Vehicle-to-Infrastructure and Vehicle-to-Vehicle Information System in Work Zones

Dedicated Short-Range Communications

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This paper describes the architecture, functionality, and field demonstration results of a newly developed dedicated short-range communication-based vehicle-to-infrastructure work zone traffic information system with vehicle-to-vehicle assistance. The new system is portable and can automatically acquire important work zone traffic information such as the travel time and the starting location of congestion and then relay this information to drivers approaching the congestion site. Such information can help drivers make informed decisions on route choice, prepare for upcoming congestion, or both. The authors had designed a similar system earlier; that system had limited congestion coverage and message broadcast ranges, but the new system can achieve a much longer broadcast range (up to a few tens of kilometers) and can handle much longer congestion coverage (up to a few kilometers) by incorporating vehicle-to-infrastructure communication assisted by vehicle-to-vehicle communication. The system requires only a single roadside unit to acquire traffic data by engaging the vehicles traveling on the road whether within or outside of its direct wireless access range. From the traffic data, the system estimates important traffic parameters such as travel time and starting location of congestion and periodically broadcasts this information back to the vehicles approaching the congestion well before they enter the congested area. The results from the field demonstration show that the new system can adapt to a dynamically changing work zone traffic environment and can handle much longer congestion lengths as compared with the previous system, which used only vehicle-to-infrastructure communication without vehicle-to-vehicle assistance.

The dedicated short-range communication (DSRC) wireless band is a frequency band reserved for active automotive traffic safety applications using both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication to increase drivers’ situational awareness and to reduce or eliminate crashes (1). The DSRC technology has continued to capture the interest of the government, automobile manufacturers, academia, and many other stakeholders as one of the best near-term viable technologies that can offer the latency, accuracy, and reliability needed for active safety and mobility features of traffic on highways (2–5). To date, many DSRC message communication protocols have been proposed and tested for their reliability, congestion control, and other characteristics (5–7). Some of the current DSRC technology applications being developed include traffic data acquisition and dissemination systems, intersection collision warning systems, and curve over-speed warning systems (8–11).

DSRC systems can be V2I, V2V, or a hybrid of both, depending on the application. V2V communication could be of two types: between two vehicles and between multiple vehicles communicating with each other in a network environment. The second type of V2V communication is usually needed for traffic data acquisition and dissemination systems. This type allows using ad hoc networks needed for safety-critical applications with minimal delays. To adapt ad hoc networks for vehicular communication, extensive research has been done on the dynamic nature of the network and the need for fast communication and data dissemination (12–20).

Issues such as message reliability and congestion are being aggressively pursued in a variety of research studies, and several approaches have been proposed to mitigate these and other issues (10, 15–18). Similarly, message security in intervehicular communication is of equal concern in both the multihopping and the single V2V communication environment in case of hacking attempts. The IEEE 1609 standard, on which the J2735 standard is built, addresses eavesdropping, spoofing, altering, and replay attacks. However, IEEE 1609 does not cover attacks from vehicle-originating messages yet. Research is being done to address the issue and make the communication more secure (21, 22).

The number of work zones is set to increase with many U.S. roads needing maintenance and repair. This situation makes the congestion worse since many of these roads already carry heavy traffic; work zones can cause lengthier delays leading to driver frustration and sometimes to accidents (23, 24). Work-zone-related congestion can grow very quickly, especially during peak hours, which highlights the need for a monitoring system with quick updates for travel time and congestion length (25, 26).

This research paper describes a DSRC-based V2I traffic information system with V2V assistance. The developed system can acquire work zone travel data such as the travel time (TT) through congestion as well as the starting location of congestion (SLoC) and periodically broadcast these parameters with DSRC-based V2V-assisted V2I communication. Before this study, a similar information system using only V2I communication was developed, which had limitations in terms of congestion coverage length and message broadcast range (27). Using DSRC-based V2V-assisted V2I communication,
the authors have significantly improved both the congestion coverage length and the message broadcast range. The new system can be used in complicated scenarios where work-zone-related congestion could be up to a few kilometers long and the message broadcast range could be up to a few tens of kilometers to provide drivers with timely information to decide about alternate routes. Furthermore, the developed system is fully portable and can adapt to a variety of congestion scenarios including accident-related congestion. A field demonstration of the developed system was conducted to evaluate the system.

