Integrated Traffic/Communications Simulation Evaluation Environment for IntelliDrive℠ Applications Using SAE J2735 Dedicated Short Range Communications Message Sets

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ABSTRACT

Vehicle-to-vehicle and vehicle-to-infrastructure communications made possible by IntelliDrive™ will enable entirely new transportation applications and services. In order to understand and quantify potential benefits anticipated from IntelliDrive™ applications, there is a strong need to properly evaluate these applications prior to field deployment. For this, the need for an evaluation environment that allows more realistic simulation of IntelliDrive™ applications is clear. Given this motivation, in this paper, an IntelliDrive™ simulation environment was developed, that (a) replicates precise vehicular movements, (b) incorporates IntelliDrive™ wireless communications based on the WAVE/DSRC standards, and (c) finally simulates real IntelliDrive™ message sets defined in the SAE J2735 standard.

A case study of a prototype lane changing advisory algorithm conducted on a freeway network in Northern Virginia has revealed that communication delays are not likely to be a significant factor, showing the maximum delays of only 55 milliseconds for the Basic Safety Message (BSM, 39 bytes) and 1.3 milliseconds for the A la Carte Message (ACM, 20 bytes). On the other hand, the probability of successful communications was found to be a critical factor that can impact the evaluation results significantly. For example, for a lane changing advisory algorithm, the probability of successful transmission of a series of required messages – three BSMs (from each of three involved vehicles to the Road Side Equipment) and one ACM (from the Road Side Equipment to the lane changing vehicle) – was only 50% when there are less than 120 vehicles within a communications radius of 50 meters, implying a significant degradation in the algorithm performance. The results of this case study demonstrates the feasibility of integrating traffic and communications simulation models, and also illustrates the need to consider both components in IntelliDrive™ evaluation.
INTRODUCTION

Advances in wireless communications technology have opened up a new era providing transportation professionals with a new set of tools to significantly improve the provision of transportation services. Utilizing these advanced technologies, the U.S. Department of Transportation (DOT), in cooperation with state and local transportation agencies and industry, have initiated the IntelliDrive℠ program, defined as “a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers’ personal communications devices (I)”. Under the IntelliDrive℠ environment, vehicles will communicate directly with nearby vehicles, the infrastructure as well as other wireless devices primarily through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.

Given that IntelliDrive℠ makes feasible entirely new applications and services, there is a need to evaluate the benefits offered by these applications. There are two evaluation approaches available: prototype testbeds and simulations. Prototype testbeds have been developed and fielded in recent years, for example in Michigan (2) and California (3). While these are very useful in testing the underlying technology, they have proven to be limited in analyzing system level applications and services due to the fact that only a small number of vehicles may feasibly be equipped (2). Thus, simulation-based research is the only feasible way to evaluate the benefits and costs of system-level IntelliDrive℠ applications.

Recent studies have utilized simulations to investigate expected benefits from a variety of applications such as traffic monitoring, ramp metering, and route guidance. Most of these studies have adapted either traffic simulations or wireless communications simulation tools. However, given that IntelliDrive℠ represents an integrated transportation/communications system, it follows that the most effective simulation environment is one that integrates traffic and wireless communications models. While there have been a few studies that have done this, they have used generic or idealized message sets, rather than those defined in the emerging SAE J2735 standard “Dedicated Short Range Communications (DSRC) Message Set Dictionary” prepared by the Society of Automotive Engineers (4).

Given this motivation, the goal of this research was to develop an IntelliDrive℠ simulation environment integrating both microscopic traffic simulation and a wireless communications network simulator. In addition, this simulation environment incorporates “real” IntelliDrive℠ messages in SAE J2735, and is also able to simulate various types of messages at the same time. Following this introduction, the paper will provide a literature review. The simulation environment and the method used by the research team will then be presented. Finally, the paper describes a case study using the simulation environment to evaluate a lane changing advisory algorithm designed to support improved ramp management.
LITERATURE REVIEW

There have been several research studies of the characteristics of wireless communications in a vehicular ad-hoc network (VANET) environment and wireless access in vehicular environments (WAVE) (5). This section summarizes some of the key efforts.

