Area Coverage Provided by Vehicle to Vehicle Communication in an Urban Network

Morgan State University
The Pennsylvania State University
University of Maryland
University of Virginia
Virginia Polytechnic Institute & State University
West Virginia University

The Pennsylvania State University
The Thomas D. Larson Pennsylvania Transportation Institute
Transportation Research Building ❖ University Park, PA 16802-4710
Phone: 814-865-1891 ❖ Fax: 814-863-3707
www.mautc.psu.edu

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By: Taehyoung Kim, Antoine G. Hobeika, and Heejin Jung

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Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University

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16. Abstract

The information obtained from connected vehicle has the potential of providing local and area-wide traffic management solutions by improving safety and mobility. The reliability and the frequency of this transmitted information have to be addressed to ensure that the users can properly utilize this information to solve traffic management issues. The first part of this research investigates the area covered in space and in time by vehicle to vehicle (V2V) communication in an urban network based on different market penetration rates of equipped vehicles and wireless communication coverage in TRANSIMS. The percentage of valid connected vehicles and area coverage level are used to assess the communication duration rate and spatial-temporal dispersion of equipped vehicles. Results show that both average communication duration rate and area coverage level increase as the market penetration rate and wireless communication coverage increase. The communication duration rate is more sensitive to the wireless communication coverage than the market penetration rate. However, the market penetration rate has a greater influence on spatial-temporal dispersion of equipped vehicles and the Selected Links case has higher average area coverage level than the Whole Network case. The average area coverage also varies by time of day and is sensitive to the density of traffic and to the aggregation level. Finally, the spatial-temporal dispersion of equipped vehicles increases as the density of traffic increases.

The second part of this research measures the performance of V2V applications and determines the required minimum level of deployment in a large urban network. Distance of information propagation and speed estimation error are used to measure the performance of event-driven and periodic applications. For event-driven applications, wireless communication coverage is the major factor because it has a greater impact on the distance of information propagation. For periodic applications, however, the market penetration rate has a greater impact on the performance than wireless communication coverage. The performance of event-driven improves in the higher traffic density conditions of peak time while the performance of periodic application improves in the lower traffic density conditions of non-peak time. The required minimum level of deployment for each application is determined to obtain reliable traffic management solutions. These study findings will be useful for making decisions about investments in cooperative vehicles in relation to the expected increase in traffic efficiency.

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Part 1: Area Coverage Provided by Vehicle-to-Vehicle Communication in an Urban Network

Taehyoung Kim
Graduate Research Assistant
Charles Via Department of Civil and Environmental Engineering
301-G, Patton Hall
Virginia Polytechnic Institute and State University
Blacksburg, VA, 24061
Tel: 540-553-5091; Email: thkim@vt.edu

Antoine G. Hobeika
Professor
Charles Via Department of Civil and Environmental Engineering
301-H, Patton Hall
Virginia Polytechnic Institute and State University
Blacksburg, VA, 24061
Tel: 540-231-7407; Email: hobeika@vt.edu

Heejin Jung
Researcher, Ph.D.
Department of Spatial Information Engineering
Institute of Spatial Information
Pukyung National University
Busan, Korea, 608-737
Tel: +82-10-8550-8721; Email: hjjung1974@gmail.com

ABSTRACT

The information obtained from Connected Vehicles has the potential of providing local and area-wide traffic management solutions which is desperately needed in most large urban areas. The reliability and the frequency of this transmitted information have to be addressed to ensure that the users can properly utilize this information to solve traffic management issues. This research investigates the area covered in space and in time by vehicle to vehicle (V2V) communication in an urban network based on different market penetration rates of equipped vehicles and wireless communication coverage in TRANSIMS. The percentage of valid connected vehicles and area coverage level are used to assess the communication duration rate and spatial-temporal dispersion of equipped vehicles. Results show that both average communication duration rate and area coverage level increase as the market penetration rate and wireless communication coverage increase. The communication duration rate of equipped vehicles is more sensitive to the wireless communication coverage than the market penetration rate. However, the market penetration rate of equipped vehicles has a greater influence on spatial-temporal dispersion of equipped vehicles and the Selected Links case has higher average area coverage level than the Whole Network case. The average area coverage also varies by time of day and is sensitive to the density of traffic and to the aggregation level. Finally, the spatial-temporal dispersion of equipped vehicles increase as the density of traffic increases, i.e. more equipped vehicles are able to communicate with one another. These study findings will be useful for making decisions about investments in cooperative vehicles in relation to the expected increase in traffic efficiency.

INTRODUCTION

Connected Vehicle research has emerged as one of the highest priorities in the transportation field. It focuses on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication using wireless technologies such as Dedicated Short Range Communications (DSRC). Most of the automakers and a number of countries are developing Connected Vehicle applications. The intent of connected vehicle is to support safety, mobility, and environmental impact that benefit the users and providers of the transportation system. Connected Vehicles can provide continuous real-time connectivity to all system users to/from vehicles, infrastructure, wireless devices, and transportation management centers. The vehicles equipped with V2V communication system can exchange their data between nearby vehicles such as position, speed, and location data. V2V communication enables an equipped vehicle to avoid crashes by receiving warning threats or hazards. V2I wireless communication enables an equipped vehicle to exchange safety and operational data with highway infrastructure.

The information obtained from connected vehicles, whether from V2V or V2I, has the potential of providing local and area-wide traffic management solutions which are desperately needed in most large urban areas. The reliability and the frequency of this transmitted information have to be addressed to ensure that the users can properly utilize this information to solve traffic management issues. This research focuses on the area covered in space and in time by V2V communication in an urban network based on different market penetration rates and wireless communication coverage. The findings will be useful for making decisions about investments in cooperative vehicles in relation to the expected increase in traffic efficiency.

LITERATURE REVIEW

The literature covers a wide range of topics in the connected vehicle research. It is ubiquitous and is not possible to cite it all in this condensed report. However, the authors will focus on selected publications that cover the areas of communications and standards and on issues related to penetration levels of Connected Vehicles and related research work conducted on probe vehicles and the requirements needed to obtain reliable information for traffic management purposes. Many countries are working on developing DSRC technology for various connected vehicle applications to improve safety and mobility. The wireless communication coverage is one of the important factors for connected vehicle functionalities. But, it is difficult to evaluate wireless vehicular communication coverage at each different site because it depends on various factors that may obstruct the vehicular communication. Gallagher, Akatsuka, and Suzuki implemented a field test for line-of-sight (LOS) and non-line-of-sight (NLOS) radio links for 5.9GHz DSRC [1]. This study made field tests for LOS and NLOS vehicular environments to determine max link range and packet error rate (PER) limits. The goals for LOS tests are to measure if V2I and V2V links meet the max range (1,000 m) and PER limits (< 10%). The goals for NLOS links are to measure the PER in V2V links with vehicle blockage on the highway. The results showed that the maximum highway V2V range is 880m (2,886 feet) with an average PER of 0.63% for LOS when there is no obstruction in the field. Also, the V2V range for NLOS is from 59 to 230m with an average PER of 17.8 %. Rui Meireles et al. studied the effect of vehicles as physical obstructions for the wireless signal using two cars equipped with DSRC [2]. They performed experimental measurements in order to collect received signal power and packet delivery ratio information in a multitude of relevant scenarios: parking lot, highway, suburban and urban canyon. The results showed that obstructing vehicles can cause significant impact on the channel quality. ASTM E2213-03, one of standards for DSRC, indicates that the communications generally occur over line-of-sight distances of less than 1000 meters for V2I or V2V [3]. This standard provides wireless communications over short distances between information sources or transaction stations on the roadside and mobile radio units, between mobile units, and between portable units and mobile units. IEEE 1609 is another standard for Wireless Access in Vehicular Environments (WAVE). This standard defines architecture and a complementary standardized set of services and interfaces that collectively enable secure V2V and V2I wireless communications. WAVE standard also mention that wireless communications occur up to 1,000 m in the vehicular environment [4].

Studies on market penetration rate of equipped vehicles for V2V are discussed next. Market penetration concept is usually used by businesses for strategic purposes such as deciding whether or not to launch their new products or services. This concept is also required in the transportation system for the potential deployment of new application or service like connected vehicle applications. Shladover et al. studied a performance of cooperative vehicle systems (CVS) based on the market penetration of equipped vehicles utilizing Monte Carlo analyses and simulations of wireless message propagation [5]. This study considered two relay modes for wireless vehicle-to-vehicle communication; 1) direct wireless transmission to nearby vehicles within a communication range and 2) transport relay, in which a vehicle carries a message to other vehicles as it travels. The effectiveness of both direct and transport relay were tested as a function of wireless communication range, market penetration, and traffic density and their influence on the speed of message propagation. The results indicated that the direct relay is more effective in a high density of equipped vehicles. But, the relays became more dependent on the transport relay in a low density of equipped vehicles. Cheol Oh et al. presented an enhanced traffic surveillance system capable of collecting probe vehicle information using GPS and V2V communications [6]. The functional requirements of the proposed system, include V2V communication range (200, 500, and 1000 m), market penetration rate of equipped vehicles (5, 10, 20, 30, and 50 %), and an aggregation interval for travel time estimation. Mean absolute percentage error (MAPE) was used to evaluate the accuracy of the proposed representative travel time estimation models based on the probe vehicle information. The evaluation results showed that travel time errors of less than 5% and 15% are achievable under normal and incident traffic conditions, respectively.

Bing Mei et al. described a simulation model for studying the impact of V2V wireless communications on traffic network operations [7]. The developed simulation model was used in a case study application to simulate vehicle dynamic route diversion and variable speed limits following a severe incident in a small network. Simulation results indicated that the model results are sensitive both to different market penetration levels of vehicles equipped with wireless communications capabilities and to various control strategies. Park and Lee examined the sustainability impacts of route guidance system under the cooperative vehicle infrastructure environment using various market penetration rates of equipped vehicles at 0%, 5%, 25%, 50%, 75%, and 100% [8]. The impacts were estimated using an incorporation of microscopic traffic simulation model and a microscopic emission and fuel consumption model. The simulation results indicated that the route guidance system under the cooperative vehicle infrastructure environment improves air qualities and fuel consumption by 10 to 18% compared to base case.

