Efficiency of Simulated Vehicle-to-Vehicle Message Propagation in Atlanta, Georgia, I-75 Corridor

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Exploitation of in-vehicle information technology (e.g., mobile computing and wireless communications) in surface transportation systems is a clearly emerging trend. Equipping vehicles with computing, communication, and sensing capabilities presents significant opportunities for a vast array of transportation services. Vehicle-to-vehicle (V2V) communication may be considered for applications such as incident detection, crash reporting, traveler information dissemination, and network operations. In-vehicle computing systems facilitate the customization of information services to the needs and characteristics of individual travelers. In addition, these systems allow coverage to extend beyond areas where roadside equipment has been placed. This study provides the initial investigation needed to test the feasibility of these advanced communication networks. Several observations may be drawn from the study. First, V2V communication is a feasible way to propagate information along the I-75 freeway in the Atlanta, Georgia, area during peak or high-density traffic periods. With sufficient fleet penetration ratio and traffic density, information can quickly propagate through the system. Second, the simulation methodology described in this study allows researchers to estimate the required fleet penetration ratio for effective communication given the traffic density and application requirements. Third, delay in message propagation is highly variable until instrumented-vehicle density reaches a critical mass. For applications requiring highly reliable, minimal message propagation delay, it may be necessary to design networks that provide extra support to avoid such variation. Research is required to examine additional traffic conditions (e.g., congestion due to an incident) and study the effectiveness of this approach for particular applications.

There has been increasing interest in exploiting information technology (IT) advances (e.g., mobile computing and wireless communications) in surface transportation systems. An emerging trend is to equip vehicles with computing, communication, and sensing capabilities, which offers the potential to significantly reduce dependence on government-maintained IT infrastructures. Such distributed systems will employ equipment that can be continually upgraded and maintained as new vehicles are purchased and existing vehicles are enhanced. In-vehicle systems allow coverage to extend beyond areas where roadside equipment has been placed. Subject to privacy considerations, in-vehicle sensors offer the potential for much more detailed, accurate data collection (e.g., second-by-second position, speed, acceleration–deceleration, and emissions) and information transfer than would otherwise be possible. In-vehicle equipment facilitates the development of new systems to monitor and optimize the transportation system. The Federal Communications Commission has allocated 75 MHz of spectrum at 5.9 GHz for dedicated short-range communications (ASTM E2213-03) between vehicles and from vehicles to roadside facilities. The recent Association for Computing Machinery Workshop on Vehicular Ad Hoc Networks is a result of this growing interest and demand for mobile communications.

Proposed applications that are designed to benefit from in-vehicle systems are generally classified as falling into safety and nonsafety categories. Safety applications include collision warning and avoidance, automated enforcement, and semiautomated vehicle control (cooperative driving) (*1*, *2*). Nonsafety applications include traffic information propagation (*3*, *4*), traveler and tourist information, automated toll services, Internet access (*5*), instant messaging, and vehicle-to-vehicle (V2V) computer gaming and entertainment. In most of these applications, V2V communication can play a critical role. However, before such applications can be deployed, studies must examine the political, organizational, technical, and legal implications of V2V communication.

Most current V2V applications employ one-hop messages, those broadcast from a single vehicle to neighbors. One-hop systems are currently being refined for use in safety applications. For example, drivers are notified by a braking vehicle upstream that they need to "watch out." These safety research efforts focus primarily on how to improve one-hop reception reliability (*6*–*8*). However, multihop forwarding (i.e., advancing a message along a roadway by transmitting the message from vehicle to vehicle to vehicle) is a low-cost approach to disseminating information for nonsafety applications in V2V networks (e.g., traffic information dissemination). The spatial propagation along the roadway is of particular interest for V2V networks because of vehicle partitioning or the potential presence of large gaps in traffic flow that will temporarily delay the propagation of a message.

In a previous paper (*9*), analytical models were developed to address this problem for some simple traffic scenarios. In this paper, multihop message propagation is modeled in more complicated and realistic traffic scenarios. A study is made of the spatial propagation speed of a message moving via V2V communications and multihop forwarding through instrumented-vehicle fleets of varying density. This problem is addressed principally in the context of a pure V2V ad

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hoc network. But the analytical methods are also applicable when a roadside network infrastructure and V2V communications coexist.