SYSTEM ARCHITECTURE

The primary objective of the DSRC-based V2I traffic information system with V2V assistance is to acquire real-time traffic data, generate useful travel safety information such as the TT and SLoC, and broadcast this information for drivers’ benefit. Previously, a portable work zone traffic safety information system was developed that utilized DSRC-based V2I communication to acquire TT and SLoC information. With that system, all vehicles with the DSRC onboard unit (OBU) within the access wireless coverage range of the DSRC roadside unit (RSU) were engaged to acquire the TT and SLoC (27).

The major limitation of that information system was that the direct wireless access range of the RSU determined the work zone coverage length as well as the message broadcast range. Because the access range of DSRC technology is about 1 km, both the work zone coverage length and the safety message broadcast range were of the same order, in fact much less than in a practical system. The traffic information system can be best utilized if the message broadcast range is much longer than the work zone length so that drivers have the option to make some alternate travel routing decisions with information about TT and SLoC well before they reach the congestion site. Similarly, the practical lengths of congestion on U.S. roadways could be much longer than 1 km. Therefore, it was necessary to find a scaling method that could increase both the congestion coverage length and the message broadcast range. The newly developed DSRC-based V2V-assisted V2I traffic information system allows for longer congestion coverage and increased message broadcast range. By using V2V communication, the system remains portable with the requirement of only one roadside DSRC unit at the congestion site, which engages all the vehicles within and beyond its wireless access range to participate in traffic data acquisition and dissemination.

The conceptual architectural schematic of the developed information system is shown in Figure 1. In the developed DSRC system the portable RSU is installed along the road on a sign post at a height that provides a clear line of sight (LoS) to vehicles traveling on the road. In addition, its positioning is such that one end of its wireless access range coincides with the ending location of congestion (ELoC), which is usually known. Although the ELoC is fixed and known, the SLoC can vary and expand well beyond the wireless access range of the portable RSU. The RSU uses V2V-assisted V2I communication to engage vehicles and acquire traffic data.

Once the RSU is installed and powered up, it will require user input to initialize a set of parameters such as the ELoC, nominal road speed limit, road width, and direction for adapting to a particular work zone or congested road environment (27). After being initialized with the required parameters, the software of the RSU will control the back-and-forth DSRC with all the vehicles passing through the congestion by using V2I or V2V communication, depending on whether the vehicle is within or beyond its direct wireless access range, to acquire the TT and SLoC information. Software of the OBU is designed in such a way that no user input is required and it can be seamlessly engaged with the portable RSU via V2I or V2V communication, or both. The OBU hardware contains DSRC radio communication capability as well as Global Positioning System technology as compared with the RSU, which only needs to have DSRC radio communication capability. The Global Positioning System capability in the OBU is needed so that the current location...
of the vehicle can be known. In the newly developed system, to maintain privacy the RSU communicates with OBUs and OBUs communicate with each other without the identity information of any OBU being known or kept.

**SYSTEM FUNCTIONALITY**

The portable RSU is placed such that its end-of-monitoring range is just beyond the ELoC on one end of the road as shown in Figure 2. When the RSU selects an OBU to receive travel data updates, the selection should be made well before the vehicle carrying the OBU enters the congestion region. The area before the congestion region in which OBUs are allowed to start engaging in communication with the RSU is termed the “desired region,” as shown in Figure 2. The desired region should be well before the SLoC so that a traveling vehicle can exchange handshake messages with the RSU to be engaged in the data acquisition process (27) and starts sending the location and speed information to the RSU before entering the congestion. Because the SLoC could vary, depending on the traffic influx, the RSU’s software is designed to vary the desired region depending on the SLoC.