Area coverage is an important measurement to determine the required market penetration rate or sample size for probe vehicles. Ygnace et al. developed an area coverage equation for probe vehicles used in San Francisco to estimate travel times as follows [9]:

$$E = 1 - \exp(-\alpha \rho L) \tag{1}$$

where E is the coverage, α is the fraction of vehicles sampled, ρ is the density of traffic per unit length, and L is the average link length. The coverage was defined as a fraction of links for which the links have been measured in the time frame of interest. This equation translates that the fraction of vehicles sampled or average link length should be increased to improve the coverage. But, this model did not consider the location error or the link type. Srinivasan and Jovanis developed a heuristic algorithm for determining number of probe vehicles required in urban network for reliability of travel time estimation and adequacy of area coverage [10]. This study indicated a greater proportion of freeway links than of major arterials can reliably be covered with a given number of probes. Also, the number of probes required increases as the desired proportion of link coverage in the network increases. BMW Group considered the potential of vehicle-generated traffic data acquisition for the generation of traffic information and local hazard warnings [11]. A method for estimating the required floating car penetration rates on the basis of traffic volume and arrival probabilities is presented. This study showed the necessary penetration rates for different road network categories. For example, at least 10% of penetration rate is required for federal roads and urban arterials in peak hours.

The use of probe vehicle is an efficient method to collect real-time traffic information. Some studies are conducted to determine the number of probe vehicles to ensure acceptable data qualities for traffic information services. Turner and Holdener investigated a statistical sampling method to obtain the minimum number of probe vehicles for obtaining real-time travel speeds and travel times in Houston [12]. The minimum number of probe vehicles was calculated by two separate statistical scenarios corresponding to a confidence level of 90 and 95%, and permitted error of 10%. It was concluded that the current number of probe vehicles from AVI tags in Houston provides reliable travel speed information with 95% confidence. Ygnace et al. evaluated the feasibility of using cell phones as traffic probes to estimate travel time in the San Francisco Bay Area network [9]. This study concluded that at least 5% of travellers on freeways that are equipped with a cell phone must be sampled for the accurate estimation of travel time. Green, Fontaine, and Smith investigated the dynamic determination of sample sizes for traffic condition monitoring systems [13]. This study used the central limit theorem (CLT) to estimate mean speed for 12 sites in Virginia. The sample sizes, based on CLT theorem, varied considerably for each site. Some sites could be satisfied with 95% confidence interval with accuracy of ± 5 mph from the sample size which has less than 5% of traffic. Ishizaka and Fukuda proposed a new methodology to estimate the number of probe vehicles required for the reliability of travel time estimation by verifying the feasibility of reducing probe vehicles from that required by the conventional methodologies [14]. This study tried to reduce the required number of probe vehicles by optimizing the percentage of each OD pair. The results showed that the new methodology estimate less required number of probe vehicles than the conventional methodology.

Estimating required market penetration rate of targeted or probe vehicles to get reliable results is one of the most major factors for the potential deployment of new transportation application or service like connected vehicle. Area coverage is an important measurement to determine the required market penetration rate. Although some previous studies on area coverage were conducted, they were mainly hypothetical and didn't use realistic and large networks. They used a cumulative area coverage level by short time durations such as 5, 10, and 15 minutes and low penetration rate such as 5%. To obtain much more fine grained area coverage level from shorter time interval, such as 1 minute and 1 second intervals, with higher time duration should be determined to get better real-time information service.

STUDY BACKGROUND

Objectives

The objectives of this research are as follows;

- Identify valid communication among the identified equipped vehicles in the realistic and large network based on various scenarios of wireless communication coverage and market penetration rates of equipped vehicles.
- Determine the success and duration rate of wireless communication among the identified equipped vehicles based on various scenarios
- Determine the dispersion of equipped vehicles in time and in space in an urban network
- Calculate the area coverage obtained by the valid communication among equipped vehicles for the different scenarios stated above.

Overview of TRANSIMS

To assess the dispersion of equipped vehicles in time and in space requires a special simulation that can trace each individual vehicle in an urban area on a second by second basis and be able to carry the identity of each driver and passenger with it at all time. The simulation that can execute these requirements is TRANSIMS (Transportation Analysis and Simulation System) which is developed by Federal Highway Administration (FHWA), USA and is available in the public domain. The underlying TRANSIMS philosophy is that to study the transportation system's performance effectively, one needs to simulate travel in a study area with a rather fine temporal and spatial resolution. Other research and developmental efforts have also come to the conclusion that the next generation of urban travel models should be based on micro-analytic simulation and that they should employ the activity-based approach for modeling travel demand. TRANSIMS differs from current travel demand forecasting methods in its underlying concepts and structure. These differences include a consistent and continuous representation of time; a detailed representation of persons and households; time-dependent routing; and a person-based microsimulator. TRANSIMS microsimulator is the only simulation tool that maintains the identity of the traveler throughout the simulation, and is capable of accessing the database of each individual (e.g., income, age, trip purpose, etc.). In other words, it traces the movement of people as well as vehicles on a second-by-second basis. In addition, TRANSIMS route planner utilizes a time-dependent, individually-based route choice model that is suitable for considering each individual response to the value of the travel information provided.

TRANSIMS consists of a series of modules that produce synthetic households, activities for individuals within each household, the choice of routes for movements among these activities, and the microsimulation of these movements to create traffic dynamics on the network, and to estimate the consequent emissions produced. The framework of TRANSIMS, as shown in Figure 2, allows each module to be executed in any desired order by a set of scripts specified by the user in the Feedback Controller. TRANSIMS starts by creating the identity of individual synthetic travelers and maintains them throughout the entire simulation process. All synthetic travelers are generated by the Population Synthesizer module using census data, land-use data, and network data. After the Population Synthesizer module estimates the number of synthetic households, and the demographic characteristics of each individual in these households and the locations of these households on the network, the Activity Generator creates an activity list for each synthetic traveler. These activities include work, shopping, school, etc. These activity estimations are based on the activity survey demographic characteristics of individuals as they are obtained from the survey data. In addition, activity times and activity locations are determined for each individual activity. The Route Planner module next computes combined route and mode trip plans to accomplish the desired activities of each individual, such as work, shopping, etc. It uses a modified version of Dijkstra's algorithm that computes the shortest path in a time-dependent, label-constrained network. Its unique feature is that it computes the shortest path in a multi-modal network. The Traffic Microsimulation module uses the intermodal paths developed in the Route Planner module to perform a regional microsimulation of vehicle interactions. The microsimulation, which employs the cellular automata principle and network partitioning to be able to microsimulate large scale transportation networks, continuously computes the operating status, including locations, speeds, and acceleration or deceleration of all vehicles throughout the simulation period. The output can provide a detailed, second by second history of every traveler in the system over a 24-hour period. Every motor vehicle in the study area is monitored in this manner to identify traffic congestion and emission concentrations, which is done by the Emissions Estimator module. Finally, the Feedback Controller module manages the feedback of information among the Activity Generator, the Route Planner, and the Traffic Microsimulator modules of TRANSIMS as shown in Figure 2. This feedback controller module makes decisions such as what percentage of the regional trips should be fed back between modules, which trips should be fed back, how far back should the trips go for re-planning, and when to stop iterating to attain a degree of stability in the results.

These unique features of TRANSIMS would allow the analyst to assess the dispersion of equipped vehicles by time and location in an urban area. There is no limit on the size of the urban area that can be simulated. In addition this system is able to include a detailed highway network such as the collector and the feeder systems. The equipped vehicles would be assigned to travelers in the Population Synthesizer Module based on their socio-economic characteristics. TRANSIMS also can map the location of the equipped vehicles in the network at every second based on the penetration level assigned in the Population Synthesizer. The transmission power of the equipped vehicles can be varied and used to create contours of vehicle to vehicle (V2V) coverage, hence giving the analyst the ability to assess the coverage level and the frequency of the information obtained from the equipped vehicles for different penetration scenarios, and determines the utility of the investment for different vehicle systems deployment levels.

RESEARCH METHODOLGY

Overview of study process

• Study area and network

The city of Alexandria, VA, USA outside of Washington D.C. was used for this study. The size of study area is around 44 km2 (17 mi2), bordered by I-395 (Henry G Shirley Memorial Highway), I-495 (Capital Beltway), and State Route 400 as shown in Figure 1. TRANSIMS provided the dataset for Alexandria as the test case. This dataset includes all the input data needed to represent and code the highway and transit networks. This highway network has 3,653 links and about 420,000 trips.