A pure V2V ad hoc network consists only of vehicles equipped with onboard computing and short-range wireless communication devices. Vehicles may also incorporate additional instrumentation, such as a Global Positioning System (GPS) device enabling the vehicle to track its space–time trajectory, digital roadway and land use maps, other sensors for reporting crashes, onboard engine diagnostics sensors, driver video or text information interfaces, and cellular communications systems. For example, 500 instrumented vehicles were deployed in Atlanta, Georgia, in 2003 and 2004 in which onboard instrumentation included a GPS system, engine computer monitor, and cellular transceiver (*10–13*). The Atlanta study has monitored nearly 1 million vehicle trips on a second-by-second basis. Given the data that can be made available from instrumented vehicles, the implementation of a V2V communication network will support many diverse systems designed to improve transportation systems with minimal deployment of the more capital-intensive fixed infrastructures.

The study reported in this paper does not assume that all vehicles are equipped with communication capabilities or other advanced instrumentation. Because of the gradual nature of market penetration, only a fraction of the vehicles on the road will be instrumented as V2V systems are initially deployed. Specifically, the term "fleet penetration ratio" is defined as the fraction of vehicles on the road that are instrumented. Only instrumented vehicles participate in the V2V system. Vehicles exchange information with others within their radio range and ad hoc wireless networks are set up to propagate information. This paper examines potential message propagation performance on a freeway corridor by exploring the rate at which messages may traverse a section of the I-75 corridor in Atlanta under varying fleet penetration ratios.

OVERVIEW OF MODELING APPROACH

CORSIM and QualNet Distributed Simulation Test Bed

The simulation infrastructure used to perform this study is composed of two independent commercial simulation packages running in a distributed fashion over multiple networked computers. CORSIM (*14*) is a microscopic traffic simulation model that simulates vehicle interaction, traffic flow, and congestion. The run-time extension facility available in CORSIM was used to extend the functionality needed to operate the simulator in a distributed manner. For example, individual vehicle identification was retained when vehicles moved between the freeway and arterial simulation modules. These unique vehicle IDs then flowed from the traffic simulation to the communications simulation. For the wireless network simulation, QualNet (*15*) was used to model and simulate internetworking aspects such as ad hoc wireless protocols and radio propagation. These two simulators were federated through a distributed simulation software package called the Federated Simulations Development Kit (FDK) (*16*) and developed at the Georgia Institute of Technology that provides services to exchange data and synchronize computations. FDK implements services defined in the Interface Specification of the High Level Architecture (*17*), a standard (IEEE 1516) developed by the U.S. Department of Defense for creating federated distributed simulation systems. In addition to FDK, the system includes software developed for this project, the CORSIM–QualNet Communication Layer (CQCL), which not only defines interactions between CORSIM and QualNet but also simplifies and streamlines management of the distributed simulation execution.

Common message formats are defined between CORSIM and QualNet for vehicle status and position information. During initialization, the transportation road network topology is transmitted to QualNet. Once the distributed simulation begins, vehicle position updates are sent to QualNet and mapped to mobile nodes in the wireless simulation. Because of the large number of update messages, CQCL aggregates messages to reduce communication overhead.

Study Area

The study area for this research effort was the I-75 corridor in the northwest quadrant of Atlanta traversing I-75 from the I-85 interchange on the south to the I-285 interchange on the north (Figure 1). The study area incorporates approximately 7.6 mi of I-75, including six exits and 20 on–off ramps. The I-75 freeway consists of five lanes in each direction, including an HOV lane in each direction, and has a posted speed limit of 55 mph. In addition to the freeway, approximately 100 mi of arterial surface streets are included within the study area.

CORSIM Traffic Simulation

CORSIM is used to represent the vehicle flow characteristics for the traffic scenarios analyzed. CORSIM uses commonly accepted vehicle and driver behavior models to represent traffic networks (*18*). Extensive geometric and operational data are required to model a network in CORSIM. Data requirements include signalized intersection control plans, turn bay layouts, number of lanes on each roadway section, roadway distances, free flow speeds, traffic flows, and turn movement ratios. CORSIM generates various output data, such as total vehicle trips, total vehicle miles, total time on the link for all vehicles, delay time per mile, stopped delay, number of stops, queue length, average volume, and average queue length by lane (*14*).