To engage a vehicle for the acquisition of traffic information, the RSU periodically transmits invitation messages to the OBUs of the vehicles in its monitoring range either using V2I communication if the desired region is within its direct access range or using V2V-assisted V2I communication if the desired region is beyond its direct wireless access range. Vehicles with OBUs traveling in the desired region (Figure 2) respond to the invitation messages by sending acknowledgements back to the RSU with either V2I- or V2V-assisted V2I communication depending on their location. One of the OBUs of the acknowledging vehicles traveling in the desired region of the monitored road (Figure 2) is selected for acquiring traffic data by the RSU. In the selection of a vehicle for data acquisition, the RSU also determines the frequency of traffic data notifications when it sends the final selection message to the chosen vehicle. The selected OBU then sends back to the RSU its location and speed information as it travels through the congestion until it reaches the ELoC. When the monitored vehicle passes the ELoC, the RSU estimates the TT and SLoC on the basis of the data received before that point. For the RSU to estimate the SLoC, a threshold-based definition of congestion is used. The SLoC is defined as the location where the speed falls below 50% of the normal rated speed of the road. If the vehicle speed does not fall below the 50% limit, the threshold is progressively redefined as 60%, 70%, 80%, 90%, and 100% of the rated speed. The TT is then calculated as the time needed to travel from SLoC to ELoC.

Once TT and SLoC are determined, the information message is updated with new TT and SLoC. The information message containing the TT and SLoC is sent to all the OBUs periodically, but the TT and SLoC are only updated when a selected vehicle passes the ELoC while completing the message handshake with the RSU as highlighted in the previous paragraph and described in detail in an earlier paper (27). Once the OBU receives an information message, it can also calculate its distance from the SLoC, which is useful along with TT in deciding to take an alternate route. A complete update of TT and SLoC is obtained when a vehicle approaching the congestion is selected by the OBU and passes through the ELoC.

Normally, only one vehicle is selected and monitored at a time. However, if the TT turns out to be greater than a predefined threshold, more vehicles are selected at a time to update the TT and SLoC more frequently. During this whole process of estimating TT and SLoC, many messages are exchanged between the selected OBU and the RSU. The Society of Automotive Engineers has specified the safety message composition for the DSRC in their draft standard SAE J2735. In this study, the messages formats that comply with this standard were used; they contain the mandatory fields of the message types such as a la carte and basic safety message. The messages used contain the data fields specified in J2735, and the entire message is encoded and communicated according to J2735. However, the directional message broadcast is controlled by the protocol designed and implemented in the software developed for this application.

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**FIGURE 2** Conceptual diagram showing desired region and coverage range of V2V-assisted V2I traffic information system.
Both the RSU and OBU programs have a reset time that is triggered by not receiving any messages for a predefined time period during the message handshake between the selected vehicle and the RSU. This process ensures that the programs are able to function correctly despite unexpected scenarios such as when the vehicle stops in the congested area for a rest, the OBU is shut down from the vehicle, or the vehicle containing the OBU is taking a U-turn to avoid the congestion.

V2V-ASSISTED V2I COMMUNICATION PROTOCOL

The system can work with only V2I communication as long as the congestion length is less than half a kilometer and the information does not need to be disseminated beyond 1 km from the RSU. However, as the congestion length increases, the V2I communication does not remain effective and V2V assistance is needed to get the handshake messages to and from the desired vehicles to the RSU.

In the developed system, the V2V-assisted V2I communication protocol was designed in such a way that it is transparent to the vehicles whether they need to use V2I communication or V2V-assisted V2I communication. The central control is still in the RSU, and once it sends the handshake messages to nearby vehicles within its direct wireless access range, the vehicles based on their location will receive and process the message to determine if a given message is intended for their internal use or to be relayed forward to other vehicles, or both. If the message is for the vehicle’s own use, it will act accordingly and if the message is to be relayed forward, the vehicle will do that using the V2V communication protocol. In V2V communication, the following two key rules are considered:

1. Selective relay. Not all the vehicles receiving a message should relay the same message forward because it will create a broadcast storm. Rather, only one of the vehicles should relay the message forward, and the selection of that one vehicle should be such that the number of hops can be minimized when a given message is conveyed to the intended vehicle.