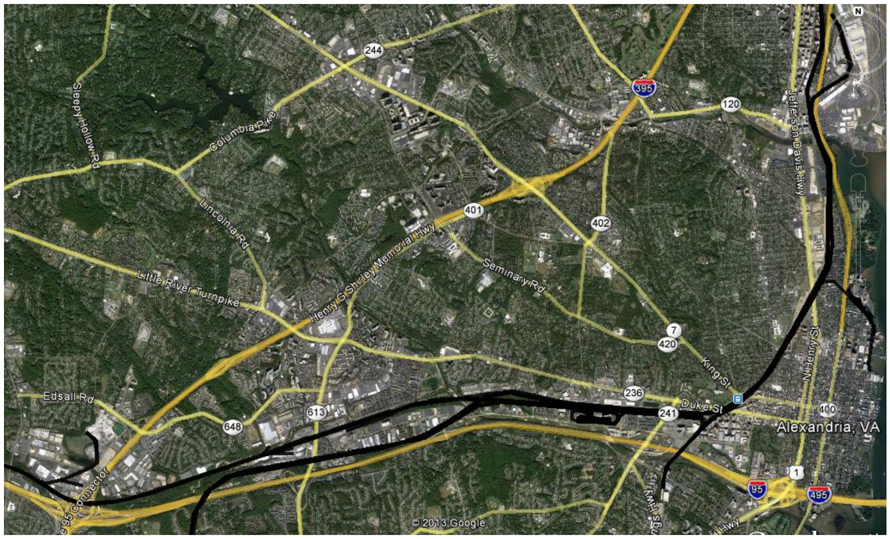

Figure 1: Alexandria study area

• Distribution of equipped vehicles

Vehicles having a specified vehicle type and subtype in TRANSIMS are assumed as the equipped vehicles that can communicate with nearby other equipped vehicles to exchange traffic and travel information among each other. The fraction of equipped vehicles to total vehicles can be changed in the population synthesizer module of TRANSIMS to represent different market penetration rates. The population synthesizer module assigns vehicles including equipped vehicles to each household according to their socio-economic characteristics [15, 16]. Then, the equipped and non-equipped vehicles are distributed onto the network through the modules of activity generator, router planner, and microsimulator. Figure 2 shows the flowchart of the study process.

• Collection of vehicle data

Each individual vehicle trajectory data are required to assess the dispersion of equipped vehicles in time and space in the study area. TRANSIMS offers detailed snapshot data as one of the output files from the microsimulator. This snapshot data include the location of each individual traveler, car, or transit vehicle on a second-by-second basis. Each equipped vehicle can be traced from the provided snapshot data such as vehicle ID, link ID with direction, lane, vehicle type, speed, x, y, and z coordinates of each vehicle at specified time points.

• Analysis of vehicle data

This study assumed a valid connected vehicle as the equipped vehicle that is able to communicate with other equipped vehicle when they are spatially within defined wireless communication coverage distance. After identifying all equipped vehicles using vehicle ID and vehicle type defined in population synthesizer module, the distances between all equipped vehicles are calculated using x and y coordinates from snapshot data. The percentage of valid connected vehicles, the success rate of communication among equipped vehicles, and the area coverage that they produce, would be used to assess the coverage level and the frequency of the information obtained from the equipped vehicles for different market penetration rates of equipped vehicles and wireless communication coverage distances.

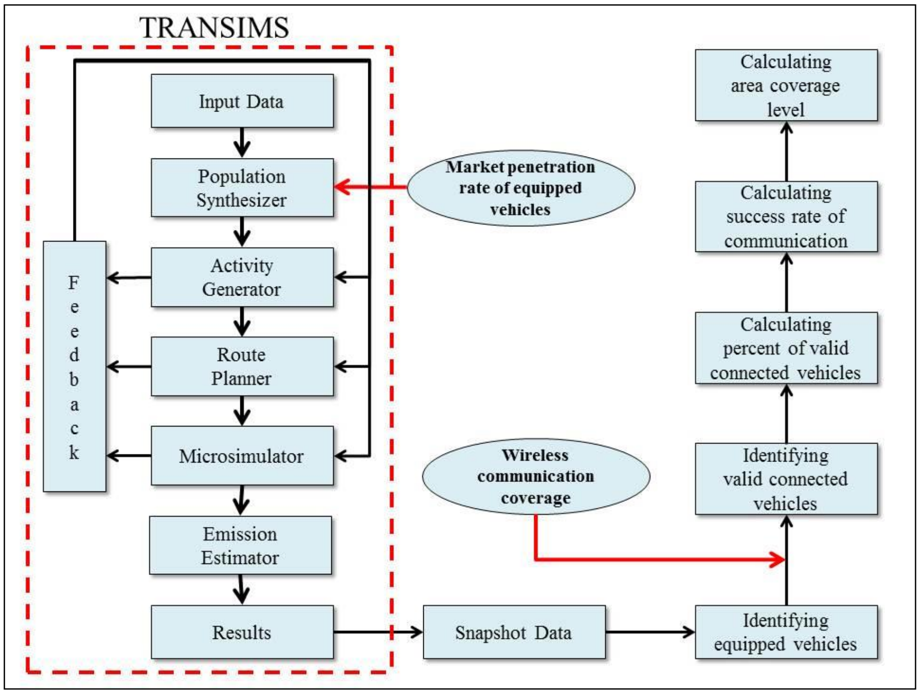

Figure 2: Study process flowchart

Scenarios

Nine scenarios are analyzed in this study based on two variables, market penetration rate of equipped vehicles and wireless communication coverage. Three market penetration rates of equipped vehicles (10%, 20%, and 40%), and three wireless communication coverage (100m, 200m, and 500m) are evaluated for the two study area networks. In this study the maximum wireless communication coverage is limited to 500m because of building and vehicular obstructions in the Alexandria network.

RESULTS

Communication duration rate of equipped vehicles

Several TRANSIMS runs were conducted to utilize the Alexandria data sets provided by FHWA. As stated earlier, TRANSIMS offers detailed snapshot data as one of the output files. The vehicle data was collected from the snapshot output file at every one minute during 4 hours from 6 to 10 a.m. Due to the huge size of the snapshot data file, the aggregation to the 1 minute level was needed in order to manage the large data for the four hours during the morning peak period. The total number of vehicles in the whole network is about 111,200 vehicles for four hours. The one second movement of these vehicles for four hours would have created around 1.2 trillion data points for only one output variable, which would be hard to manage for multiple variables without utilizing super computers. Besides, the vehicles' movements in one second are too small to create any change in the dispersion results of equipped vehicles. However, the authors did organize the data at 10 seconds interval level for a 30 minutes period in order to gauge the differences in results.

The results of the percentage of valid connected vehicle by three market penetration rates of equipped vehicles (10, 20, and 40%) and three wireless communication coverage (100, 200, and 500m) are shown in Table 1. If one equipped vehicle communicates with other equipped vehicles at least one time during the analysis period, this equipped vehicle is regarded as a valid connected vehicle. The percentage of valid connected vehicles to total vehicles in the study area is calculated to assess the strength of communication among V2V in an urban network. The actual market penetration rate of equipped vehicles obtained from snapshot data during the analysis period (6-10 a.m.) is less than the designated market penetration rate, which is calculated as a percent of the total daily vehicles to be assigned onto the network. The actual market penetration rate is influenced by the assignment of equipped vehicle(s) to a household carried by the Population Synthesizer module based on the household's socio-economic characteristics. In addition, it is influenced by the loading of equipped and non-equipped vehicles based on each household daily travel activity onto the network which varies from one hour to another hour, particularly in the morning peak period.

Table 1: Percentage of valid connected vehicle

		Market Penetration Rate of Equipped Vehicles over 20-hours		
		10 %	20 %	40 %
Actual Market Penetration Rates of Equipped Vehicles over 4 hours		6.23 %	12.29 %	24.39 %
Wireless Communication Coverage	100m	6.15 %	12.16 %	24.18 %
	200m	6.21 %	12.26 %	24.33 %
	500m	6.23 %	12.29 %	24.39 %

The percentage of valid connected vehicles increases as market penetration rate of equipped vehicles and wireless communication coverage increase as shown in Table 1. The percentage of valid connected vehicles is more sensitive to the market penetration rate of equipped vehicles than the range of wireless communication coverage. The increase in wireless communication coverage from 100m to 500m for the same daily market penetration rate of 10% of equipped vehicles only produced an increase of 0.08 percent of valid connected vehicles. While, an increase of daily market penetration rate from 10% to 20% for the same wireless communication coverage of 100m produced a 6.01% increase in valid connected vehicles. The conclusion is that market penetration rate has a greater influence on the validity of connected vehicles than the communication area coverage.

The success rate of communication among equipped vehicles in the study area is shown in Table 2. Unlike the results of the above percentage of valid connected vehicles, these communication success rates of equipped vehicles did not change very much although the market penetration rate of equipped vehicles and wireless communication coverage did change. The difference between the minimum and maximum communication success rate of equipped vehicles is 1.24%. At least 98% of equipped vehicles are able to communicate with nearby equipped vehicles in this network. They can exchange their information among one another and get a benefit from V2V based applications at least one time. Eighty two equipped vehicles among 6,568 equipped vehicles failed to communicate with nearby equipped vehicles in the case with 10% of market penetration rate and 100m of wireless communication coverage. Two hundred and twenty equipped vehicles among 25,717 equipped vehicles didn't success to communicate with other equipped vehicles when the market penetration rate is 40% and wireless communication coverage is 100m. But, only one equipped vehicle failed to communicate with nearby equipped vehicles when the wireless communication coverage is 500m with 20% and 40% of market penetration rate. Almost all equipped vehicles are able to communicate with other equipped vehicles when they are spatially within 500m of wireless communication coverage regardless of the level of market penetration rate of equipped vehicles.

Table 2: Success rate* of communication among equipped vehicles

		Market Penetration Rate of Equipped Vehicles		
		10 %	20 %	40 %
Wireless Communication Coverage	100m	98.76 %	98.92 %	99.14 %
	200m	99.67 %	99.71 %	99.77 %
	500m	100.00 %	99.99 %	100.00 %

*Success rate of communication = (Number of valid connected vehicles / Number of equipped vehicles) * 100

The communication success rate of equipped vehicles is calculated in the previous section. If one equipped vehicle communicates with other equipped vehicles just one time during the analysis period, this equipped vehicle is regarded as a successful communication. However, some equipped vehicles may success to communicate during short time period such as 1 or 2 minutes although some equipped vehicles can communicate during the whole time period when they stayed in the network. So, the communication duration rate of equipped vehicles is investigated from Equation (2) in this section.

$$\text{Communication Duration Rate} = \frac{\sum D_i}{\sum T_i} \times 100 \quad (2)$$

where, Di = Valid communication duration time of equipped vehicle i and

Ti = Total time stayed in the network of equipped vehicle i

The communication duration rate of equipped vehicles increases as the market penetration rate of equipped vehicles and wireless communication coverage increase as shown in Table 3. The case with 10 % of market penetration rate and 100m of wireless communication coverage has the lowest value of communication duration rate. The communication duration rate of this case is 87.01 % although 98.76 % of equipped vehicles succeed to communicate with other equipped vehicles at least one time during the analysis period. The wireless communication coverage has a greater influence on the communication duration rate of equipped vehicles than market penetration rate. An increase of wireless communication coverage from 100m to 500m produced a 5.30% increase in communication duration rate of equipped vehicles when the market penetration rate of equipped vehicles is 10%. However, the communication duration rate is increased by 12.87% when the market penetration rate is changed from 10% to 40% in the case for 100m of wireless communication coverage. As shown in Table 3, equipped vehicles kept a status of valid communicated vehicle at least during 99.88% of the time stayed in the network when the wireless communication coverage is 500m. Results of communication duration rate show that longer wireless communication coverage is needed to improve the performance of V2V based applications in the initial deployment with low level of market penetration rate of equipped vehicles.