Network Development

The primary data source for geometric and traffic flow data used to develop CORSIM models was the Atlanta Regional Council's (ARC) Regional Transportation Plan model. The ARC model is a macroscopic transportation planning and travel demand forecasting model covering the greater Atlanta region. Roadway section (link) data used from the ARC model included the number of lanes, link length, free flow speed, and presence of an HOV lane. Intersection (node) information included turn movement ratios and turn bay lengths. Freeway entrance and exit ramp volume ratios were also obtained from the ARC model. Geometric data were verified with U.S. Geological Survey aerial photos with a 1-ft resolution. From these aerial photos, lane configurations were verified, the presence of turn bays was confirmed, and turn bay and roadway section lengths were measured.

Vehicle flows were based on the traffic assignment results of the ARC model for 2004. The flows from this model were used as input data for all entering link volumes and all intersection turn movement ratios in the CORSIM network. On the basis of the diurnal distribution of travel in the Atlanta Metropolitan Area, the evening peak hour was determined to be from 5 pm to 6 pm, which represented 7.8% of all daily trips, or 27.4% of trips during the 4-h afternoon peak

(a) (b)

FIGURE 1 I-75 corridor study area location (*a*) shown as part of Greater Atlanta region and (*b*) enlarged for detail.

period (*19*). Trip productions and attractions at zone centroids were represented as source–sink link volumes in the CORSIM network to account for interzonal trips within the study area. Limited field validation studies were also conducted to calibrate the modeled turning movements, vehicle flows, and queue length at critical intersections.

The overall CORSIM network contains 189 nodes (119 surface nodes and 70 freeway nodes) and 365 links (295 surface links and 70 freeway links). Of the surface streets, 45 nodes represent signalized intersections. Signal control data for the signalized intersections were obtained from the city of Atlanta and Cobb County Departments of Transportation. Thus, all coded signal timings were an accurate reflection of existing signal control.

CORSIM Calibration

Given the broad nature of data from macroscopic travel demand models, a calibration effort was undertaken to ensure that the CORSIM model provided a reasonable representation of actual operations. For this study, extensive resources were not available for a fine-tuning of all model parameters, although future data collection will be undertaken to further calibrate and expand the model.

In several instances, the ARC-based turn movement ratios and field-based signal control green-time ratios did not appear consistent. For example, signal control data showed some intersection approaches having minimal left-turn green time, while the travel demand model displayed a high percentage of left-turn vehicles on the same approaches. These intersection approaches tended to generate excessive delay and queuing. Field surveys were conducted for these inconsistent links and intersections. Specifically, field data were collected for six intersections on Wednesday, December 3, and Thursday, December 4, 2003. Peak-hour turning movement traffic counts were undertaken for all approaches and signal-timing operations (cycle length phase pattern and green, yellow, and all-red clearance times) were observed. The CORSIM model was adjusted to reflect the field studies. Travel speed data were also collected for the network from vehicles deployed as part of the Georgia Institute of Technology Commute Atlanta project, sponsored by the FHWA and the Georgia Department of Transportation. GPS-based weekday morning trip data for 591 freeway trips and 601 surface trips were used. The GPS trip data contained second-by-second speed, acceleration, and deceleration data for the instrumented vehicles.

