used for the EoC check in the OBU to disengage OBU from V2I communication with the RSU.</td>
</tr>
<tr>
<td>Start of monitoring range location</td>
<td>Longitude, latitude</td>
<td>This point is located well before the SoC on the road where RSU coverage range just begins. It is used to engage the vehicles with OBUs to participate in V2I communication to estimate TT and SoC location.</td>
</tr>
<tr>
<td>Road width</td>
<td>ft</td>
<td>This is the road width for one direction of travel. This is used for location check for the vehicles approaching the work zone to participate in the V2I communication.</td>
</tr>
<tr>
<td>Road name and descriptive direction</td>
<td>100 characters maximum</td>
<td>This is an easily understood name for the road and descriptive direction, which is broadcast along with the TT and SoC location by the RSU for drivers to know whether a message pertains to them.</td>
</tr>
</tbody>
</table>
communicating the data (distance to the SoC and TT) to the driver. A different interface could also be used—for example, by audio using text-to-speech conversion or by visual display on a dashboard screen.

**SYSTEM FUNCTIONALITY AND V2I COMMUNICATION PROTOCOL**

Once the RSU is initialized and running, it is placed so that the end of its coverage range is just beyond the end of congestion (EoC) location at one end of the road and is well before the SoC at the other end of the road, as shown in Figure 2. One end of the RSU coverage range before the SoC becomes the start of the monitoring range from which point incoming vehicles with OBUs and traveling toward congestion can be engaged in V2I communication (Figure 2). The V2I communication between RSUs and OBUs is performed by exchanging short messages with the following general format:

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header + operation + data + footer
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where the header is used to distinguish that the message is for a specific application and Footer ensures that the end of the message has been reached to avoid data-processing omissions. The operation and data fields are the distinctive features of each message, with operation being an identifier to determine the source, destination, and processing of the associated data.

Five types of operations are used in this application. Three of the five operations—invite, chosen, and broadcast—originate from the RSU and are intended for the OBU. The remaining two operations—accept and notify—originate at the OBU and are intended for the RSU. The operation of each message determines the associated data format.

**V2I DSRC Communication Flow**

Once the RSU is initialized and becomes operational, it transmits the invite message to all vehicles within its coverage range every 1 s. All vehicles with an OBU perform a direction and preliminary location check upon receiving the invite message. The direction and preliminary location checks are done to see if a vehicle is traveling in the right direction and whether it is positioned at a desired location on the road (i.e., before congestion starts, as shown in Figure 2). Once the direction and preliminary location checks are passed, the OBU sends an accept message to the RSU. There may be more than one OBU that can pass the direction and preliminary location checks and send the accept message to the RSU. However, the first received accept message is processed first by the RSU. The RSU then performs a fine location check to ensure that the vehicle is at the desired location on the correct road and not on a nearby parallel road. After ensuring the correct location of the vehicle, the RSU sends the chosen message to the OBU and then continues to monitor the time, location, and speed of the selected vehicle until it passes through the congestion. These parameters are monitored through the OBU sending notify messages periodically to the RSU containing time, location, speed, and EoC indicator as its data, while passing through the congestion until the EoC point is reached. The selected vehicle does not transmit its own identity at any time but rather a randomly generated identification that identifies the vehicle so that traffic data can be distinguished in case more than one vehicle is providing traffic data to the RSU at the same time.

After the RSU receives a notify message containing the positive EoC indicator, it estimates TT by identifying the SoC location from the received traffic data. The estimated TT and the SoC location along with the road name and descriptive location are packaged as Data of the broadcast message and are sent to all vehicles within the coverage range of the RSU. The broadcast message is transmitted every 1 s; however, the new TT and SoC location update is done only when available, which is every TT or fraction of TT set by the RSU. All vehicles receiving the broadcast message can estimate their distance to the SoC because their own location is known to them. Then the TT, distance to SoC, and descriptive name of the road are sent as a text message to a BT-enabled cell phone in the vehicle.