Initially IntelliDriveSM research consisted primarily of testbeds for only traffic simulation. Tanikella et al. (6) and Smith and Park (7) developed IntelliDriveSM simulation testbeds that can be used to quantify potential benefits of two sophisticated IntelliDriveSM applications: (a) a traffic monitoring application in the Tyson’s Corner network in Virginia using AIMSUN (8), and (b) a ramp metering application in Irvine, California, using PARAMICS (9). These simulation test-beds consist of a microscopic traffic simulation model and an IntelliDriveSM layer that filters every vehicle snapshot and generates IntelliDriveSM data. Yet, the IntelliDriveSM layers assumed a perfect communications performance: for example, no delays occur if vehicles are within the communication zone. In reality, there are transmission delays as well as packet drops during radio communications. Further study has illustrated that it is essential to integrate the communications network simulator with the traffic simulator. The reason for using an integrated simulation instead of feeding post-processed results from one simulation to another is that the result of the communication simulation will impact the future movement of vehicles in the traffic network, which would in turn impact the future communication that will be performed since the distances between the vehicles and the positions will change. This is why it is impossible to first run the communication simulation on pre-computed vehicle trajectories, since these trajectories will change after the communication results are used within applications in the traffic network. While the assumptions made in the IntelliDriveSM layer are acceptable for traffic monitoring applications, they will likely be limited for safety or traffic control related applications such as freeway merge assistance.

Researchers from the fields of electrical engineering and/or computer engineering also have tried to investigate the performance of a vehicular wireless communications network that can be applied to IntelliDriveSM applications. Saleh et al. (10) addressed the performance of beacon message dissemination in VANET. According to the DSRC standard (5), the beacon message refers to a data packet that is periodically (i.e., 50ms) broadcasted to and monitored by every receiver in the communication range. Therefore, beacon messages are used not only for the dissemination of safety data such as individual vehicles’ instantaneous locations or velocities but also for non-safety data establishing a mobile network. By employing GloMoSim (11), a communication simulation model, the authors investigated the packet delivery rates and delays under free flow traffic conditions. However, this study employed a simplified mobility model that was derived from the flow-density relationship resulting in a constant speed for every vehicle and an original Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as a Medium Access Control (MAC) layer protocol in the IEEE 802.11 standard, which differs from the up-to-date IntelliDriveSM standard, Enhanced Distributed Channel Access (EDCA), an enhanced version of the CSMA/CS (12, 13).

Wang and Chou (14) tested the performance of a Wi-Fi-based wireless vehicular communication network by fastening a communications network simulator, NCTUns (15), developed by Wang,
unlike \((10)\), to a microscopic car-following model based on kinematic relationships between two consecutive vehicles. Based on the five categories of driving maneuver characteristics defining maximum acceleration/deceleration rates and maximum speeds for vehicles, the movements of vehicles were simulated. However, this car following model was insufficient to represent actual movements of vehicles as the driving maneuvers are determined by the limited behaviors. Furthermore, the study does not take into consideration the lane changing behaviors of vehicles, making it difficult to apply to any generic IntelliDrive\textsuperscript{SM} applications.