The GPS probe vehicle speeds were compared with the CORSIM-generated vehicle speeds, which are based on simulated link travel times. Initial speed comparisons showed that simulated travel speeds were lower than the GPS-based speeds in the overall network area. In the initial simulation development, the I-75 posted speed of 55 mph was used as the free flow speed. The ARC travel demand model used a 65-mph free flow speed for the Interstate freeway and higher-than-speed-limit free flow speeds on some arterials. For the current CORSIM model, ARC free flow speeds were adopted for all freeway, principal, and minor arterials. Simulations using these speeds provide a more realistic comparison with which to probe vehicle data, although differences still exist. For example, the simulated morning average speed on the I-75 corridor by CORSIM was 54.9 mph northbound and 54.6 mph southbound. The measured speeds of the probe vehicle were 60.3 mph northbound and 60.5 mph southbound. On arterials, CORSIM sometimes underestimates and sometimes overestimates average speeds. For example, average speed is somewhat underestimated on Northside Parkway and Marietta Boulevard but overestimated on Mount Paran Road and Collier Road. Average speeds are slightly underestimated on Northside Parkway, where simulated average speeds are 23.7 mph southbound and 23.2 mph northbound and measured speeds are 25.8 mph and 24.2 mph (differences of 8.1% and 4.1%, respectively). On Collier Road, average speeds are slightly overestimated, with simulated average speeds of 16.7 mph southbound and 25.6 mph northbound while measured speeds are 15.1 mph and 23.6 mph (differences of 10.6% and 8.5%, respectively). However, given the speed at which messages travel from vehicle to vehicle, minor differences in simulated versus monitored vehicle speeds have no significant effect on communications performance (except under conditions of low instrumented-vehicle density) and are ignored for the purposes of this paper.

QualNet Network Simulator

QualNet is a commercial packet-level communication network simulator (*15*). Communication network designers and researchers often use QualNet to plan upgrades before deployment or to test new communication algorithms and protocols. It incorporates a comprehensive set of network protocol models, from application models to physical ones. QualNet also has high-fidelity wireless models that incorporate physical environment effects (e.g., fading and shadowing). QualNet comes with Animator, Designer, Analyzer, Tracer, and Simulator modules. Users can set up network simulation scenarios by using either the graphical animator or a configuration script. The Designer module allows users to create their own network models. Extensive performance metrics for a complete understanding of network behavior can be studied in the Analyzer module. The Tracer is a packet-level visualization tool for viewing the contents of a packet as it traverses the protocol stack.

Instrumented vehicles in CORSIM are mapped to mobile nodes in QualNet, so that their movement follows that of the simulated vehicle. The primary metrics collected include end-to-end (E2E) delay and number of partitions traversed (a partition is a set of vehicles interconnected by wireless links, as discussed later). Some recent research (*20, 21*) measured the communication performance between vehicles and between vehicles and roadside access points using IEEE 802.11b–compliant devices. In consideration of these results, a data propagation scheme was adopted in the general sense. A vehicle was referred to as "informed" if it carried the message being propagated. When an uninformed vehicle entered the radio range of an informed vehicle, the uninformed vehicle became informed. Every instrumented vehicle was assumed to have the same radio transmission range, r. The message transfer time from informed to uninformed vehicle was a function of the communications system. It was assumed that a vehicle required a specific amount of time (t_r) to receive and process a message before it was available for further retransmission. In this way, the analysis was neutral to specific wireless technologies (e.g., 802.11x, HiperLan, etc). Many real-world communication aspects are not considered (e.g., signal interference, bandwidth constraint, and link quality variation, etc.). However, this communication scheme helped simplify the problem studied and allowed for an examination of best propagation rates. For these experiments, communications range r is set as 250 m (within the typical clear path range of an IEEE 802.11 communication system). The time for receiving and processing a message t_r is set at 4 ms, which is the transmission delay of a packet of 768 bytes in a wireless channel of 2 Mbps, including computing and communication overhead. While a 768-byte message may seem small, this message can contain a wealth of information. For example, one such message can contain 15 s of detailed second-by-second data for a single vehicle, including 15 values for each of the following variables: vehicle position, vehicle speed, acceleration rate, throttle position, manifold pressure, engine speed, and other engine parameters. Such a message could also carry the average speed data for a 5- or 10-min window for groups of coordinated instrumented vehicles operating at 30 different freeway link locations.

EXPERIMENTAL DESIGN

A V2V network (simulated using QualNet) was overlaid on top of the underlying road network (modeled in CORSIM), yielding a graph-like topology. Because of the limited communication range of 250 m, V2V networks are typically partitioned. Partitioning occurs when, under certain operating conditions, there are groups of instrumented vehicles on the roadway that are separated by more than the communications range (in this case, 250 m). So, while a communication path exists between any two vehicles within the same partition, there is no communication link to enable the message to jump between partitions. Partitions tend to exist under conditions of low instrumented-vehicle density, at which instrumented-vehicle density is a combined function of traffic density and fleet penetration rate. Under conditions at which partitions are present, vehicle movement propagates the information between partitions. This situation occurs when an instrumented vehicle carrying a message overtakes another partition. Vehicles in both directions can be used to propagate information. Messages can cross over the roadway into oncoming vehicles and then cross back over the roadway into vehicles farther downstream from the original message-carrying vehicle. This phenomenon occurs because the speed of message propagation is much faster than vehicle motion.