**Direction Check**

One critical aspect of DSRC-based V2I communication is to identify a traveling vehicle that is traveling in the right direction (i.e., approaching the work-zone area so that it can be selected to acquire relevant traffic data). The direction check is done in the OBU. When an invite message is sent by the RSU, it goes to all vehicles within the coverage range. The data of the invite message include the desired direction of travel in terms of an angle (with north being 0° and the angle increasing in a clockwise direction). Immediately upon receiving the invite message, the OBU takes a GPS reading

![FIGURE 2](image-url)  
**FIGURE 2**  Schematic diagram showing RSU placement across a work zone and desired location to start engaging vehicles on the road for V2I communication.
(longitude and latitude); then it takes another GPS reading after waiting for a finite period of initial time interval also contained in the data of the invite message. Once it determines two locations and the time interval between them, it calculates the angle of travel and compares it with the desired angle of travel. If the angle of travel of the vehicle is within $\pm 10^\circ$ of the desired angle, it passes the direction test and moves on to perform the location test; $\pm 10^\circ$ of tolerance was chosen to eliminate vehicles traveling in the direction opposite the congestion while still within the error bounds of the angle calculation of GPS technology. When characterized, the error bounds of the GPS units used in this system turned out to be $\pm 10^\circ$ for two points at least 10 m apart with the error bound decreasing for larger separation. The initial time interval was intentionally chosen by the RSU based on the nominal speed limit of the road to ensure that the two points are at least 10 m apart. In practice, they are much more than 10 m apart.

**Location Check**

The direction check alone as described above cannot ensure that the selected vehicle is on the desired location, as shown in Figure 2. For that purpose, a location check is needed. The location check is performed in two steps: the preliminary detection circle check, which is performed in the OBU, and the fine detection circle check, which is performed in the RSU. The idea behind the detection circle check is that the desired location area on the congested road is split into overlapping circles, as shown in Figure 3. Preliminary circles are chosen with a much larger radius (10 to 20 times the road width) so that they cover all of the desired location on the congested road. The center points and the radius of the preliminary circles are sent as data of the invite message from the RSU to the OBU. Ideally, one preliminary circle with a large enough radius is sufficient for the test. However, a few more overlapping circles are used to make the V2I communication more efficient by reducing and distributing the processing burden on both the OBU and the RSU. The OBU, after passing a direction check, performs a preliminary location check by comparing the distance between its location and the center of a preliminary circle. If the distance is less than the radius of the preliminary circle, it passes the test and potentially could be at the desired location. If not, it repeats the process for all the consecutive preliminary circles.

The radius of the preliminary detection circle is quite large so it is possible that a vehicle that passes the preliminary circle test could still fall on a nearby parallel road, as shown in Figure 3. To ensure that the vehicle is on the desired road, a fine location check is performed in the RSU. The idea of the fine location test is very similar to the preliminary circle test. The major difference is that the radius for fine circle test is much smaller. The radius of the fine detection circle is chosen in such a way that the two consecutive overlapping circles cover the whole of the road width, as shown in the inset of Figure 3. The condition shown in the inset of Figure 3 is described by the following equation:

$$R^2 = \left(\frac{D}{2}\right)^2 + \left(\frac{W}{2}\right)^2$$  \hspace{1cm} (1)

where

- $R = $ radius of the circle,
- $D = $ distance between the centers of the two consecutive circles, and
- $W = $ one-sided road width.

A range of values for $R$ and $D$ can fulfill the above equation. However, one limitation on $R$ is that it should be small enough not to include another parallel road and still larger than $W/2$ to cover the full one-sided road width. The optimal $R$ value occurs when $D = W$. That value will bring $R$ to $0.7W$ with Equation 1, which is small enough not to include another parallel road and still larger than $W/2$.

The RSU needs to check only the fine detection circles associated with one preliminary circle passed by the OBU. This information is sent by the OBU to the RSU as the data of the accept message.

![FIGURE 3. Schematic diagram showing detection circles for preliminary and fine location checks in OBU and RSU: (inset) enlarged version of two consecutive fine detection circles showing radius ($R$) and separation ($D$) with respect to one-sided road width ($W$).](image-url)
After the fine location check in the RSU is passed, it is finally determined that the chosen vehicle is traveling in the right direction on the desired road and is positioned at the desired location.