2. Directional relay. Similarly, the message propagation should be only in the desired direction (forward or backward depending on the message type) to avoid the same message’s being relayed back and forth causing message congestion. If an information message is going from the RSU to the vehicles, it should be relayed in the direction of the road from which the vehicles are approaching the congestion.

These two rules handle the message until the message is relayed to the intended recipient vehicle. The implementation details of the two rules are given in the following subsections.

Selective Relay

When a message originates from an RSU or an OBU, it will be received by many vehicles in its vicinity and some of the receiving OBUs will be near the message-originating unit and some will be farther away, as shown in Figure 3.

If the message is to be relayed, it is important to choose the farthest reliable OBU to forward the message. This procedure decreases the number of hops, which in turn avoids delay and bandwidth congestion. To achieve this condition, whenever an OBU receives a message it will check its distance from the last message origination unit and randomly select a waiting time from a predetermined time band (tb) depending on its distance from the last message origination unit. The waiting time band will decrease as the distance from the last message origination unit increases, as shown in Figure 3, where \( tb_5 < tb_4 < tb_3 < tb_2 < tb_1 \).

Once all of the receiving OBUs are in the waiting mode to retransmit, one of the OBUs in the farthest distance band from the message originating unit with the least amount of waiting time will be first to relay the message. The other OBUs waiting to relay will detect having received the same message again and will discard the received message and also remove the message from the message queue waiting to be rebroadcast. In this way, only one of the OBUs in the farthest distance band will relay the message. This chain can be repeated to move the message forward. The antenna of the DSRC RSU or OBU should be omnidirectional to obtain the best efficiency.

For the current system, the distance was divided in five distance bands of 100-m width as shown in Figure 3. This design is used because the reliable practical wireless access range of the DSRC units with omnidirectional antennas is a little more than 500 m. All of the receiving OBUs in the farthest-distance band (400 to 500 m) will randomly select a waiting time from 0 to 5 ms and the next-

FIGURE 3 Selective relay functionality of V2V-assisted V2I communication protocol (tb = time band).
distance band (300 to 400 m) will randomly select a waiting time from 5 to 10 ms, and so on, whereas the OBUs in the nearest-distance band (0 to 100 m) will randomly select a waiting time from 20 to 25 ms. This scheme ensures that one of the OBUs in the outermost band will relay first and also allows for the possibility of having no DSRC units in the outer bands at a given time, in which case one of the inner-band units will be able to transmit. This situation could occur because it is assumed that DSRC penetration is less than 100% as well as to account for light traffic conditions at certain times and locations. Furthermore, the random time delay ensures that not more than one unit can transmit at the same time to avoid message collision.

**Directional Relay**

Selective relay minimizes the number of hops to convey a given message to the intended destination. However, this scheme cannot ensure that the message is only relayed in one direction, for example, left to right (Figure 3). OBUs on a road that crosses or runs parallel to the concerned road (the work zone road) have to be rejected from taking part in V2V communication to avoid unnecessary buildup of message congestion. Similarly, to avoid relaying of any given message back and forth, which can ultimately cause message congestion to build up, it is important to ensure that the message goes in only one direction, such as from left to right as shown in Figures 3 and 4. To ensure that the message propagates only in the desired direction, a few checks are included in the V2V-assisted V2I communication protocol.

**Angular Region Check**

The purpose of the angular region check is to block the OBUs outside of the broadcast coverage region from participating in the V2V communication. There might be roads that run parallel or otherwise to the desired work zone road inside the broadcast coverage range. Although the OBUs on those roads may be able to contribute to V2V communication, they are not necessary, and if allowed to join could cause message congestion to grow rapidly. To avoid this occurrence, an angular region is defined around the desired work zone road for a given broadcast coverage range as shown in Figure 4. The angular region is defined by using three parameters: focal point, direction of angle with respect to north, and angle width. These parameters are set in the RSU upon initialization, which in turn sends these parameters to the surrounding vehicles in a message format as part of the message handshake process.

