Simulated Vehicle-to-Vehicle Message Propagation Efficiency on Atlanta’s I-75 Corridor

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ABSTRACT

Exploitation of in-vehicle information technology (e.g., mobile computing and wireless communications) in surface transportation systems is a clear emerging trend. Equipping vehicles with computing, communication, and sensing capabilities presents significant opportunities for a vast array of transportation services. Vehicle-to-vehicle communication may be considered for applications such as incident detection, traveler information dissemination, network operations, etc. In-vehicle computing systems facilitate the customization of information services to the needs and characteristics of individual travelers. In addition, in-vehicle 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 this study. First, vehicle-to-vehicle communication is a feasible way to propagate information along freeways in metro areas, although propagation performance depends critically on factors such as the density of instrumented vehicles along the end-to-end path. Second, the simulation methodology described within this study allows one to estimate the minimum required fleet penetration ratio for effective communication, given the traffic density and application requirements. Third, the message propagation delay is highly variable when instrumented vehicle density is low. A particular delay may be well below or above the average depending on traffic conditions. For applications requiring highly reliable, minimal message propagation it may be necessary to design networks that provide extra support to avoid such variation. Future 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.
INTRODUCTION

There has been increasing interest in exploiting information technology 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, offering the potential to greatly lessen 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, emissions, etc.) 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 FCC has allocated 75MHz of spectrum at 5.9GHz for Dedicated Short-Range Communications (DSRC) [1] between vehicles and from vehicles to roadside facilities. The recent ACM VANET conference 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 non-safety categories. Safety applications include collision warning and avoidance, automated enforcement, semi-automated vehicle control (cooperative driving) [2] [3], etc. Non-safety applications include traffic information propagation [4] [5], traveler and tourist information, automated toll services, Internet access [6], instant messaging, vehicle-to-vehicle computer gaming and entertainment, etc. In most of these applications, vehicle-to-vehicle (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, broadcast from a single vehicle to neighbors. One-hop systems are currently being refined for use in safety applications. For example, a driver is notified by a braking vehicle upstream that they need to “watch out.” These safety research efforts primarily focus on how to improve one-hop reception reliability [7-9]. However, multi-hop 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 non-safety applications in V2V networks (e.g., traffic information dissemination). The spatial propagation along the roadway is of particular interest for V2V networks due to vehicle partitioning, or potential presence of large gaps in traffic flow that will temporarily delay the propagation of a message.

In our previous work [10], we developed analytical models to address this problem for some simple traffic scenarios. In this paper, we simulate multi-hop message propagation in more complicated and realistic traffic scenarios. We study the spatial propagation speed of a message moving via V2V communications via multi-hop forwarding through instrumented vehicle fleets of varying density. We address this problem principally in the context of a pure V2V ad-hoc network. But, our 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 on-board computing and short-range wireless communication devices. Vehicles may also incorporate additional instrumentation, such as: a GPS device enabling the vehicle to track its space-time trajectory, digital roadway and land use maps, other sensors for reporting crashes, engine on-board diagnostics sensors, driver video or text information interfaces, cellular communications systems, etc. For example, 500 instrumented vehicles were deployed in Atlanta from 2003-2004 in which onboard instrumentation included a GPS system, engine computer monitor, and cellular transceiver [11-14]. The Atlanta study has monitored nearly one 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. Due to 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, Georgia, 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 [15] is a microscopic traffic simulation model that simulates vehicle interaction, traffic flow, and congestion. The Run-Time Extension (RTE) facility available in CORSIM was utilized to extend the functionality necessary to operate the simulator in a distributed manner. For example, individual vehicle identification is retained when vehicles move between the freeway and arterial simulation modules. These unique vehicle IDs then flow from the traffic simulation to the communications simulation. For the wireless network simulation, QualNet [16] was used to model and simulate inter-networking aspects such as ad-hoc wireless protocols and radio propagation. These two simulators were federated using a distributed simulation software package called the Federated Simulations Development Kit (FDK) [17] developed at Georgia Tech that provides services to exchange data and synchronize computations. FDK implements services defined in the Interface Specification of the High Level Architecture [18], 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 called the CORSIM-QualNet Communication Layer (CQCL) that not only defines interactions between CORSIM and QualNet, but also simplifies and streamlines the 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 are mapped to mobile nodes in the wireless simulation. Due to the large number of update messages, CQCL aggregates messages to reduce communication overhead.

Study Area

The study area for this research effort is the I-75 corridor in the northwest quadrant of Atlanta, Georgia, traversing I-75 from the I-85 interchange to the south to the I-285 interchange to the north (Figure 1). The study area incorporates approximately 7.6 miles of I-75, including 6 exits and 20 on/off ramps. I-75 freeway consists of five lanes in each direction, including a HOV lane in each direction, and has a posted speed limit of 55 mph. In addition to the freeway, approximately 100 miles of arterials 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 utilizes commonly accepted vehicle and driver behavior models to represent traffic networks [19]. 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, turn movement ratios, etc. 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 [15].