Table 3: Communication duration rate of equipped vehicles

		Market Penetration Rate of Equipped Vehicles		
		10 %	20 %	40 %
Wireless Communication Coverage	100m	87.01 %	89.46 %	92.31 %
	200m	96.23 %	97.21 %	98.02 %
	500m	99.88 %	99.93 %	99.96 %

Spatial-temporal dispersion of equipped vehicles

Figure 3 shows a snapshot of the spatial dispersion of each vehicle travelling in a small portion of the Alexandria network at 08:03:30 a.m. This small network, bordered by I-395 (Henry G Shirley Memorial Highway) and Duke Street, has the highest traffic density during rush hour in Alexandria. This snapshot picture is taken from the output of the scenario that has 20% of market penetration rate and 200m of wireless communication coverage. The red circle in Figure 3 depicts the 200m of wireless communication coverage for each valid connected vehicle which is marked in red. Most valid connected vehicles are on major roadways such as freeway and major arterial. There are twelve equipped vehicles marked in blue circle that are not able to communicate with other vehicles because no equipped vehicles are within 200m of wireless communication coverage. This figure also shows that most minor roadways aren't covered by valid connected vehicles.

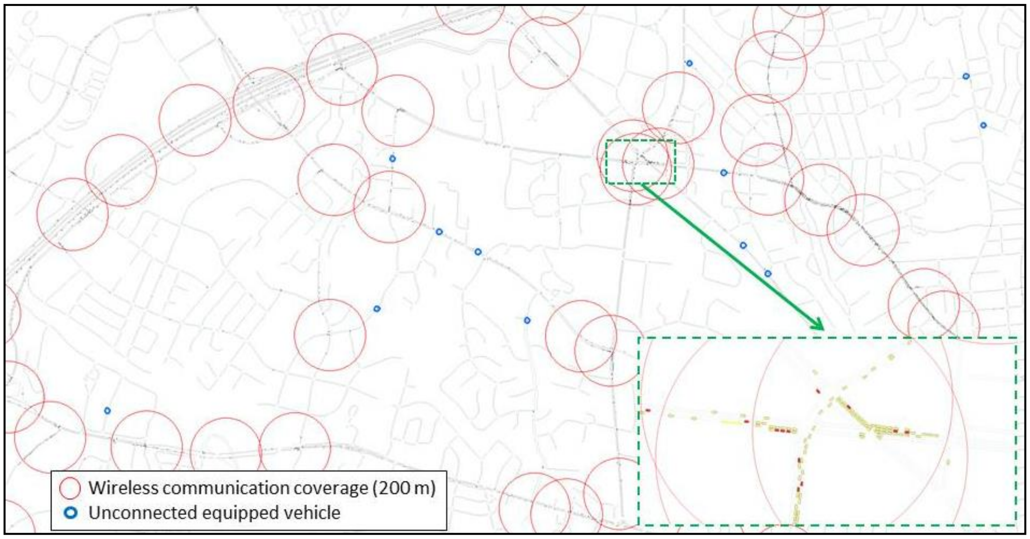

Figure 3: Spatial dispersion of vehicles with 200m communication coverage

The area coverage level of valid connected vehicle is used to assess the spatial-temporal dispersion of equipped vehicles. The concept of area coverage level adopted in this study is different from the ones used in previous studies that are discussed in the literature review. The cumulative fraction of number of covered links by probe vehicles was used in previous studies. Also, if one probe vehicle is on a certain link, this link was assumed to be covered to estimate travel time or speed. In addition, previous studies only considered short time durations such as 5, 10, and 15 minutes and low penetration rate of probe vehicles such as 5%. This study uses the average fraction of links covered by platoons of valid connected vehicles over total lengths of all links in the study area at every 1 minute during 4 hours. Figure 4 depicts pictorially the concept to compute coverage length on a link in this study, where L is the length of link and l is the length of a platoon of valid connected vehicles.

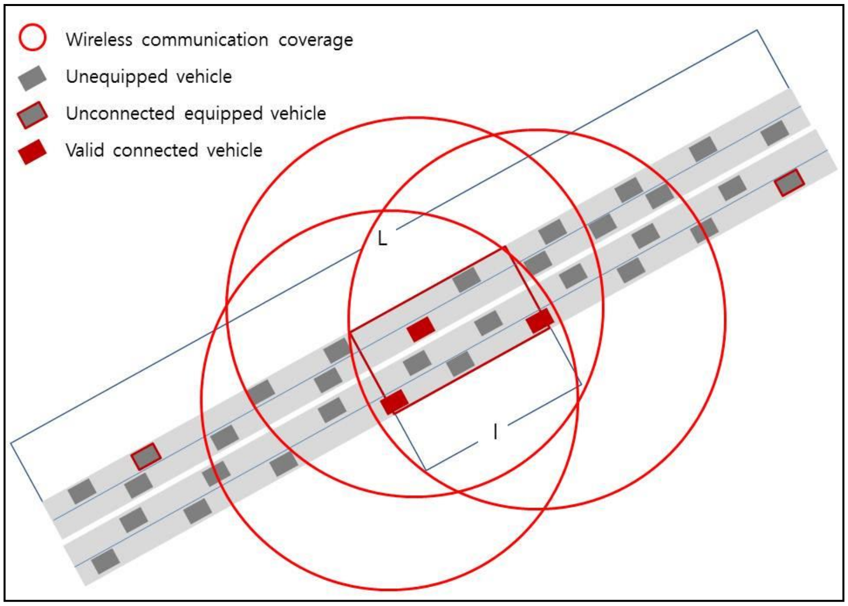

Figure 4: Computation of coverage length on a link

Table 4 shows the average percentage of the study area covered by valid communication of equipped vehicles for the 3x3 scenarios of market penetration rate and communication coverage. The average area coverage level is the proportion between the linear lengths of links covered by valid connected vehicles and the total linear lengths of all links in the study area. This section of the area coverage level considers two networks within the study area; the Whole Network and the Selected Links network. Two freeways, one expressway, and four major arterials are identified to compose the Selected Links network case in Alexandria while the Whole Network case covers all the links in the Alexandria network. The Selected Links network represents the higher functional class of the roadways which traditionally carries more than 70 % of all travel at any time of the day and is worthy of studying it as a separate case. The results of area coverage level have a similar pattern with the communication duration rate that is it increased as the market penetration rate and wireless communication coverage increased as shown in Table 4. But, the average area coverage levels in the Whole Network case are much lower than results of communication success rate and duration rate presented in section 5.1. Only 1.39% of links in the Whole Network are covered by valid connected vehicles when the market penetration rate is 10% and wireless communication coverage is 100m. The maximum value of the average area coverage levels on Whole Network cases is 12.27% although the market penetration rate and wireless communication coverage are increased to 40% and 500m, respectively. The market penetration rate has a greater influence on the average area coverage level of valid connected vehicles than wireless communication coverage. An increase of the market penetration rate of equipped vehicles from 10% to 40% produced a 7.04% of increase in the average area coverage levels in the Whole Network case when the wireless communication coverage is 100m. However, the average area coverage level is increased by 1.99% when the wireless communication coverage is changed from 100m to 500m in the case for 10% of market penetration rate. All average area coverage levels on the Selected Links case are higher than those of the Whole Network cases because a higher percentage of equipped vehicles are on the selected links than the whole network. About 77.5 % of total vehicles are on these selected links and the total lengths of selected links are much smaller than the total lengths of all links in the study area. The difference of the average area coverage levels between the Whole Network and the Selected Links cases increases as the market penetration rate and wireless communication coverage increase. 30.30% of links in the Selected Links are covered by valid connected vehicles when the market penetration rate is 40% and wireless communication coverage is 500m.