Figure 2 illustrates how vehicles can move from partition to partition as a function of difference in vehicle speed. The arrow represents the road. The circles below the arrow represent vehicles traveling to the right (in the positive direction), and circles above the arrow represent vehicles traveling to the left (in the negative direction). Consider a message propagating in the positive direction from a vehicle at location H at time $t0$. The "message head" at time t is defined as the rightmost informed vehicle at time t. At time $t1$, the message reaches the frontmost vehicle of its current partition through multihop forwarding and begins to travel with the message head. The message cannot reach the next partition at this time because the gap between the foremost instrumented vehicle in the first partition and the rearmost instrumented vehicle in the second partition is greater than the vehicle transmission range. At time $t2$, the message head catches the next partition through the relative movement of vehicles. At time $t3$, the message traverses the next partition, and then the above process repeats again. Partitions are dynamic and depend on the transmission range. When a message is propagating from one location to another, it propagates in either one of two processes, the forward process or the catch-up process (*9*). The forward process involves the rapid propagation of the message within a partition via multihop forwarding. In the catch-up process, the message moves along with its carrying vehicle until it comes within the radio range of the last uninformed vehicle in the partition ahead of it. The propagation speed in the catch-up process will normally be much slower than that in the forward process. The E2E delay due to network partitioning is one of the major limitations of V2V networks. Such E2E delays can be reduced by increasing fleet penetration rates. Alternatively, V2V networks can be supplemented with a roadside communications infrastructure that rapidly forwards the message to other locations (this aspect is a future research topic).

In a previous paper (*9*), analytical models were developed for spatial propagation of information by assuming a simplified model of free flow traffic. It was assumed that vehicles are moving independently and that each vehicle travels with an average speed that is selected from a random distribution. This model, though simplified,

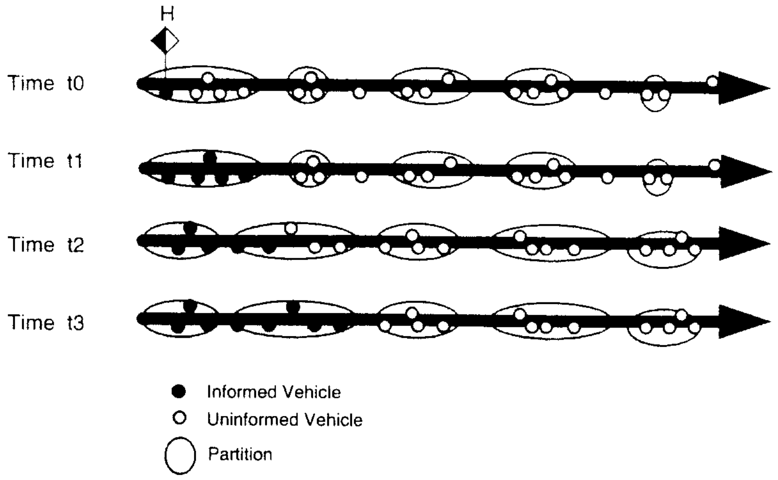


FIGURE 2 Downstream message propagation and vehicle movement.

captured vehicle interaction dynamics, which allowed one to identify the important traffic characteristics that significantly influence the rate of information propagation. The modeling revealed that instrumented-vehicle density, average vehicle speed, and relative speed among vehicles were all important parameters in predicting the speed of message propagation. Instrumented-vehicle density determines the extent of network partitioning and the gap between partitions. Average vehicle speed and speed distributions affect the information propagation speed during the catch-up process. Some of these initial analytical results are verified by the simulation results presented here. As mentioned earlier, the CORSIM-predicted speeds in our model were somewhat lower than the GPS-probed speeds (5 mph on the freeways). However, on the basis of the analyses, this speed difference did not significantly affect the result in the scenarios studied. When instrumented-vehicle density was high, the forward process of information propagation dominated and was so fast that vehicle speed was irrelevant. When instrumented-vehicle density was moderate, relative vehicle speeds determined message catch-up time; the average speed was not critical. It was only when instrumented-vehicle density was low that information propagation relied primarily on vehicle movement, which made the 5-mph speed difference relevant in determining the information propagation speed. This paper focuses primarily on the impact of traffic volume and fleet penetration ratio on information propagation, so the 5-mph speed difference was not examined directly under these conditions. The next research stage will focus on message propagation under adverse conditions (e.g., when an incident blocks multiple vehicle lanes) in which such speed differences may be more relevant.