Network Development

The primary data source for geometric and traffic flow data used to develop the CORSIM model was the Atlanta Regional Council’s (ARC) Regional Transportation Plan (RTP) model. The ARC model is a macroscopic transportation planning and travel demand forecasting model covering the greater Atlanta region. Roadway section (link) data utilized from the ARC model includes: number of lanes, link length, free flow speed, and the 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 utilizing United States Geological Survey (USGS) aerial photos with a one-foot 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 2004 year traffic assignment results of the ARC model. 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. Based on the diurnal distribution of travel in the Atlanta Metropolitan Area, the evening peak hour was determined to be from 5 pm to 6 pm representing 7.8% of all daily trips, or 27.4% of trips during the four-hour pm peak period [20]. Trip productions and attractions at zone centroids were represented as source/sink link
volumes in the CORSIM network to account for inter-zonal 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 street 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 are 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 provides a reasonable representation of actual operations. As part of 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 3rd, and Thursday, December 4th, 2003. Peak hour turn movement traffic counts were undertaken for all approaches and signal timing operations (cycle length phase pattern, and green, yellow, 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 Federal Highway Administration and Georgia Department of Transportation. GPS-based weekday AM trip data for 591 freeway trips and 601 surface trips were utilized. The GPS trip data contains second-by-second speed, acceleration and deceleration data for the instrumented vehicle vehicles.

The GPS probe vehicle speeds were compared to the CORSIM generated vehicle speeds, which are based upon 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 utilized 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 utilizing these speeds provide a more realistic comparison to probe vehicle data, although differences still exist. For example, the simulated AM average speed on the I-75 corridor by CORSIM is 54.9 mph northbound and 54.6 mph southbound. Probe vehicle measured speeds are 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 over estimated on Mt. 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 over estimated, 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 vs. monitored vehicle speeds have no significant effect on communications performance (except under low instrumented-vehicle-density conditions) and are ignored for the purposes of this paper.

QualNet Network Simulator

QualNet is a commercial packet-level communication network simulator [16]. Communication network designers and researchers often use QualNet (for example) to plan upgrades prior to deployment or to test new communication algorithms and protocols. QualNet incorporates a comprehensive set of network protocol models, from application models to physical models. QualNet also has high fidelity wireless models that incorporate physical environment effects, e.g., fading, shadowing, etc. QualNet comes with Animator, Designer, Analyzer, Tracer and Simulator modules. Users can set up network simulation scenarios using either the graphical animator or a configuration script. Designer allows users to create their own network models. Extensive performance metrics for a complete understanding of network behavior can be studied in the analyzer. 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 [21, 22] measured the communication performance between vehicles, and between vehicles and roadside access points using IEEE 802.11b compliant devices. Bearing these results in mind, we adopted a data propagation scheme in the general sense. A vehicle is referred to as informed if it carries the message being propagated. When an uninformed vehicle enters the radio range of an informed vehicle, the uninformed vehicle becomes informed. Every instrumented vehicle is assumed to have the same radio transmission range $r$. The message transfer time from informed to uninformed vehicle is a function of the communications system. We assume a vehicle requires a specific amount of time ($t_i$) to receive and process a message before it is available for further retransmission. In this way, the analysis is 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 examined in this paper helps simplify the problem studied and allows for an examination of best propagation rates. For these experiments, communications range $r$ is set as 250 meters (within the typical clear path range of an 802.11 communication system). The time for receiving and processing a message $t$, 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 seconds of detailed second-by-second data for a single vehicle, including 15 values for each of the following: 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 minute window for groups of coordinated instrumented vehicles operating at 30 different freeway link locations.

**EXPERIMENTAL DESIGN**

A V2V network (simulated using QualNet) is overlaid on top of the underlying road network (modeled in CORSIM) yielding a graph-like topology. Due to the limited communication range of 250 meters, 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 meters). 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 low instrumented-vehicle-density conditions, where instrumented-vehicle-density is a combined function of traffic density and fleet penetration rate. Under conditions where partitions are present, vehicle movement propagates the information between partitions. This occurs when an instrumented vehicle carrying a message overtakes another partition. Vehicles in both directions can be utilized to propagate information. Messages can cross over the roadway into oncoming vehicles, and then cross back over the roadway into vehicles further downstream from the original message-carrying vehicle. This 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 (positive direction), and circles above the arrow represent vehicles traveling to the left (negative direction). Consider a message propagating in the positive direction from a vehicle at location H at time 0. The message head at time $t$ is defined as the rightmost informed vehicle at time $t$. At time $t_1$, the message reaches the front most vehicle of its current partition through multi-hop 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 $t_2$, the message head catches the next partition through the relative movement of vehicles, and then this process repeats again. Note that 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 termed the forward process and the catch-up process [10]. The forward process involves the rapid propagation of the message within a partition via multi-hop 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 beyond the scope of this paper).
In our previous work [10], we developed analytical models for spatial propagation of information by assuming a simplified model of free-flow traffic. We 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, captures vehicle interaction dynamics allowing 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 are somewhat lower than the GPS probed speeds (5 mph on the freeways). However, based on our analyses, this speed difference does not significantly impact the result in the scenarios studied. When instrumented-vehicle-density is high, the forward process of information propagation dominates and is so fast that vehicle speed is irrelevant. When instrumented-vehicle-density is moderate, the relative vehicle speeds determines message catch-up time, and the average speed is not critical. It is only when instrumented-vehicle-density is low that information propagation relies primarily on vehicle movement, making the 5 mph speed difference relevant in determining the information propagation speed. This paper focuses primarily upon the impact of traffic volume and fleet penetration ratio on information propagation, so the 5mph speed difference is not examined directly under these conditions. The next research stage will focus upon 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 miles is simulated in this research effort. Vehicle traffic in both directions is exploited in relaying the message. The 4-millisecond message transfer time is so much faster than vehicle operating speeds that messages readily propagate across the center divider to an oncoming car and then back across the center divider to a car further 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 utilized to generate 600-second traffic traces, using a different random number seed for each trace. The simulation results for all scenarios (except for penetration ratio of 0.05), are obtained by partitioning each 600-second trace into five 100-second samples; the first 100 seconds of the trace is not used while the system initially populates. Each sample then begins with the propagation of a single message. For each penetration ratio, 10 traces are examined for a total of 50 samples. For the 0.05 fleet penetration ratio, 20 traces were generated and one sample was collected from each trace. This arrangement of random seed variation and 100 second samples was utilized to lessen the correlation between successive message propagations.