As reviewed so far, using either a traffic simulator or a communications simulator might be challenging to fully investigate the performance of IntelliDrive\textsuperscript{SM} applications. For this reason, several researchers proposed an integrated simulation approach by coupling the traffic and communications simulators. Sommer et al. \((16)\) developed an integrated simulation model by enabling bidirectional couplings with the following two simulation models: SUMO \((17)\), a microscopic traffic simulation model, and OMNeT++ \((18)\), an open-source network simulation model. In \((16)\), the authors pursued a truly interactive simulation environment. That is, the traffic simulator updates mobility data for individual vehicles, including locations and speeds, at every simulation interval and sends them to the network simulator. Then, the network simulator simulates the communication performance using the vehicular information coming from the traffic simulator and resends the results to the traffic simulator. If an event such as a packet drop or a long delay occurs and affects the drivers’ behaviors, the traffic simulator updates the vehicle’s driving behavior including deceleration or stopping the vehicle based on the communication network simulation results. Although this coupling effort appeared to be ideal and the authors were able to successfully demonstrate the outcomes, the issue related to the wireless communications standards still remains. More specifically, the wireless communication standard they applied for the study was a Wi-Fi utilizing existing IEEE 802.11a/b/g standards \((19)\) because OMNeT++ did not support the WAVE/DSRC communication standard \((11, 20-23)\), a wireless communication standard for IntelliDrive\textsuperscript{SM}.

While the integrated simulation approach sounds ideal, they still have a critical challenge when it comes to practical uses for the studies of IntelliDrive\textsuperscript{SM} applications due to its significant simulation running time. To overcome such a challenge, Assemacher et al. \((24)\) and Lee and Park \((25)\) proposed a hybrid simulation approach using an on-line communications simulation with off-line vehicular trajectories. In \((24)\), the VISSIM \((26)\) microscopic simulation program was used to create realistic vehicular trajectories that are fed into the network simulator NS-2 \((27)\). A mathematical packet reception probability model with communicating distances as an independent variable was derived from NS-2 outputs and embedded into VISSIM to be used for ITS application studies. However, the communication standards they used were far from those of IntelliDrive\textsuperscript{SM} because the NS-2 version used in this study did not support the communication protocols of WAVE/DSRC. On the other hand, Lee and Park proposed a hybrid-simulation framework enabling a unique channel operation scheme defined in WAVE/DSRC communication standards, namely multi-channel operation, by employing NCTUns. The proposed simulation framework was applied for a calibrated traffic network modeled from an actual freeway merging section in Virginia as a case study. The research addressed several findings: (a) the number of On-Board Equipment (OBE) was the most crucial component in communications delay, but (b) no significant impacts on delays of OBEs’ speeds and distances
from a Road Side Equipment (RSE) were observed, as long as the OBEs are located within the RSE communication range. Although their research came closer to actual IntelliDriveSM communication standards, the message set they applied was arbitrarily determined, because the proper message set standard for IntelliDriveSM applications, such as SAE J2735, has not been completed before their study. While (25) is based on an off-line simulation framework, a SUMO-based on-line integrated simulation platform, namely Integrated Wireless and Traffic Simulation Platform for Real-time Road Traffic Management Solutions (iTETRIS) (28), has recently been developed based on a modified NS-3 (29). The NS-3 was originally developed to improve the well-known scalability issues of NS-2 and to fully accommodate Intelligent Transport Systems for 5GHz (ITS G5) (30), referred as European WAVE/DSRC standards. By enhancing the original NS-3, iTETRIS was designed for the evaluations of various VANET-based strategies for traffic operations and management. Although iTETRIS successfully demonstrated the online integrations of SUMO and NS-3 by overcoming the scalability issues, the results of its applications to the VANET-based strategies are not fully addressed yet.

In summary, despite the contributions made by the efforts reviewed, none of them fully satisfy the requirements for an IntelliDriveSM simulation environment. Such requirements are: (a) precise vehicular mobility models, (b) WAVE/DSRC communication standards including the multi-channel operations, and (c) IntelliDriveSM applications-dedicated message sets defined in the SAE J2735 standard.

SAE J2735 STANDARD: REAL MESSAGE SETS FOR INTELLIDRIVE\textsuperscript{SM}

The SAE J2735 standard entitled “Dedicated Short Range Communications (DSRC) Message Set Dictionary” was published by SubCarrier Systems Corp (SCSC) for the DSRC committee of the Society of Automotive Engineers (SAE). The first version of this standard was prepared in December 2006 containing only six message sets. Then the second edition, which is the latest, with 15 message sets was published in November 2009 after going through numerous internal revisions incorporating feedback from early deployment experiences (4).