The average area coverage level at every 15 minute interval during 4 hours (6-10 a.m.) is presented to investigate variations of area coverage level in Figure 5 for one scenario having 20% of market penetration rate and 200m of wireless communication coverage. This Figure indicates that the average area coverage varies by time of day and is sensitive to the density of traffic and to the aggregation level. It shows that the area coverage could be as high as 9.56% at 8:00 a.m. and as low as 0.15% at 10:00 a.m. on the Whole Network case. Also, the Selected Links case has the higher average area coverage level than Whole Network case

Table 4: Average area coverage level* of valid connected vehicles

		Study Area					
		Whole Network			Selected Links		
Market Penetration Rate of Equipped Vehicles		10 %	20 %	40 %	10 %	20 %	40 %
Wireless Communication Coverage	100m	1.39 %	4.08%	8.43 %	2.33 %	8.07 %	19.69 %
	200m	2.37 %	5.83 %	10.96 %	4.52 %	12.53 %	26.32 %
	500m	3.38 %	7.29 %	12.27 %	7.29 %	16.60 %	30.33 %

* Average area coverage level = (Linear lengths of highways covered by valid connected vehicles / Total linear lengths of highways in the study area) * 100

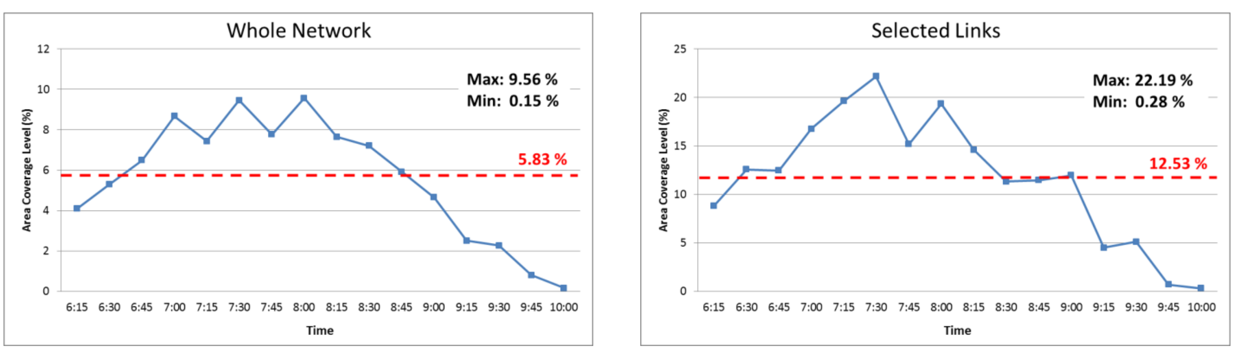

Figure 5: Average area coverage level for 15 min interval during 4 hours

Spatial-temporal dispersion of equipped vehicles using a 10 seconds time interval

Instead of the one minute update interval that was presented earlier, the authors investigated the spatial-temporal distribution of equipped vehicles using 10 seconds interval for a 30-minute period during peak traffic volumes from 7:45 a.m. to 8:15 a.m. This 30-minute period was selected because our study area has the highest traffic density at 8:00 a.m. The 10 seconds update interval would produce higher density of vehicular traffic which is expected to produce higher percentage of valid communications among the equipped vehicles. One scenario having 20% of market penetration rate and 200m of wireless communication coverage was analyzed for this case. The total numbers of vehicles and equipped vehicles in the Whole Network case are 21,490 and 2,866 respectively during this 30-minute period, while the numbers of total and equipped vehicles for the Selected Links case are 16,363 and 2,370 respectively.

The average area coverage levels for the Whole Network and Selected Links cases are calculated at every 10 seconds during 30 minutes and the results are shown in Figure 6. The average area coverage levels of valid connected vehicles in the whole network and the selected links cases are 8.84 and 18.81 % respectively. Figure 8 shows the variations in average area coverage aggregated at 1 minute level from the 10 seconds results for the whole network and for the selected link cases. Similar to Figure 5, this Figure shows that the levels of average area coverage are sensitive to time and density of traffic even at the 10 seconds intervals. The spatial-temporal dispersion results of equipped vehicles during 30 minutes (from 7:45 to 8:15 a.m.) at every 10 seconds in both Whole Network and Selected Links cases are higher than the previous results obtained during 4 hours (from 6:00 to 10:00 a.m.) as shown in Table 5. Especially, average area coverage levels in both Whole Network and Selected Links cases are increased by 50 % compared with the previous results from 4 hours analysis. Because, this 30 minutes period provided a much higher density of traffic. As the traffic density increases, more equipped vehicles are able to communicate with one another.

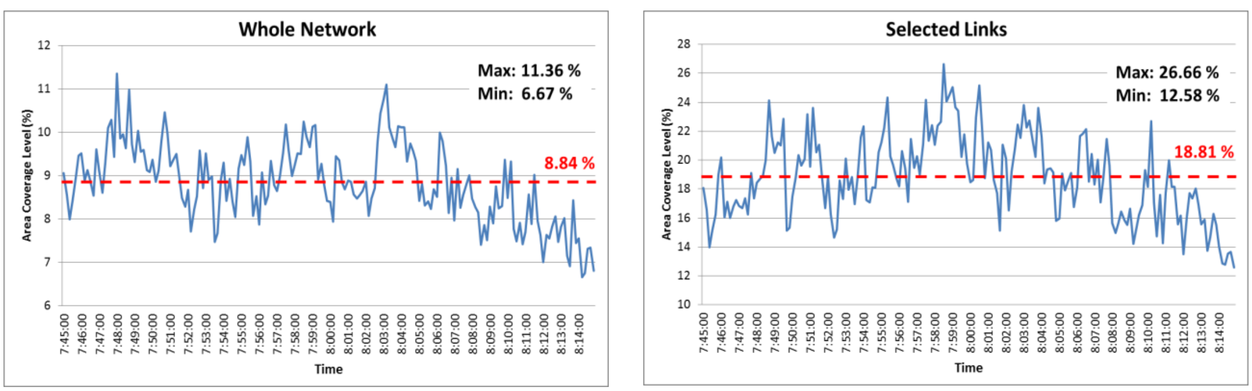

Figure 6: Average area coverage level for 10 seconds interval during 30 minutes

Table 5: Comparison on average percentage and average area coverage level of valid connected vehicles

Study area	1 minute interval during 4 hours	10 seconds interval during 30 minutes
Whole Network	5.83 %	8.84 % (+51.63%*)
Selected Links	12.53 %	18.81 % (+50.12%*)

* Percent difference with results from 1- minute update and 4 hours analysis

CONCLUSIONS

The communication duration rate and spatial-temporal dispersion of equipped vehicles for V2V are investigated based on the market penetration rate of equipped vehicles and wireless communication coverage in the realistic and large network. The communication duration rate and average area coverage level increase as the market penetration rate and wireless communication coverage increase. The percentages of equipped and valid connected vehicles are calculated to assess the success and duration rate of communication among equipped vehicles. The communication duration rate of equipped vehicles is more sensitive to the wireless communication coverage than the market penetration rate. Equipped vehicles are able to keep the status of valid communicated vehicle at least during 99.88% of the time the equipped vehicle stayed in the network when the wireless communication coverage is 500m.

The area coverage level is used to assess the spatial-temporal dispersion of equipped vehicles for two study areas; the Whole Network and the Selected Links cases. Only 12.27% of links in the Whole Network are covered by valid connected vehicles when the market penetration rate is 40% and wireless communication coverage is 500m. The market penetration rate of equipped vehicles has a greater influence on spatial-temporal dispersion of equipped vehicles. The Selected Links case has higher average area coverage level than the Whole Network case because a higher percentage of equipped vehicles are on the selected links than on the whole network and the total lengths of selected links are also much smaller than the total lengths of all links in the study area. The area coverage varies by time of day and is sensitive to the density of traffic and to the aggregation level. Finally, the spatial-temporal dispersion of equipped vehicles increase as the density of traffic increases, i.e. more equipped vehicles are able to communicate with one another. These study findings will be useful for making decisions about investments in cooperative vehicles.

Future works will include determining the distance of information propagation from one and multiple information sources through wireless multi-hop. In addition, ownership of equipped vehicles from a socio-economic aspect will also be considered. Sufficient levels of deployment of connected vehicle based applications will be determined for obtaining reliable traffic management solutions.

ACKNOWLEDGMENT

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Part 2: Assessment of Vehicle-to-Vehicle Communication based Applications in an Urban Network

Taehyoung Kim
Graduate Research Assistant
Charles Via Department of Civil and Environmental Engineering
301-G, Patton Hall
Virginia Polytechnic Institute and State University
Blacksburg, VA, 24061
Tel: 540-553-5091; Email: thkim@vt.edu

Antoine G. Hobeika
Professor
Charles Via Department of Civil and Environmental Engineering
301-H, Patton Hall
Virginia Polytechnic Institute and State University
Blacksburg, VA, 24061
Tel: 540-231-7407; Email: hobeika@vt.edu

Heejin Jung
Researcher, Ph.D.
Department of Spatial Information Engineering
Institute of Spatial Information
Pukyung National University
Busan, Korea, 608-737
Tel: +82-10-8550-8721; Email: hjjung1974@gmail.com

ABSTRACT

Connected vehicle technology has the potential to improve safety and mobility for local and wide-area traffic management. Most previous studies of connected vehicle applications have used simple and hypothetical networks; measurements in realistic and large networks are required if connected vehicle applications are to be deployed in the real world. This paper measures the performance of vehicle-to-vehicle (V2V) applications and determines the required minimum level of deployment for V2V applications in a large urban network. Distance of information propagation and speed estimation error are used to measure the performance of event-driven and periodic applications with different market penetration rates of equipped vehicles and wireless communication coverage, at both morning peak and non-peak times. As wireless communication coverage and market penetration rates of equipped vehicles increase, distance of information propagation increases while speed estimation error decreases in our study area. For event-driven applications, wireless communication coverage is the major factor because it has a greater impact on the distance of information propagation. For periodic applications, however, the market penetration rate of equipped vehicles has a greater impact on the performance than wireless communication coverage; this is because the speed estimation error more decreases as the market penetration rate increases. The performance of event-driven improves in the higher traffic density conditions of peak time while the performance of periodic application improves in the lower traffic density conditions of non-peak time. The required minimum level of deployment for each application is determined to obtain reliable traffic management solutions. These study findings will be useful for deployments of connected vehicle applications. In particular, event-driven applications can be deployed reliably in the initial stage of deployment, despite their low level of market penetration.

INTRODUCTION

Connected vehicle technology has the potential to improve safety and mobility for local and wide-area traffic management. Thanks to the development of wireless communication technology, many automotive manufacturers and countries have developed and evaluated various connected vehicle based applications and services. Connected vehicle applications and technologies are still in the stage of field testing due to policy and institutional issues. But these applications may be deployed in the real world soon because the U.S. Department of Transportation's (DOT) National Highway Traffic Safety Administration recently issued advance notice of proposed rulemaking to start implementation of vehicle-to-vehicle (V2V) communication for light vehicles.