RESULTS

Detailed examination of the information propagation process shows that vehicle traffic in both directions play equal important roles in propagating information within partitions. Vehicle traffic in the direction in which the information is propagating plays the more important role in moving the message from one partition to another.

Average End-to-End 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. The delay tends to decrease as the fleet penetration ratio increases, but not linearly. To achieve an average delay below 2 seconds for the 6-mile message propagation, a fleet penetration ratio of 0.15 or greater is required for evening peak traffic, while the penetration ratio has to reach 0.80 for nighttime traffic (given the sparse traffic volumes on the roadway at night). Since intra-partition vehicle forwarding is relatively fast, the majority of the propagation time is spent moving information from one partition to another. The shortest E2E delay for 6 miles observed is 0.164 seconds given the parameters used here, where an E2E path exists. For nighttime traffic, when the fleet penetration ratio is below 0.10, information propagation is principally driven by vehicle movement. This agrees with previous analyses [10]. During evening peak traffic (Figure 3), message delay reaches a minimum at a fleet penetration ratio of around 0.20. Further fleet penetration beyond 0.20 does not significantly reduce propagation delay.

Delay Variance

Figure 5 shows the message propagation time distribution for several penetration ratios. As expected, the propagation time varies significantly. This variation is primarily due to path vulnerability, i.e. the likelihood of
partitioning. When a contiguous E2E path exists, message propagation can finish within one second. 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 exist (e.g., penetration ratio > 0.20 for evening peak traffic) do we observe stable performance. Thus, a message only has a high probability of rapid propagation in an environment of higher density of instrumented vehicles.

**E2E Connectivity**

Most routing protocols for ad hoc networks assume E2E connectivity [23-25]. 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 exists for evening peak traffic. When the fleet penetration ratio exceeds 0.20, the connectivity can reach nearly 100%. When the penetration ratio is lower than 0.10, the connectivity is below 15%. However the connectivity is only 82% even with 100% fleet penetration (i.e. every vehicle is instrumented) for nighttime traffic. Traffic volumes are so low that distance separations create multiple partitions. Figure 7 demonstrates the E2E connectivity versus the propagation distance when the fleet penetration ratio is 0.10 for evening peak traffic. Dousse, et al. [26] demonstrated that E2E connectivity decreases with distance for one-dimensional network topologies. Not surprisingly, our results also reflect this trend. When the propagation distance is 1 mile, the E2E connectivity can reach about 70%, while it is only 16% for the propagation distance of 6 miles.

**DISCUSSION OF RESULTS**

Several observations may be made based on the preceding results. First, V2V communication appears feasible for propagating information along the I-75 freeway in the Atlanta metro areas, as well as other roadway systems with similar traffic characteristics as Atlanta during peak or high traffic density periods (times during which the propagation of traffic information is most needed). The 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 low traffic density periods, e.g., nighttime, presents challenges and may require some additional mechanism to support communications, e.g., 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 0.20 is sufficient for efficient 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 vehicle-to-vehicle communication. For applications where immediate data are not critical, other non-fixed-infrastructure based solutions may be explored. For example, vehicles can cache data and use this information when up-to-date information is not available.

Lastly, 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 [25], as required by some applications (e.g., multimedia applications), are suitable only for a high density of instrumented vehicles or short propagation distances. Opportunistic forwarding algorithms relaxing E2E connectivity [27] 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 clear emerging trend. Equipping vehicles with computing, communication, and sensing capabilities presents significant opportunities for a variety of transportation systems. Vehicle-to-vehicle communication may be applied to incident detection, crash reporting, traveler information systems, network operations, etc. In addition, in-vehicle
systems allow coverage to extend beyond areas where roadside equipment has been placed. This study provides an initial investigation needed to implement and test the feasibility of these advanced communication networks. The traffic density and instrumented vehicle penetration ratio are 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 study the effectiveness of this approach for specific applications.
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