What is significant about SAE J2735 is that it specifies “a message set, and its data frames and data elements specifically for use by applications intended to utilize the 5.9 GHz Dedicated Short Range Communications for Wireless Access in Vehicular Environments (DSRC/WAVE) communications systems.” Therefore, it should be noted that, in developing, implementing, and evaluating IntelliDriveSM applications especially those send/receive data via DSRC, the message sets defined in this standard should be used.

There are 15 message sets currently included in SAE J2735. These messages can be categorized into four types according to the sender of data and the number of its recipients: V2V (V2I) broadcast, V2V (V2I) unicast, I2V broadcast and I2V unicast. Hence, in order to be able to conduct realistic evaluations of any IntelliDriveSM applications, the simulation environment used in the evaluation should be able to simulate these four types of messages and, moreover, simultaneously. This function has not been achieved so far but is included in the simulation environment developed in this paper.
SAE J2735 is still a work in progress and therefore will be revised continuously. For example, various DSRC committees and subcommittees under SAE are working to develop more critical messages such as MSG_Mayday, MSG_AlternativeModeTravelTimes (AMTT), MSG_CooperativeCruiseControl (CCC) and, if found useful, some of these messages will be included in the next edition of SAE J2735.

DEVELOPMENT OF INTELLIDRIVE\textsuperscript{SM} SIMULATION ENVIRONMENT

As mentioned previously, in order to accomplish more realistic evaluations of IntelliDrive\textsuperscript{SM} applications, it is essential to develop and use an IntelliDrive\textsuperscript{SM} simulation environment that (a) replicates precise vehicular movements, (b) incorporates IntelliDrive\textsuperscript{SM} wireless communications based on the WAVE/DSRC standards, and (c) finally simulates real IntelliDrive\textsuperscript{SM} message sets defined in the SAE J2735 standard. To this end, the overall framework of the IntelliDrive\textsuperscript{SM} simulation environment was prepared in this research and presented in Figure 1.

![IntelliDrive Simulation Environment Diagram](image)

**Figure 1 IntelliDrive\textsuperscript{SM} Simulation Environment**

The major focus of the simulation environment is the integration of two heterogeneous simulators: (a) a microscopic traffic simulator and (b) a wireless communications simulator. Given that almost all traffic simulators are time-based while wireless communications simulators are event-driven, an inconsistency exists in exchanging data between the two simulators. Thus, in this research, two additional components, a traffic simulator agent and a communications network simulator agent, were deployed to smoothly stream out required data and run both simulators simultaneously. Details on each component in the proposed simulation environment are presented below.

**Microscopic Traffic Simulator: VISSIM**

The roles of a microscopic traffic simulator in this integrated simulation environment are in two folds: (a) implementing IntelliDrive\textsuperscript{SM} applications such as a lane changing advisory application,
collision avoidance system, etc., and (b) producing corresponding vehicular movements under such applications. To satisfy the latter, any existing simulators such as CORSIM (31), VISSIM, AIMSUN, PARAMICS, etc. can be used as they are all capable of producing vehicular trajectories. In other words, vehicular responses to successfully transmitted application messages are determined in a traffic simulator. Yet, implementing IntelliDriveSM applications would be beyond the capability of these embedded functions, i.e. simply producing vehicular trajectories. Candidate simulators therefore must have an interface allowing advanced requirements such as real-time communications with external programs and the manipulations of infrastructure components in a traffic network. Given such requirements, VISSIM, AIMSUN, and PARAMICS would be eligible as the traffic simulator for the proposed simulation environment. In this research, however, VISSIM was selected for its outstanding illustration capabilities, including three-dimensional animations for a potential demonstration purpose. Besides, given that the VISSIM program can produce the vehicular movement information at every simulation interval as little as 0.1 second (which is same as the generation/transmission interval of the Basic Safety Message that needs to be transmitted most frequently), VISSIM satisfies the transmission/generation requirements of all the messages defined in SAE J2735.