Many connected vehicle research projects have been conducted to identify available applications and investigate the feasibility of these applications [1]. Since 2002, the U.S. DOT has been conducting research to assess the feasibility of developing effective crash avoidance systems using V2V communications. Automotive manufacturers working with the U.S. DOT established a consortium for a vehicle safety communications project [2]. This consortium identified more than 75 vehicle application scenarios and selected eight safety application scenarios for further study. Connected vehicle applications can be divided into three types, according to their objectives: 1) safety, 2) mobility, 3) environmental applications [3]. Safety applications can increase situational awareness and prevent crashes through wireless communication. Mobility applications can provide real-time and multi-modal traffic data for travelers, operators, and agencies. Real-time traffic information from connected vehicles can be used to improve the overall road environment by enabling travelers to avoid congested routes. Connected vehicle applications can also be categorized into event-driven and periodic applications, using the transmission mode [2, 4]. In event-driven applications such as forward collision warning and road condition warning applications for safety, the transmission is sent by some event, such as an incident situation. Event-driven applications need a shorter update interval than periodic application in order to prevent secondary accidents. Most mobility and environmental applications can be categorized as periodic applications, in which transmissions are sent automatically at regular intervals.

To assess the feasibility of available connected vehicle applications, the performance of these applications needs to be measured, and many measurements are used to investigate the performance of connected vehicle systems. Some studies have used information propagation via wireless communication to measure the performance of V2V communication. The further and quicker propagation of traffic incident information is important for traffic incident management because traffic incidents cause secondary incidents, and about 20 percent of all incidents are secondary incidents [5]. If an incident or mechanical breakdown on the link disables a vehicle, this information needs to be delivered to approaching traffic far and quickly. Shladover et al. [6] used an average wireless message propagation distance to measure the performance of cooperative vehicle systems (CVS) based on the market penetration rate of equipped vehicles and traffic density. The distance of message propagation increased as the market penetration rate of equipped vehicles and traffic density increased. This distance of message propagation also increased rapidly as the ratio of the communication range to the mean separation between vehicles increased. Jung et al. [7] studied the performance of inter-vehicle communications (IVC) using a communication network simulator (ns-2). The information propagation distance was measured to investigate the success rate by setting one vehicle as an information source. Results showed that the average maximum information propagation distances generally increase as the transmission range increases, because shorter transmission range and low traffic density negatively affects the message propagation in IVC over multiple vehicles. However, this study considered only one level (10%) of market penetration level for equipped vehicles. Yang and Recker tested traffic information propagation and probability of communication success in freeway and arterial networks within a simulation framework [8]. The maximum information propagation distance was measured based on various combinations with market penetration rate of IVC-capable vehicle, communication radius range, traffic conditions, and level of service (LOS) under incident conditions. This study also used a hypothetical study area with a simple grid network.

Connected vehicles can be used as probe vehicles to monitor and control real-time traffic information such as travel time, speed, and delay. The error rate of travel time estimated by connected vehicles has been used to measure the performance of connected vehicle applications. Rim et al. estimated lane-level travel times under V2V and vehicle-to-infrastructure (V2I) based traffic information systems [9]. The error rate of travel time estimation is 6% to 9% when the penetration of equipped vehicles is more than 20%. Li et al. used vehicle–infrastructure integration probe data to measure arterial performance in real time [10]. Oh et al. evaluated the performance of travel time estimation models using GPS and V2V communications under normal and incident traffic conditions [11]. The V2V communication range, the market penetration rate of equipped vehicles, and the travel time aggregation interval were investigated as the functional requirements. The speed estimation error by connected vehicles has also been used to assess the performance of connected vehicle applications or real-time traffic information systems using probe vehicles. Argote et al. used Connected Vehicle data to develop estimation methods for measures of effectiveness (MOEs) and determine the required penetration rates for each MOE: average speed, delay, number of stops, and acceleration noise [12]. The average speed was estimated by the total distance traveled and total time spent of connected vehicles. The average speed can be estimated accurately when the penetration rate is higher than 50% within a 10% of the error. Li et al. developed a probe sample size model to estimate an average link speed using different penetration rates of probe vehicles, speed estimation interval, and probe report interval [13]. The average link speed was more accurate as the penetration rate of probe vehicles increased and probe report interval decreased.

Estimating the critical market penetration rate of equipped units is one of the most important factors in evaluating the feasibility of deploying new transportation applications or services. There are no specific guidelines for the required market penetration rate of equipped vehicles, although some studies used market penetration rate as a variable to measure the performance of connected vehicle applications. Some studies measured the minimum required market penetration rate of equipped vehicles with communication devices for connected vehicle applications. Barria and Thajchayapong found that a penetration rate of at least 20% is required to detect and classify traffic anomalies with low false alarm rates [14]. Mustafa Ergen introduced a closed mathematical formula to investigate the critical market penetration rate of equipped vehicles [15]. The information propagation distance was calculated according to different market penetration rates of equipped vehicles and LOS. Ergen concluded that the critical market penetration rate of equipped vehicles for most of the V2V applications is 10%.

Though various measurements have been used to assess the performance of connected vehicle applications in previous studies, they have all used hypothetical study areas with simple networks. Moreover, none of the studies have determined the required minimum level of deployment of connected vehicle applications based on combinations of various parameters, such as market penetration rate of equipped vehicles, wireless communication coverage, and traffic density. Our study assesses the performance of selected applications in a realistic and large network and determines the required minimum level of deployment for each application in various scenarios. This paper is organized as follows. The next section presents the objectives and approach of this study. The following methodology section explains the study flow, including selecting study site, identifying equipped and connected vehicles, and measurements for each application. The results section investigates the performance and required minimum level of deployment for each application.

STUDY APPROACH

Connected vehicle technologies can provide local and area-wide traffic management solutions, but connected vehicle based applications have not yet been deployed in the real world. However, many research projects have identified available applications and evaluated their feasibility. Connected vehicle applications and technologies are still in the stage of field testing and have been tested under real-world operating conditions at several connected vehicle test beds. Prior to real-world experiments, simulation study is always conducted to assess the impacts and to define the variables and conditions that needs to be executed in the real world. Most previous studies used simple and hypothetical networks; a realistic and large network is needed to further assess the performance of connected vehicle applications. The required minimum level of deployment for connected vehicle application needs to be determined according to the type of application. In the early stages of deployment, connected vehicle applications may perform insufficiently, due to the low market penetration rate of vehicles equipped with wireless communication devices.

This study has two objectives: 1) to measure the performance of V2V applications and 2) to determine the required minimum level of deployment for V2V applications. In our previous study, we developed a simulation model to represent a connected vehicle environment. That study identified connected vehicles among equipped vehicles with wireless communication devices in a realistic and large network based on various scenarios with wireless communication coverage and market penetration rates of equipped vehicles in TRANSIMS [16]. TRANSIMS differs from current travel demand forecasting methods and software in its underlying concepts and structure such as a consistent and continuous representation of time; a detailed representation of persons and households; time-dependent routing; and a person-based microsimulator. TRANSIMS assigns all vehicles onto the network based on each individual socio-economic characteristic (e.g., income, age, trip purpose, etc.). It traces the movement of people as well as vehicles on a second-by-second basis through microsimulator module [17]. TRANSIMS also can map the location of the individual vehicle in the network at every second based through ArcGIS. Route planner in TRANSIMS utilizes a time-dependent, individually-based route choice model that is suitable for considering each individual response to the value of the travel information provided [18, 19]. This study considers two types of connected vehicle applications: event-driven and periodic application. The performance of each event-driven and periodic application is assessed by each selected measurement under 3X3 scenarios with wireless communication coverage and market penetration rates of equipped vehicles. The required minimum level of deployment for each application to obtain a reliable traffic management solution is then determined.

METHODOLGY

While most previous studies used simple and hypothetical networks to assess the performance of connected vehicle applications, this study uses a realistic and large network. The city of Alexandria, VA, USA outside of Washington D.C. was selected as a study area because TRANSIMS provided the dataset for Alexandria as the test case. This dataset includes all the input data needed to represent and code the highway and transit networks. This network has 3,653 links and about 420,000 trips. The size of study area is around 44 km^2 ($17\ mi^2$), bordered by I-395 (Henry G Shirley Memorial Highway), I-495 (Capital Beltway), and State Route 400 (FIGURE 1).

FIGURE 1 Study area.

Our previous study developed a simulation model to represent a connected vehicle environment in TRANSIMS [16]. That study determined the dispersion of equipped vehicles in time and space in an urban network by tracing all vehicles (including equipped vehicles) on a second-by-second basis from the provided snapshot data, one of the output files from the microsimulator module in TRANSIMS. In TRANSIMS, vehicles equipped with wireless communication devices are assumed as having a specified vehicle type and subtype. The equipped vehicles can communicate with nearby equipped vehicles to exchange traffic and travel information such as speed and location. As connected vehicles, these equipped vehicles receiving information are also able to relay their information to nearby equipped vehicles within the wireless communication coverage through a multi-hop based wireless relay (repeater). This study has other assumptions to represent a connected vehicle environment in TRANSIMS: 1) There are no obstructions that block wireless communications to guarantee line-of-sight of wireless communication in the network; 2) The wireless communication used in this study doesn't have a packet loss and delay.

Equipped vehicles were distributed onto the network according to different market penetration rates of equipped vehicles in the population synthesizer module of TRANSIMS. Valid wireless communication among equipped vehicles was also identified by measuring distances between all equipped vehicles using x and y coordinates from snapshot data based on various scenarios with wireless communication coverage and market penetration rates. A connected vehicle was defined as an equipped vehicle that is able to communicate with another equipped vehicle when both vehicles are within a defined wireless communication coverage distance. This study uses the same methodology used in our previous study to identify equipped vehicles and valid wireless communication.