**Travel Time and Start of Congestion Estimation**

Once the fine location check is passed in the RSU, a chosen message is sent to the selected OBU. Upon receiving the chosen message, the OBU periodically sends the notify messages containing time, speed, and location information to the RSU while it travels through the congestion until it reaches the EoC location. To ensure that the OBU has crossed the EoC location, an EoC location test is performed at the OBU. The EoC point and the proximity distance threshold for the EoC location test are sent to the OBU as data of the chosen message. When the EoC test is passed in the OBU, it activates the EoC indicator in the data of the notify message so that the RSU knows that the EoC has been reached. Once in communication with the RSU, the OBU sends notify messages along with the EoC identifier every 1 s. However, the OBU updates the current location and time every communication time interval, which is sent to the OBU as part of the data in the chosen message. The communication time interval is usually a few seconds, depending on TT and congestion length. Therefore, more than one notify message sent to the RSU will have the same data in terms of time, location, speed, and EoC indicator. The redundancy ensures that the RSU gets more opportunity to receive data even if one or more OBU notify messages are lost due to a temporarily blocked line of sight (LoS). Upon receiving a notify message with a positive EoC indicator, the RSU stops processing any more incoming notify messages from the OBU and calculates and updates SoC and TT before preparing itself to be shut down from the vehicle, or the vehicle containing the OBU being shut down from the vehicle, or the vehicle containing the OBU making a U-turn to avoid congestion.

**FIELD DEMONSTRATION RESULTS AND DISCUSSION**

For the field demonstration, DSRC units from Savari Networks were used. The OBU was equipped with a GPS unit using a USB port on the Savari DSRC unit. Also, the OBU was connected with the previously developed communication interface device for relaying the broadcast message to the BT-enabled cell phone in the vehicle. The software of both the OBU and the RSU were written in C++ language using a Unix platform. The two units were field tested from time to time on various roads. However, the final demonstration was done on Rice Lake Road in Duluth, Minnesota, as shown in Figure 4. This road was chosen because it had no elevation, giving a clear LoS from the RSU to the OBU throughout the coverage range. The RSU was placed on top of a parked vehicle. Therefore, the elevation of the road could hide the RSU from the OBU completely at certain points. In practice, the RSU should be installed at a reasonable elevation to overcome the variation in elevation of the road, providing a clear LoS between the RSU and the OBU throughout the coverage range. The coverage range of the RSU is shown in Figure 4. The RSU device covered a range of about 1 km (0.75 km on the left and 0.25 km on the right). The coverage range of the RSU was asymmetric because this coverage range is intended for the OBU, which was placed on...
the dashboard of the vehicle traveling from left to right (Figure 4). When the vehicle was traveling toward the RSU (placed on top of a parked vehicle), the windscreen provided a clear LoS. However, when the vehicle was going away from the RSU, the back side of the traveling vehicle blocked the LoS, reducing the coverage range.

For demonstration purposes, the RSU was powered up and the program was started by initializing the input parameters for Rice Lake Road. In this part of the demonstration, only one OBU was used traveling through the congestion and communicating with the RSU. The vehicle containing the OBU was driven at 40 mph (17.88 m/s) from left to right many times, reducing speed at different SoC locations on the road and ramping up again to 40 mph at the EoC point. The RSU captured the traffic data from the OBU and estimated TT and SoC location. The estimated TT and SoC location data were broadcast every 1 s by the RSU. During the demonstration, various RSU parameters were changed to test the control of the RSU on V2I DSRC communication. The demonstration worked smoothly without the need to change anything in the OBU. The OBU adapted to the changing parameters in the RSU during multiple runs of field demonstrations and worked seamlessly to facilitate TT and SoC location estimates.

In the first step of the field demonstration, a fixed landmark for the SoC was chosen and the speed of the traveling vehicle containing the OBU was always decreased at that landmark for many runs. While the speed was decreased to simulate congestion, the vehicle was driven on the shoulder of the road to give way to regular traffic. With the fixed landmark for the SoC, the congestion length was a little short of 500 m. The estimated TT was between 100 and 200 s for various runs of demonstrations. The variation in TT was caused by speed control by the driver during the simulated congestion and sometimes there was traffic running at a nominal speed on the road, so merging from the shoulder to the actual road and ramping up at the EoC were delayed while waiting for a clear spot on the road.