Communications Network Simulator: Modified NCTUns 6.0

To correctly simulate IntelliDriveSM communication environment, a communications network simulator must be able to perform multi-channel operations defined in the WAVE/DSRC communication standard. Of existing commercial/non-commercial communications-network simulators such as NS-2, OPNET (32), GlomoSim, NCTUns, etc., to the best of our knowledge, NCTUns is one of the simulators that implement most of the protocol layers of this standard that are required in the proposed IntelliDriveSM testing environment.

NCTUns is an open-source network simulator that is designed to run on a Linux platform and was developed by Wang et al. at the National Chiao Tung University in Taiwan. From the perspective of an ITS researcher, the most unique feature of NCTUns is its capability of modeling the IntelliDriveSM communication standards (i.e., the IEEE 802.11p and IEEE 1609 family as mentioned above). In addition, unlike NS-2, which employs a Tool Command Language (TCL) (33), NCTUns provides an easy-to-use Graphical User Interface (GUI) to create or edit communication network modules.

Despite such unique features of NCTUns, it appears that NCTUns does not fully meet the requirements of the SAE J2735 standard, which necessitates four distinct message dissemination techniques: V2V (or V2I) broadcast, V2V (or V2I) unicast, I2V broadcast, and I2V unicast. Since the latest NCTUns version supports only broadcasting for both BSM and ACM dissemination, it is necessary to add unicasting features to NCTUns code. To this end, the research team modified the original NCTUns program by adding a module that enables these four types of transmissions.
Traffic Simulator Agent

Given vehicular movement information resulting from the implementation of an IntelliDrive SM application, the traffic simulator agent (a) gathers the trajectory of every vehicle and (b) creates a proper message set as defined in SAE J2735, e.g. a Basic Safety Message, a Probe Vehicle Data, an A La Carte Message, and so on, required by the IntelliDrive SM applications of interest.

The traffic simulator agent is also responsible for both sending vehicular trajectory information to NCTUns and receiving communication performance results from NCTUns. This communication is accomplished through transmission control protocol and internet protocol (TCP/IP) socket connection. As mentioned above, the NCTUns program runs on a Linux platform, while VISSIM runs on a Windows platform. TCP/IP socket communication is a flexible mechanism that can be used for inter-process communications even when the communicating processes run on different operating systems.

Communications Simulator Agent

The major role of the communication simulator agent developed in this simulation environment is to accept messages from the traffic simulator agent, and prepare an input dataset for the NCTUns program. This dataset includes: (a) message dissemination schedules, (b) individual vehicular trajectory information, and (c) communication environment parameters such as transmission rate, transmitter power, etc.

Once the vehicular trajectories are received from the traffic simulator agent, the communications simulator agent assigns each of the messages a dissemination time that is randomly generated for transmission on an appropriate channel. With this dataset, NCTUns is invoked and produces raw communications performance results, which include packet drops and transmission latencies for each of the simulated messages. Once the communications simulator agent gathers the performance results, it sends them through the same TCP socket to the traffic simulator agent that is awaiting these results.

CASE STUDY

In this section, a case study using a prototype application is presented to demonstrate how the IntelliDrive SM simulation environment developed in this work can be customized for a certain application, and furthermore how this can promote more realistic evaluations of IntelliDrive SM applications.

Lane Changing Advisory Application

A simplified version of the lane changing advisory application previously developed by the University of Virginia Center for Transportation Studies was selected as a prototype application for a case study. This application provides lane changing advisories to freeway travelers...
upstream of on-ramps to encourage early mainline lane changes in an attempt to open up more
spaces in ramp merging areas (34). A brief description of the application procedure is as follows:

- Step1: Data collection
  - This step collects data for all the vehicles in the network including vehicle ID, speed, position (x-y-z coordinates), vehicle length, and so on.

- Step2: Selection of vehicles for advisory message provision
  - In this step, vehicles – to which advisory messages are provided – are selected based on the presence of available gaps.