This study considers two types of connected vehicle applications: event-driven and periodic application. Two different measurements were calculated to assess the performance of each connected vehicle application and determine a required minimum scenario for each application (FIGURE 2). The first measurement is a distance of information propagation to investigate the performance of event-driven application under incident traffic conditions. One stopped and equipped vehicle on a selected link, Henry G Shirley Memorial highway in the study area, was assumed as the disabled vehicle and information source. To represent incident traffic conditions in TRANSIMS, a land use file among network data was used to block one selected lane during the incident periods [20]. Then, the snapshot file was updated to add the disabled equipped vehicle on the blocked lane as an incident information source after finishing the simulation run of TRANSIMS. After identifying equipped vehicles and valid wireless communication through MATLAB coding, the distance of incident information propagation through multi-hop wireless relay was measured at every 10 seconds for 30 minutes by calculating the distance between the disabled vehicle and the last equipped vehicle receiving incident information from the disabled vehicle. Each distance of information propagation was measured to investigate the performance of event-driven applications for each scenario with different market penetration rates and wireless communication coverage.

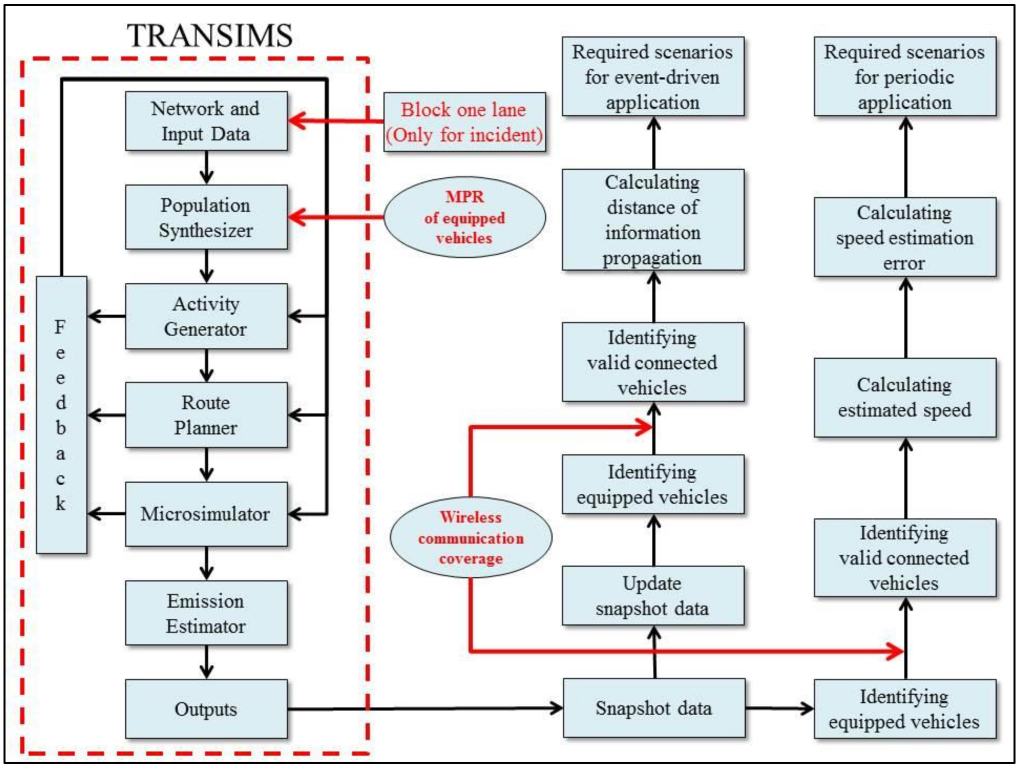

FIGURE 2 Study flow chart.

Connected vehicles can be used as probe vehicles to estimate real-time traffic information, such as speed, travel time, and delay. The error rate of real-time information such as speed or travel time estimated by connected vehicles can be used to measure the performance of periodic application. The speed estimation error is used as another measurement to investigate the performance of periodic application under non-incident condition in this study. The snapshot data includes the speed of each individual car or transit vehicle on a second-by-second basis. The speed of the selected roadway was estimated by the speed of the connected vehicles. This estimated speed by the connected vehicles was then compared with an observed speed of all vehicles, in order to calculate the speed estimation error. The speed estimation error was also calculated based on different market penetration rates and wireless communication coverage. Finally, the required minimum levels of deployment for both event-driven and periodic applications were determined according to the proposed methodology. Nine scenarios were analyzed based on two variables, market penetration rate (10%, 20%, and 40%) of equipped vehicles and wireless communication coverage (100m, 200m, and 500m) during two different time periods: morning peak and non-peak times. The wireless communication coverage can be up to 1,000 meters according to standards for the dedicated short range communications (DSRC) [21, 22]; but, because the real network has obstructions such as buildings and heavy vehicles, the maximum wireless communication coverage in this study is limited to 500 meters.

RESULTS

Measurement of the performance of event-driven application

The distance of incident information propagation from one disabled equipped vehicle through multi-hop wireless relay was measured to investigate the performance of event-driven application like forward collision warning or road condition warning applications under incident traffic conditions. To represent the incident situation, we introduced a disabled equipped vehicle for 30 minutes, from 8:00 to 8:30 a.m. on a selected link, the Henry G. Shirley Memorial highway in Alexandria. The distance of information propagation for each scenario with different market penetration rates and wireless communication coverage was then measured every 10 seconds for 30 minutes (8:00-8:30 a.m.) during the morning peak. Each result in this section is the averaged value from 10 simulation runs in TRANSIMS for each scenario. The average distance of information propagation during 30 minutes increases as the market penetration rate of equipped vehicles and wireless communication coverage increase (TABLE 1). The wireless communication coverage has a greater influence on the distance of information propagation than the market penetration rate of equipped vehicles. An increase of the wireless communication coverage from 100m to 200m produces a 1,691% (from 90.7 to 1,625.1 meters) increase in the average distance of information propagation when the market penetration rate of equipped vehicles is 10%. However, the average distance of information propagation increases by only 20% (from 90.7 to 108.4 meters) when the market penetration rate of equipped vehicles is changed from 10% to 20%, in the case of 100m of wireless communication coverage. Most links on the Henry G. Shirley Memorial highway are covered by the incident information when the wireless communication coverage is 500 meters. This means that most equipped vehicles in our study area approaching the incident location can receive this incident information through V2V communication because the distance between incident location and boundary of selected freeway is 5,850 meters.

TABLE 1 Average distances of information propagation

		Peak time (8-8:30 a.m.)			Non-peak time (6-6:30 a.m.)		
Market penetration rate of equipped vehicles		10 %	20 %	40 %	10 %	20 %	40 %
Wireless communication coverage	100m	90.7	108.4	205.7	30.5	43.5	72.3
	200m	1625.1	**2646.6**	**4054.3**	229.4	429.6	985.6
	500m	**5742.9**	**5783.9**	**5802.5**	**3789.7**	**4901.3**	**5560.6**

Density can have a major impact on the performance of connected vehicle applications as some previous studies (such as those listed in the introduction of this paper) used different traffic volumes or densities as one of their variables. This study measured the distance of information propagation in the morning non-peak time, from 6:00 to 6:30 a.m. to consider low traffic volume conditions. We introduced an incident situation with a disabled equipped vehicle at 6:00 a.m.

lasting 30 minutes. All other simulation and traffic conditions were the same as those for the peak time case. The resulting average distance of information propagation in non-peak time displays the same pattern as the results in peak time: average distance increases as the market penetration rate of equipped vehicles and wireless communication coverage increase (TABLE 1). However, all average distances of information propagation of each scenario in the non-peak time are shorter than those in the peak time. The average distance of information propagation in non-peak time decreases significantly from 2,646.6 to 429.6 meters, as compared to the results in peak time when the market penetration rate of equipped vehicles is 20% and wireless communication coverage is 200m. This means that a higher density of traffic allows the traffic information to be transmitted farther. About 7,170 vehicles are on Henry G Shirley Memorial highway during 30 minutes of morning peak time, while there are 4,730 vehicles during morning non-peak time.

Though some previous studies have used the distance of information propagation to measure the performance of connected vehicle application, they have not determined the critical level of information propagation distance required to deploy connected vehicle application. One previous study provided the critical distance of information propagation for cooperative vehicle system use cases [6]. The range of information or message propagation distance for stopped–slow vehicle warnings and post-crash notifications to neighboring vehicles is between 50 and 1,500 meters. An information propagation distance of more than 1,500 meters for the event-driven application in peak time would require a 10% market penetration rate and 200m of wireless communication coverage (TABLE 1). In other words, at least 200m of wireless communication coverage are required to deploy the event-driven application, although the market penetration rate of equipped vehicles can be as low as 10%. During the non-peak time, the wireless communication coverage should be longer than 500m to operate the event-driven application.

However, it's difficult to conclude that the critical distance of information propagation is 1,500 meters for every network, because the distance of information propagation via connected vehicles also depends on other parameters, such as road networks, traffic pattern, location of event, and event duration. An individual level of distance of information propagation is needed for each network having different parameters. The distance between incident location and the nearest exit on the upstream can be used to determine the critical distance of information propagation for event-driven application like forward collision warning. The incident information should be delivered to give warning and detour information to vehicles that are approaching the incident in the same direction of traffic. The disabled vehicle was located on Henry G. Shirley Memorial highway (I-395) between Exit 3 and Exit 2 for 30 minutes to represent the incident situation. The minimum distance of information propagation is 2.5 km for this study area, because the distance between the incident and first exit on the upstream is 2.5 km. (In other words, approaching drivers can only make a detour to avoid the incident if they receive the information while they are at least 2.5 km from the incident.) When the critical distance of information propagation is 2.5 km, the required minimum scenario for event-driven application in peak time is 20% of market penetration rate and 200m of wireless communication coverage (TABLE 1). Only three scenarios have a longer distance of information propagation than 2.5 km during non-peak time. These results show that event-driven application can be deployed reliably in the initial stage of deployment even when the level of market penetration rate of equipped vehicles is low, as long as wireless communication coverage is longer without wireless communication obstructions such as buildings, hills or large trucks. More factors on information propagation should be considered because results of distance can vary by location of disabled vehicle, location of selected link, event starting time, event duration time, and so on.