The spatial propagation of information southbound along I-75 for a distance of 6 mi was simulated in this research effort. Vehicle traffic in both directions was exploited in relaying the message. The 4-ms message transfer time is so much faster than vehicle operating speeds that messages readily propagated across the center divider to an oncoming car and then back across the center divider to a car farther downstream. Message propagation was simulated under two traffic scenarios (evening peak and nighttime traffic, with typical traffic volumes derived from the regional travel demand model) and for various fleet penetration ratios.

CORSIM was used to generate 600-s traffic traces through a different random number seed for each trace. The simulation results for all scenarios (except for the penetration ratio of .05), were obtained by partitioning each 600-s trace into five 100-s samples; the first 100 s of the trace was not used while the system initially populated. Each sample then began with the propagation of a single message. For each penetration ratio, 10 traces were examined, for a total of 50 samples. For the .05 fleet penetration ratio, 20 traces were generated and one sample was collected from each trace. This arrangement of random seed variation and 100-s samples was used to lessen the correlation between successive message propagations.

RESULTS

Detailed examination of the information propagation process showed that vehicle traffic in both directions played equally important roles in propagating information within partitions. Vehicle traffic in the direction in which the information was propagating played the more important role in moving the message from one partition to another.

Average E2E Delay

Figures 3 and 4 illustrate the average E2E propagation delay as a function of the fleet penetration ratio for evening peak and nighttime traffic, respectively. For evening peak traffic, the penetration ratio

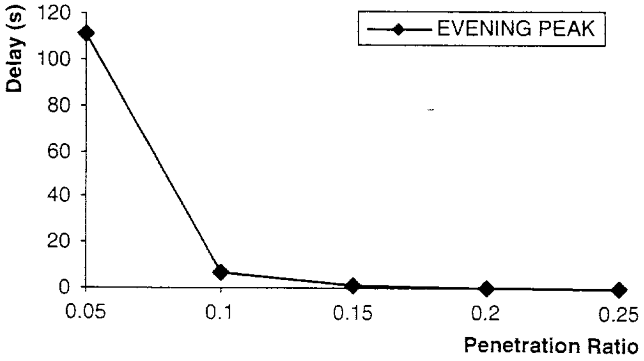


FIGURE 3 Evening peak end-to-end propagation delay.

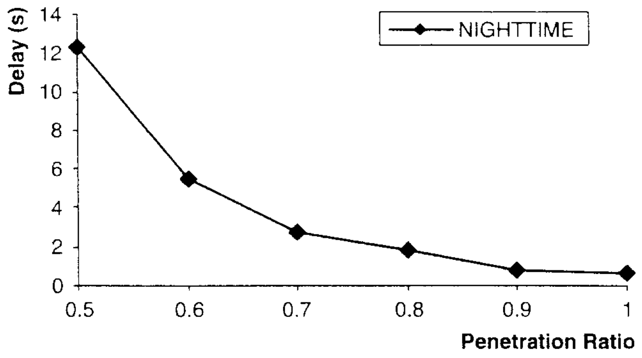


FIGURE 4 Nighttime end-to-end propagation delay.