- Step3: Lane changing advisory provision
  - The final step is to actually provide advisory messages to the selected vehicles.

This procedure applies to most infrastructure-based applications that collect vehicular data, make decisions, and finally advise drivers to adjust their behaviors, e.g. lane change, speed adjustment, and so on.

Message Set Selection from SAE J2735

Different applications require different sets of messages and data elements, message generation intervals and transmission rates. Hence appropriate messages should be selected from the standard whenever possible, but new messages can be created if none of the existing messages are suitable. The lane changing advisory application utilizes two types of wireless communications – V2I and I2V. V2I communications are used for vehicle data dissemination (Step 1 above), i.e., all vehicles send their positional data, speed, heading, acceleration, etc. to the nearby Road Side Equipment (RSE). I2V communications are used for the transmission of advisory messages (Step 3 above) from the RSE to individual vehicles.

After reviewing the message sets in the SAE J2735 standard, the BasicSafetyMessage (BSM) was selected for the V2I component. BSM is a broadcast message from every vehicle to all nearby vehicles and RSEs. Part I of the BSM contains all the data required for the purposes of this application. Therefore, Part II (optional) of BSM is not sent. This means that the size of each broadcast BasicSafetyMessage payload is 39 bytes as determined from the standard. The second component, I2V advisories, is sent using AlaCarteMessages (ACMs). None of the current messages defined in SAE J2735 satisfy the requirements for this message. Hence a simple ACM was designed, with a size of 20 bytes, to carry the lane changing advisory. Originally, each ACM advisory was unicast every 5 seconds (original control interval). However, for more rigorous testing of communications performance, ACM messages were sent every 100ms, which is the same interval used for BSM transmissions. Table 1 summarizes the data requirements and selected messages for the lane changing advisory application.

<table>
<thead>
<tr>
<th>Data Elements Required</th>
<th>Generation Intervals</th>
<th>Transmission Intervals</th>
<th>Selected Messages from J2735</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2I Data Collection</td>
<td>time, lat, lon, elev, speed, acceleration, vehicle length</td>
<td>0.1sec</td>
<td>0.1sec</td>
</tr>
<tr>
<td>I2V Advisory Provision</td>
<td>Lane changing advisory</td>
<td>0.1sec (5sec)</td>
<td>0.1 sec</td>
</tr>
</tbody>
</table>
Given that previous research efforts so far have been utilizing imaginary messages, of which all the related parameters (such as size, generation interval, transmission rates, etc.) were arbitrarily determined, it was difficult to interpret the simulation results directly to a meaningful changes in reality with confidence. However, the proposed IntelliDrive™ testing environment makes it possible to make such direct interpretation by utilizing “actual” (and specifically designed) message sets that can be again “actually” implemented for a specific application in reality.

**Message Transmission Schedule**

The BSM required by the V2I component will be broadcast using the IEEE 1609.3 WAVE Short Message Protocol (WSMP) (22) as recommended by the SAE J2735 standard. Since this message is broadcast, no retransmissions occur if there are bit errors or packet losses. The MAC 802.11e QoS (23) priority level of these messages is 5, which corresponds to Access Category 2 (AC 2) (4). The BSM is broadcast every 0.1 seconds. The instant at which each vehicle broadcasts its BSM is chosen at random within the 50 ms interval during which the vehicle’s OBE is tuned to the control channel (CCH). BSM transmission can be switched to the service channel (SCH) easily in the developed simulation environment, if required.

The ACM messages are unicast and may be sent on the CCH or SCH. Each of these messages will require an acknowledgement from the receiver. If an acknowledgement is not received, the sender should repeatedly attempt retransmissions for 500ms. If an acknowledgement is still not received after this time period, retransmission attempts are suspended and the packet is dropped by the sender. The MAC 802.11e QoS priority level of these messages is 3, which corresponds to Access Category 1 (AC 1) (4). Finally, Figure 2 presents the detailed message transmission schedule designed for the lane changing advisory application.