The number of all equipped vehicles connected with one disabled vehicle as an information source was also counted in both time periods (TABLE 2). The average number of multi-hops of connected vehicles has similar results to the average distance of information propagation. The average number of multi-hops of connected vehicles increases as the market penetration rate of equipped vehicles and wireless communication coverage increases. Additionally, wireless communication coverage is a more important factor in the number of multi-hops of connected vehicles than the market penetration rate. When the market penetration rate is 40% and wireless communication coverage is 500m, 310 connected vehicles in both directions are connected with the disabled vehicle during the morning peak. This means that 310 equipped vehicles can receive incident information from one disabled vehicle. However, only seven equipped vehicles can receive incident information via wireless communication during peak time when the wireless communication coverage is 100m with 40% of the market penetration rate. The average number of multi-hops of connected vehicles in the non-peak time also significantly decreases as traffic volume decreases. When the market penetration rate is 40% and wireless communication coverage is 500m, 111 vehicles are connected in both directions with the disabled vehicle during non-peak time.

TABLE 2 Average numbers of multi-hops of connected vehicles

		Peak time (8-8:30 a.m.)			Non-Peak time (6-6:30 a.m.)		
Market penetration rate of equipped vehicles		10 %	20 %	40 %	10 %	20 %	40 %
Wireless communication coverage	100m	3.1	3.7	6.9	1.6	1.9	2.6
	200m	49.4	96.5	204.0	3.9	7.1	19.7
	500m	229.8	245.6	310.5	43.4	71.0	111.7

Measurement of the performance of periodic application

The error rate of speed estimated by connected vehicles is used to measure the performance of periodic application for mobility or environment applications, such as real-time information management application under normal traffic conditions. We computed the average speed every 10 seconds using the speeds of each vehicle including connected vehicles obtained from snapshot data according to scenarios with different market penetration rate and wireless communication coverage. The speed estimation error is calculated by the difference rate between the estimated speed by connected vehicles and actual speed of all vehicles in the following equation:

$$\text{Speed estimation error}(t) = \left|\frac{V(t) - V_e(t)}{V(t)}\right| \times 100 \qquad (1)$$

Where,

$V(t)$ = Actual speed of all vehicles at time step t and

$V_e(t)$ = Estimated speed by connected vehicles at time step t.

The speed estimation error was computed every 10 seconds during 30 minutes from 5 simulation runs for each scenario in morning peak and non-peak times. FIGURE 3shows one result of the speed estimation error with 200m of wireless communication coverage in morning peak time on the selected freeway. Our study area has two freeways, one expressway, and four major arterials as the higher functional class of roadways which traditionally carry more than 70% of all vehicles travels. One freeway (Capital Beltway, I-495) and one major arterial (King Street) were selected for measurement of the performance of periodic application. There are about 21,900 vehicles in morning peak and 12,160 vehicles in non-peak time in the whole network. About 3,370 and 2,370 vehicles exist on the selected freeway and about 3,360 and 2,480 vehicles exist on the selected major arterial in morning peak and non-peak times, respectively.

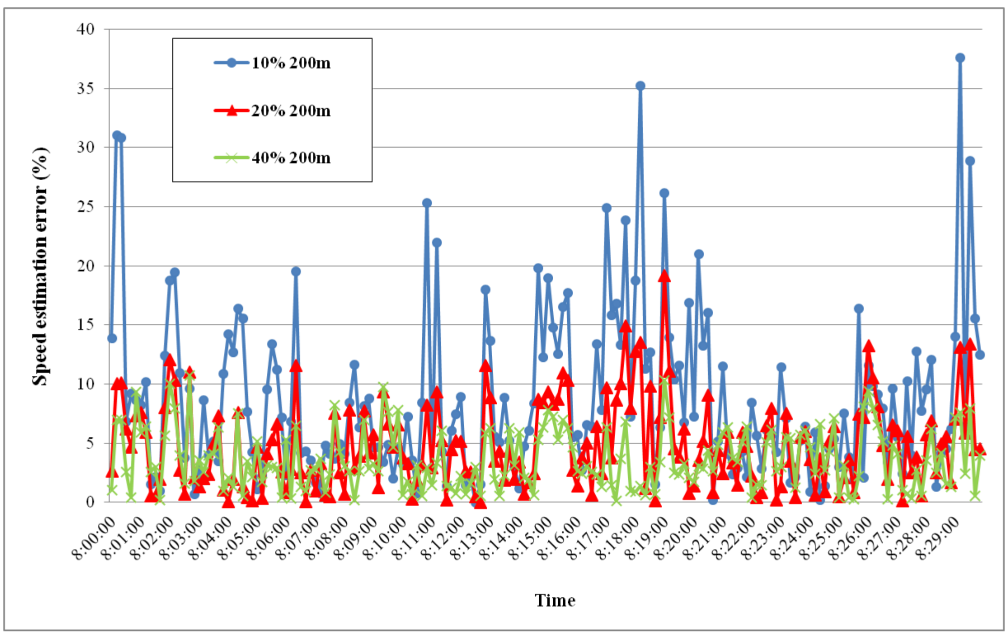

FIGURE 3 Speed estimation errors with 200m wireless communication coverage in peak time on the freeway.

As the market penetration rate of equipped vehicles and wireless communication coverage increase, the speed estimation error on each roadway decreases, at both peak and non-peak times (TABLE 3). The speed estimation error has the lowest value (2.2 %) when the market penetration rate is 40% and wireless communication coverage is 500m in non-peak time on the selected freeway. The market penetration rate of equipped vehicles has more impact on the performance of periodic application than the wireless communication coverage. The increase in market penetration rate from 10% to 40% for the same wireless communication coverage of 100m produced a decrease of 17.15 % in the average speed estimation error during peak time on the freeway. The increase of wireless communication coverage from 100m to 500m, however, produced only a 14.39 % decrease of speed estimation error when the market penetration rate is 10%. Both selected roadways in all scenarios have lower speed estimation errors in non-peak time than in peak time. A low traffic density condition with less congestion in non-peak time (6-6:30 a.m.) can have lower speed estimation error in our study. Results of freeway and major arterial have a difficulty to be compared directly with the same measurement because each roadway has a different functional class. However, the selected major arterial in all scenarios has higher speed estimation errors than freeway in both peak and non-peak times. Speeds of vehicles on arterials can be more changeable than freeways because traffic signals much impact on arterial operations.

TABLE 3 Average speed estimation error (%) on the selected roadways

Roadway	Analysis period		Peak time (8-8:30 a.m.)			Non-Peak time (6-6:30 a.m.)		
	Market penetration rate of equipped vehicles		10 %	20 %	40 %	10 %	20 %	40 %
Freeway	Wireless communication coverage	100m	21.22	**8.11**	**4.07**	17.11	**7.86**	**3.67**
		200m	12.07	**5.06**	**2.82**	11.42	**4.94**	**2.51**
		500m	**6.83**	**3.73**	**2.50**	**6.67**	**3.58**	**2.24**
Major arterial		100m	35.38	22.54	12.39	28.44	15.30	**7.99**
		200m	23.26	15.35	**9.75**	19.97	10.48	**6.56**
		500m	18.41	13.29	**9.36**	14.67	**9.17**	**6.14**

The speed estimation error is also used to determine the required minimum level of deployment for periodic application. According to most previous studies, the error rate of real-time traffic information estimated by connected vehicles or probe vehicles to reliably manage traffic should be less than 10%. Most scenarios on the freeway have lower speed estimation error than 10% (TABLE 3). The required minimum level of deployment for periodic application is a scenario with 10% market penetration rate and 500m of wireless communication coverage for the freeway in peak time. Periodic application can be deployed on this freeway even when the level of market penetration rate of equipped vehicles is low in the initial stage of deployment, as long as wireless communication coverage is longer than 500m. However, a high level of market penetration rate for equipped vehicles is required to deploy the periodic application on the selected major arterial because two scenarios in peak and all scenarios in non-peak time with 40% of market penetration rate have lower speed estimation error than 10%.

CONCLUSION

This paper investigates the performance of V2V applications and determines the required minimum level of deployment for V2V applications in an urban network. The distance of information propagation and speed estimation error are used to measure the performance of event-driven and periodic applications with different market penetration rates of equipped vehicles and wireless communication coverage in both morning peak and non-peak times. As the market penetration rate and wireless communication coverage increase, the distance of information propagation increases while speed estimation error decreases in our study area. For event-driven applications, wireless communication coverage is the major factor because it has a greater influence on the distance of information propagation. For periodic application, however, the market penetration rate of equipped vehicles has more impact on performance than the wireless communication coverage, because the speed estimation error more decreases as the market penetration rate increases. The performance of event-driven improves in the higher traffic density conditions of peak time while the performance of periodic application improves in the lower traffic density conditions of non-peak time. The required minimum level of deployment for each application is determined for various scenarios. These study findings will be useful for deployments of connected vehicle applications. Notably, event-driven applications can even be reliably deployed in the initial stage of deployment despite the low level of market penetration, as long as sufficient wireless communication coverage is provided.

Future works will consider more factors impacting the performance of connected vehicle applications because the performance of event-driven vehicle application can vary with other parameters, such as road networks, traffic pattern, location of event, and event duration. Wireless communication signal interferences such as packet loss or delay also will be considered in future works. The speed (or travel time) estimation error will be measured for the lower functional class of roadways like minor arterial or collector during several time periods. Other measurements for the performance of connected vehicle application can be investigated with the same methodology.

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