A typical set of data containing the speed of the traveling vehicle, captured by the RSU to estimate TT and SoC, is shown in Figure 5. Once the RSU captured these data while the chosen OBU was traveling through congestion, it estimated the SoC location and TT. One important RSU parameter, communication time interval, was varied to capture the data again and again, and SoC location and TT were estimated correctly each time. The broadcast message was sent every 1 s that contained the SoC location, TT, and the descriptive name and direction of the road as its data. The SoC location was broadcast in terms of longitude and latitude and TT was broadcast in seconds to all vehicles in the coverage range of the RSU. The descriptive name of the road was Rice Lake Road towards airport. Once an OBU received the three parameters, it calculated the distance from its own position to the SoC and then relayed three parameters to the BT-enabled phone in the vehicle as a text message. The three parameters were TT, distance to the SoC, and the descriptive name of the road. The distance to the SoC location was an important safety parameter, which allows drivers to slow down when approaching congestion. This message could be intercepted by vehicles traveling on other roads; however, it is assumed that the human factor would keep any confusion from occurring as the driver would know the message was intended for a particular road and direction.

Next, the RSU parameters were fixed with communication time interval equal to 2 s and the vehicle with the OBU was driven through the congestion many times, simulating growing congestion with time. The RSU kept on capturing the data successfully and estimated the TT and SoC correctly each time. The three typical data sets for three positions of the SoC are shown in Figure 6a, where the congestion length was varied from smaller to longer with increasing TT. The TT associated with the three sets of curves was 78, 150, and 250 s, respectively, from the shortest to the longest congestion length. Similarly, another scenario was tested by varying not only the SoC location but also the congestion depth. The congestion depth is defined as the relative speed reduction compared with the maximum rated speed. The different set of data captured by the RSU is shown in Figure 6b. The TT associated with three curves was 22, 70, and 150 s, respectively, from the smallest to the longest congestion depth. Each time the SoC location and TT were estimated correctly and the broadcast message was received successfully.

Although the field demonstration was successful in accurately estimating SoC location and TT and periodically broadcasting the same in due course, the congestion length and broadcast range handled by this V2I DSRC communication system was less than 1 km. This kind of system can be best used if the message broadcast range can be increased so that drivers have more time to make decisions about their travel route based on prior information of the TT and SoC location. If a vehicle is within 1 km (half a mile) of the work zone when it receives the SoC and TT information, it may give the traveler some awareness but may not help him or her make alternate route decisions. This is necessary for increased safety and managing rapid growth of traffic congestion on an already problematic roadway resulting from work-zone- or accident-related congestion. Similarly, the practical lengths of congested U.S. roadways initiated by work zones or accidents could be much longer than 1 km, making the SoC outside the

![FIGURE 5 Speed of vehicle traveling through congestion captured by RSU: (a) versus relative distance and (b) versus time.](image-url)
RSU range. Therefore, it is necessary to come up with a scaling method that can increase both the congestion coverage length and the message broadcast range in the currently developed system. This scaling can be accomplished with multiple RSUs periodically placed across the road. This can help increase both congestion coverage and the message broadcast range using V2I communication.

However, V2I communication could be more costly and requires more maintenance and management. A preferred solution would be to take advantage of onboard DSRC units of the vehicles utilizing V2V communication for increased congestion coverage length and message broadcast range. By doing so, the system will remain portable with a requirement of only one roadside DSRC unit at the sight of the congestion area, which engages all vehicles carrying DSRC OBUs to participate in traffic data acquisition and transportation of useful traffic safety information back to travelers. A system that can handle much longer congestion lengths (up to a few kilometers) and a much larger safety message broadcast range (up to a few tens of kilometers) using V2V DSRC communication is being developed.

**CONCLUSIONS**

A portable safety information system using DSRC-based V2I communication was developed for the work-zone environment. This system can be installed on any U.S. roadway with congestion caused by a work zone or an accident. This system can accurately estimate TT and SoC location in real time, as these parameters change with varying traffic influx of the road. The estimated SoC location and TT are broadcast to all vehicles approaching the congestion area. The SoC location is converted to the distance to the SoC for a given vehicle before it is communicated to the driver. The TT and the distance to the SoC can help prepare drivers to slow down or make an informed decision about rerouting their vehicles. This system was extensively tested in a field demonstration using actual DSRC units. The field demonstration results have shown that the newly developed system can adapt to changing road situations and works smoothly under various congestion scenarios on the road.

**ACKNOWLEDGMENTS**

The authors thank Hai Quang Dinh, a University of Minnesota–Duluth student, for his invaluable help during the field demonstration; Ravi Puvvala of Savari Networks for his help with the DSRC units; and Beau Roodell for his insight and advice on the BT-enabled phone interface of the project.

**REFERENCES**