![Figure 2 Detailed Message Transmission Schedule](image-url)
Simulation Settings

A well-calibrated simulation network of an actual freeway merge area on Interstate Highway 66 in Virginia (35) was selected for a demonstration of the lane changing advisory application. A snapshot of the network is displayed in Figure 3. The mainline section has 2 lanes, and about 600 feet of the merge section has 3 lanes. The total length of the entire freeway, excluding the ramp section, is about 3,650 feet. In addition, under a jammed condition on the entire freeway, the mean number of the vehicles observed was about 310 vehicles.

For an IntelliDrive™ communication environment, several wireless communication environment variables must be specified. Of these, two variables are most easily understood by transportation engineers: (a) transmission rate, which is the rate at which bits are emitted by the wireless link transmitter, and (b) transmit power, which is the most dominant factor in determining the physical radio communication range. First, out of the possible data rates defined in the WAVE/DSRC standard (6, 9, 12 and 27 mega-bits-per-second [Mbps]), the 6 Mbps data rate was selected to make the most conservative communication conditions. In addition, the 27 Mbps data rate was used to obtain a “best-case” set of performance results. Second, 33-dBm was chosen as a transmit power for the case study. This was assumed for both the RSEs and the OBEs in the entire freeway section.

In order to investigate the communication performance under various congestion levels, two traffic volume scenarios are designed by varying the maximum number of vehicles on the entire freeway section, including the ramp area. The volume scenarios are (a) a light-to-moderate case with a range of maximum volume from 10 to 120 vehicles, and (b) a moderate-to-congested case with a range of maximum volume from 120 to 200 vehicles. Each simulation run of duration 300 seconds was replicated five times for each scenario. Note that the average simulation run time for each scenario was about six hours (for a light-to-moderate case) and 12 hours (for a moderate-to-congested case), respectively.

In simulating wireless communications, the shadowing model was used instead of the two-ray ground model as a large scale propagation model. The two-ray ground model performs on deterministic calculations based on distance, while the shadowing model is a stochastic model.
that assumes variation of the received power at identical distances. The two-ray ground model, therefore, is generally effective at remote areas where the signal usually takes only two paths and does not reflect off of any more objects, but decreases in effectiveness in more urban environments or in areas where the path between the transmitter and receiver is obstructed. For this reason, the shadowing model was implemented in this research. In addition to the large scale propagation model, the Nakagami fading model was also employed to capture small scale fading effects incurred by the reflections, and scatterings of radio wave propagations, and Doppler effects typically observed for high speed mobile nodes.

RESULTS

Utilizing the proposed IntelliDrive℠ simulation environment, communications performance for two messages (V2I BSMs and I2V ACMs) were obtained and analyzed in terms of (a) communication delays and (b) the probability of successful communications. The results and findings are summarized below.

Communication Delays

The first part of the evaluation was conducted for communication delays. Communication delay is defined as the duration to transmit a data packet from a sender’s MAC layer to a receiver’s MAC layer. BSM delays are measured from the OBE MAC layer to the RSE MAC layer and vice versa for ACM delays. Delay histograms shown in Figure 4 are classified by the number of OBEs (same as the number of vehicles), and transmission rate (i.e., 27Mbps and 6Mbps).

As seen in Figure 4, the delays are quite small. The maximum delay for V2I BSMs is 55milliseconds (ms) and for I2V ACMs, the delay is only 1.3ms. Taking into consideration the “small” size of the BSM and ACM, 39 bytes and 20 bytes respectively, such results are expected even for the 6Mbps data rate case.

The reason why the maximum delays of V2I communications are longer than those of I2V is due to the multi-channel operation specified in the WAVE/DSRC standard, which requires OBEs and RSEs to switch between the control channel and service channel every 50ms. Thus, if a BSM packet is not transmitted in the current control channel interval, the message will be sent during the next control channel period, resulting in an extra 50ms delay.