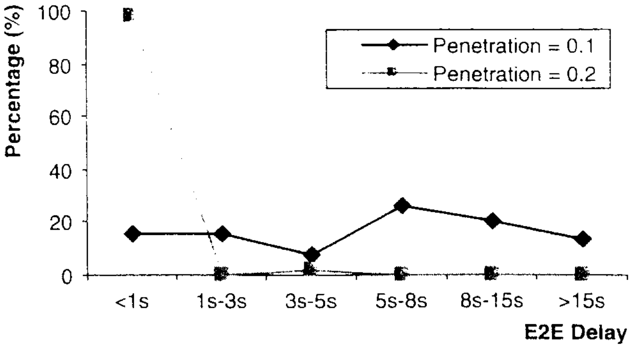
shown started from .05, while for nighttime traffic, it started from .5. The reason for this is that, when the penetration ratio was below .5 for nighttime traffic, some samples required a propagation time of more than 100 s. One can expect that the delay was much higher when the penetration ratio was below .5 on the basis of the trends that are shown in Figures 3 and 4. When the fleet penetration ratio was below .10, the trials showed that information propagation was principally driven by vehicle movement. This result agrees with previous analyses (*9*). Overall, the delay tended to decrease as the fleet penetration ratio increased, but not linearly. To achieve an average delay below 2 s for the 6-mi message propagation, a fleet penetration ratio of .15 or greater was required for evening peak traffic, while the penetration ratio had to reach .80 for nighttime traffic (given the sparse traffic volumes on the roadway at night). Since intrapartition vehicle forwarding is relatively fast, the majority of the propagation time was spent moving information from one partition to another. The shortest observed E2E delay for 6 mi was .164 s given the parameters used here, where an E2E path existed. During evening peak traffic (Figure 3), message delay reached a minimum at a fleet penetration ratio of about .20. Further fleet penetration beyond .20 did not significantly reduce propagation delay.

Delay Variance

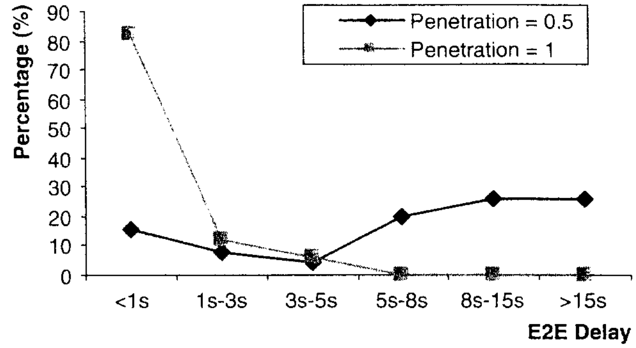
Figure 5 shows the message propagation time distribution for several penetration ratios. As expected, the propagation time varied significantly. This variation was primarily the result of path vulnerability (i.e., the likelihood of partitioning). When a contiguous E2E path exists, message propagation can finish within 1 s. When an E2E path does not exist (i.e., the communication network contains separated partitions) seconds or even minutes may be necessary for a message to propagate through the chosen distance, depending on the number of partitions traversed and the distance between partitions. Only with a high density of instrumented vehicles where the E2E paths almost always existed (e.g., penetration ratio >.20 for evening peak traffic) was stable performance observed. Thus, a message had a higher probability of rapid propagation only in an environment with a higher density of instrumented vehicles.

E2E Connectivity

Most routing protocols for ad hoc networks assume E2E connectivity (*22–24*). One natural question is then, under what circumstances can E2E connectivity be safely assumed in V2V networks? Figure 6 shows the percentage of propagation paths where E2E connectivity existed for evening peak traffic. When the fleet penetration ratio exceeded .20, the connectivity could reach nearly 100%. When the penetration ratio was lower than .10, the connectivity was below 15%. However, the connectivity was only 82% even with 100% fleet penetration (i.e., every vehicle is instrumented) for nighttime traffic. Traffic volumes were so low that distance separations created multiple partitions. Figure 7 demonstrates the E2E connectivity versus the propagation distance when the fleet penetration ratio was .10 for evening peak traffic. Dousse et al. (*25*) demonstrated that E2E connectivity decreases with distance for one-dimensional network topologies. Not surprisingly, the results of the current study also reflect this



(a)



(b)

FIGURE 5 End-to-end delay distribution.