The angular focal point could be taken as the same as the RSU location or a different location to minimize the angle width. Many practical road scenarios were considered and it was found that an angle width of less than 10 degrees is sufficient to cover a large span of 20 to 30 km of curved road. Whenever an OBU receives a message, it checks whether it is within the angular region before processing the message any further. If it is outside the angular region, it will drop the message immediately. If within the angular region, it will process the message and relay the message forward to the vehicles ahead. Figure 4 shows a similar scenario, in which after Hop 2, the OBU outside of the angular region will not be selected and the OBU located within the angular region will continue the relay. The messages are given a desired direction (downstream or upstream) to be transmitted upon origin, and propagation in that direction can be facilitated by any OBUs traveling in either the upstream or the downstream direction as long as they are in the angular region. This process can make the message broadcast more efficient in a scenario of less-than-optimal market penetration of the DSRC units.

**Reference Angle Check**

Sometimes when a given OBU receives a message within the angular region, it is possible that this OBU is on a road crossing the monitored road. If this OBU participates in retransmission, it is likely to propagate away from the monitored road, and because of selective relay, the OBU on the monitored road (in the same distance band) will cease to propagate any further. This occurrence could change the message propagation direction and the message may never reach the desired region or remote vehicles on the work zone road, especially if the road has significant curvature and many crossing roads. Since the road curvature can be diverse and over a long distance range, it is a burden on data communication to specify values to filter out
vehicles on so many other roads. Instead a reference angle check is used to ensure that the message propagates along the natural curvature of the road.

Whenever an OBU receives a message, it will calculate the direction from its current location to the last transmission origination and compare that with the direction given in the last transmission hop. If the difference is within a certain error bound (±10 degrees in this case), which can be attributed to the road curvature, the message will be processed. However, if the difference is too large, the message is not processed; this step avoids unwanted propagation direction and ensures that the message stays on the desired road. For example, in Figure 4, in Hop 8, the OBU on the crossing road will not pass the reference angle test and therefore will not relay the message. Instead the OBU on the desired road will propagate the message forward.

**Back-Propagation Check**

When a message is transmitted, it is received by the DSRC units that are behind the transmitting unit in addition to the units up ahead on the road. These units should not retransmit the message since the message has reached the current location by passing through these units and if these units also retransmit, the message will keep on relaying back and forth. In this test the units will measure their current distance from a reference point, for example, the RSU location, and will compare that against the distance to the same reference point from the previous transmission location. By comparing the two distances, an OBU can determine if the message is being propagated in the forward or backward direction. If the message originates from the RSU and is intended for a remote vehicle, it should only be relayed by an OBU that is farther from the RSU as compared with the OBU at a previous transmission location. Similarly, if the message originates from a remote vehicle and is intended for the RSU, it should only be relayed by an OBU that is closer to the RSU as compared with the OBU at a previous transmission location. This test ensures that a message can smoothly propagate from the RSU to a remote vehicle or vice versa and does not relay back and forth within the angular region and cause message congestion.

**FIELD DEMONSTRATION RESULTS AND DISCUSSION**

The main purpose of the field testing was to demonstrate the extended message broadcast range and congestion coverage range using V2I communication with V2V assistance. For the demonstration, five DSRC units currently available on the market were used. The wireless access range of each of these units was around 500 m using omnidirectional antennas and there was a clear LoS. One of the five units was used as the RSU and the remaining units were used as OBUs.

The demonstration site chosen for this field testing was Rice Lake Road in Duluth, Minnesota, as shown in Figure 5. The RSU was mounted on one side of the road on a pole at a reasonable height (~ 6 ft) so that it could have a clear LoS to the passing vehicles. A fixed point was assumed for the ELoC, and the RSU was mounted quite close to that point. Although the ELoC could be 500 m away from the RSU because of the wireless access range of the RSU, in this case it was only about 200 m. The reason was that when the OBU was placed on the dashboard of the vehicle, it created an asymmetric range on the front and back of the vehicle due to the LoS’s being blocked from the back of the vehicle. When the vehicle was moving with the OBU on the dashboard, it was facing the RSU, with a clear LoS giving the full available DSRC range (500 m). But as soon as it crossed the RSU, the vehicle structure blocked the LoS reducing the range to only about 200 m.