The delay results presented in Figure 4 are obtained for only successfully transmitted messages. Given safety-critical IntelliDrive℠ applications such as collision avoidance systems and lane changing advisory systems, 50ms delay time is insignificant and hence can be ignored. However, packets can be received in error or lost. The impact of this possibility is studied next.
(a) V2I BSMs: 27Mbps Data Rate

(b) V2I BSMs: 6Mbps Data Rate

(c) I2V ACMs: 27Mbps Data Rate

(d) I2V ACMs: 6Mbps Data Rate

Figure 4 Communication Delays
Probability of Successful Communications

The next part of the evaluation was performed to examine the probability of successful communications under the IntelliDrive℠ simulation environment. The probability of successful communications is defined as:

\[ p = \frac{\text{total number of packets received at receivers}}{\text{total number of packets transmitted by senders}} \]

In exploring this aspect, two environmental factors that may have a significant impact were considered: (a) the distance between OBEs and the RSE, and (b) the total number of OBEs within communication range of the RSE. Only the 27Mbps data rate is used in this analysis.

Figure 5 shows the probabilities of successful communications respectively for (a) V2I BSM, (b) I2V ACM and (c) all the messages needed for one full cycle of application execution. Detailed interpretations of the results are as follows:

- First, it was discovered for all cases that the probabilities decrease as the distance from the RSE increases and the number of vehicles in the RSE range increases. Success rate was never 100%. The highest success probability observed is 95% for I2V ACM with less than 40 vehicles (representing an uncongested condition) within a 30-meter communications distance.
- Second, the probabilities obtained for I2V ACM are better than those for V2I BSM. One of the reasons could be the smaller packet size (20 bytes for ACM vs. 39 bytes for BSM).
- Last and most important, Figure 5 (c) shows the communications success probability of a “series” of messages. More specifically, for a lane changing advisory application, selected as a prototype in this study, three BSMs from each of three vehicles (leading, lane changing, and lagging) to the RSE and one ACM from the RSE to this “specific” lane changing vehicle are required. The probability plotted in Figure 5 (c) represents the event that all four messages were received successfully. Therefore, this is the most important probability metric that needs to be considered in evaluating the lane change advisory application. The success probabilities in this case are worse than those obtained for each individual message. For example, assuming a moderate traffic condition (with less than 120 vehicles) and a communications distance of 50 meters, only 50% of disseminated advisories will actually get to the drivers even with 100% market penetration. This was not accounted for in any previous studies, but clearly needs to be considered for realistic evaluations.

In summary, contrary to the case with communications delays, the probability of successful communications is a critical factor that has the potential to result in a significant impact on the performance of IntelliDrive℠ applications.
Figure 5 Probabilities of Successful Communications
CONCLUSIONS

In this paper, a simulation environment for evaluating IntelliDrive℠ applications was developed. This environment integrates a microscopic traffic simulator and a wireless communications network simulator and also incorporates IntelliDrive℠ messages defined in SAE J2735, allowing more realistic evaluation of IntelliDrive℠ applications.

A case study of a lane changing advisory algorithm using a freeway network in Northern Virginia was carried out to demonstrate how the developed environment can contribute to a more realistic evaluation. The results from the case study have shown that the communication delays do not have significant impact in the performance of applications. The maximum delays observed were only 55 milliseconds for a Basic Safety Message (39 bytes) and 1.3 milliseconds for an A la Carte Message (20 bytes, designed for advisories). On the other hand, the probability of successful communications was found to be a critical factor that can change the evaluation results significantly. For example, for a lane changing advisory algorithm, the probability of successful transmission of a series of the required messages for one algorithm execution – three BSMs (from each of three involved vehicles to the RSE) and one ACM (from the RSE to the lane changing vehicle) – was only 50% when there are less than 120 vehicles within a communications radius of 50 meters. In other words, only 50% of advisories can actually reach the vehicles in this case, implying a significant degradation in the algorithm performance. Considering most of IntelliDrive℠ applications need a series of messages (for data collection, decision making and result dissemination) for their implementation, this finding is of significance.

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REFERENCES