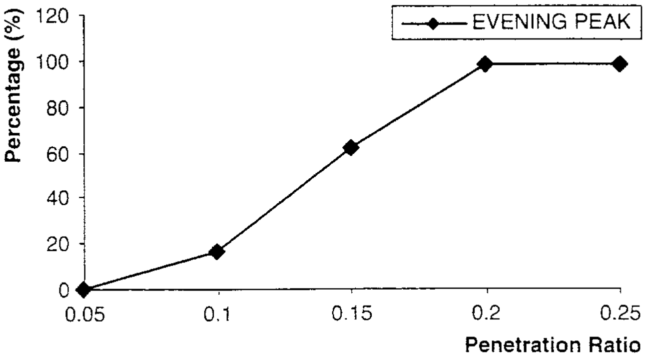


FIGURE 6 Evening peak end-to-end delay connectivity over corridor.

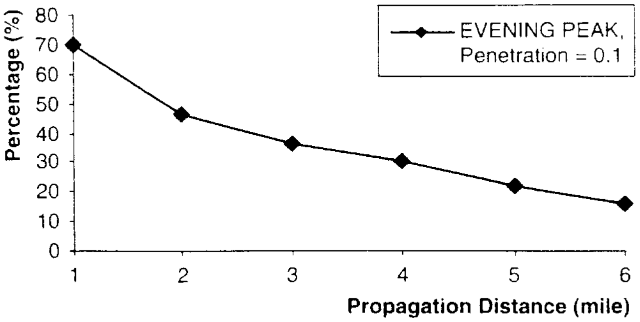


FIGURE 7 Evening peak end-to-end delay connectivity for fleet penetration ratio of .1.

trend. When the propagation distance was 1 mi, the E2E connectivity reached about 70%, while it was only 16% for a propagation distance of 6 mi.

DISCUSSION OF RESULTS

Several observations may be made on the basis of the preceding results. First, V2V communication appears feasible for propagating information along the I-75 freeway in the Atlanta metropolitan areas, as well as along other roadway systems with similar traffic characteristics as Atlanta's during periods of peak or high traffic density (times during which the propagation of traffic information is most needed). Propagation performance depends largely on the density of instrumented vehicles along the E2E path, which is a function of the traffic density and fleet penetration ratio. With a sufficient fleet penetration ratio and traffic flow rate, information can quickly propagate through the system. Rapid message propagation during periods of low traffic density (e.g., nighttime) presents challenges and may require some additional mechanism to support communications, for example, deployment of fixed-location roadside relay stations.

Second, the simulation methodology described here allows one to determine a target penetration ratio for effective communication as a function of application requirements and traffic density. For example, when rapid message propagation is desired during the evening peak, a penetration ratio of approximately .20 is sufficient for effective information propagation.

Third, the message propagation delay is highly variable except when vehicle density becomes saturated. A particular delay may be well below or above the average, depending on prevailing traffic conditions. For applications requiring highly reliable, minimal message propagation times, it may be necessary to design networks that provide extra support to avoid such variations. For example, to reduce path vulnerability, roadside relays could supplement the communication infrastructure in critical areas. Or a subset of vehicles could be equipped with cellular messaging systems, through which critical information would be reliably relayed without being dependent upon a V2V communication. For applications where immediate data are not critical, other solutions that are based on nonfixed infrastructures may be explored. For example, vehicles can cache data and use this information when up-to-date information is not available.

Last, E2E distance is an important factor. E2E connectivity is possible over long distances when instrumented-vehicle density is high or at slightly lower densities when propagation distances are short. This result allows some insights for designing data dissemination algorithms. Algorithms assuming E2E connectivity (24), as required by some applications (e.g., multimedia), are suitable only for a high density of instrumented vehicles or short propagation distances. Opportunistic forwarding algorithms relaxing E2E connectivity (26) can adapt to a wider spectrum of traffic conditions.

CONCLUSION

Information technology (e.g., mobile computing and wireless communications) in surface transportation systems is a clearly emerging trend. Equipping vehicles with computing, communication, and sensing capabilities presents significant opportunities for a variety of transportation systems. V2V communication may be applied to incident detection, crash reporting, traveler information systems, network operations, and the like. In addition, in-vehicle systems allow coverage to extend beyond areas with roadside equipment. This study provided an initial investigation needed to implement and test the feasibility of these advanced communication networks. The traffic density and instrumented-vehicle penetration ratio were shown to be significant factors in communication network performance. Future research will extend this study to examine additional traffic conditions (e.g., congestion due to an incident) and to investigate the effectiveness of this approach for specific applications.

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