Three of the four OBUs were placed on stationary vehicles on the road as shown in Figure 5 so that the wireless access range of the RSU on the SLoC side was extended by using V2V-assisted V2I communication. Previously, with the V2I-only system design, the SLoC could only be varied within the direct wireless access range of the RSU. But now the SLoC could be varied beyond the direct wireless access range of the RSU with the help of OBUs using V2V communication. The final OBU was in the test drive vehicle, which communicated with the RSU so that TT and SLoC could be acquired. The test drive vehicle OBU was also used to monitor whether the updated information message (carrying TT and SLoC) from the RSU was received correctly regardless of the location of the test drive vehicle (i.e., within or outside of the direct wireless access range of the RSU). Two of the OBUs were placed near each other to test the timing delay implemented in the timing bands, and the farther OBU was found to always retransmit the message before the other OBU as dictated by the protocol.

In this demonstration the speed limit of the road was considered as 40 mph (17.88 m/s) and the vehicle with the moving OBU was driven near this speed before it entered the congestion area. Once the vehicle was in the congestion area the speed was reduced until the ELoC was reached, at which point the vehicle speeded up again. The messages being received and transmitted were observed at all times by using a laptop terminal session via Ethernet/Minicom connection with the DSRC unit.

![FIGURE 5  Field demonstration site showing placement of DSRC units and coverage range of V2V-assisted V2I traffic system.](image-url)
Once the moving OBU entered the desired region before the SLoC, it responded to the RSU handshake messages and kept on sending speed and location information back to the RSU by using V2I communication with V2V assistance. The RSU received the traffic data from the OBU and once the OBU indicated that it had passed the ELoC, the RSU estimated the TT and SLoC and updated the information message with the new data. Some of the test runs are shown in Figure 6, where the speed of the monitored vehicle is plotted versus distance and time and varying SLoC and ELoC points are shown. These data were extracted from the data log of the RSU.

Previously, with the V2I-only communication system, a maximum congestion length of only 300 m could be demonstrated (27). However, with V2V-assisted V2I communication, a congestion length up to 1,400 m was possible (Figure 6a). The congestion coverage range in this demonstration was larger than before but still limited by the number of OBUs being used. Functionally, the design can accommodate the congestion coverage range of up to a few kilometers. Similarly, the message broadcast range can be enhanced by the design up to a few tens of kilometers. However, because of the limited number of OBUs, a message broadcast range larger than 2 km could not be shown. The authors are planning to get more units and will be able to demonstrate much larger congestion length as well as message broadcast range in the future.

CONCLUSIONS

An information system using V2V-assisted V2I communication was developed and demonstrated that has a significantly improved congestion length coverage and message broadcast range as compared with the previously developed V2I-only communication system. The new system can handle work zone sites with a congestion length of up to a few kilometers. Furthermore, the message broadcast coverage range could be up to a few tens of kilometers with only one RSU, which makes it easily deployable on any work zone site. The increased range would make it possible for drivers to receive information messages much earlier, when it is possible to make alternate route choices, leading to less congestion in the work zone.

During the demonstration, the portable V2V-assisted V2I traffic information system proved to be able to accurately estimate the TT and SLoC and to update these values as they changed with the varying traffic influx of the road. The estimated SLoC and TT were broadcast to all the vehicles approaching the congestion area. The SLoC was converted to the distance to the SLoC from the given vehicle’s location before it was communicated to the driver. The TT and distance to the SLoC can help drivers to be prepared to slow down or make an informed decision about rerouting their vehicles, or both. The field demonstration results showed that the newly developed system can adapt to changing congestion scenarios on the road and cover a longer congestion area and broadcast range.

REFERENCES


The Intelligent Transportation Systems Committee peer-reviewed this paper.