Computer-Aided Civil and Infrastructure Engineering **23** (2008) 575–595

Evaluation of Information Applications of a Self-Organizing Distributed Traffic Information System for a Large-Scale Real-World Traffic Network

Xu Yang

Institute of Transportation Studies, University of California, Irvine, CA 92697

&

Will Recker*

Institute of Transportation Studies and Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697

Abstract: *This article presents an evaluation of the system performance of a proposed self-organizing, distributed traffic information system based on vehicle-to-vehicle information-sharing architecture. Using microsimulation, several information applications derived from this system are analyzed relative to the effectiveness and efficiency of the system to estimate traffic conditions along each individual path in the network, to identify possible incidents in the traffic network, and to provide rerouting strategies for vehicles to escape congested spots in the network. A subset of vehicles in the traffic network is equipped with specific intervehicle communication devices capable of autonomous traffic surveillance, peer-to-peer information sharing, and self-data processing. A self-organizing traffic information overlay on the existing vehicular roadway network assists their independent evaluation of route information, detection of traffic incidents, and dynamic rerouting in the network based both on historical information stored in an in-vehicle database and on real-time information disseminated through intervehicle communications. A path-based microsimulation model is developed for these information applications and the proposed distributed traffic information system is tested in a large-scale real-world network. Based on simulation study results, potential benefits both for travelers with such equipment as well as for the traffic system as a whole are demonstrated.*

1 INTRODUCTION

Federal, state, and local public expenditures on transportation have exceeded $100 billion annually over the last decade; another $600 billion annually is spent on purchasing, operating, and maintaining private household vehicles. In California, for example, each year, 24 million vehicles travel 155 billion vehicle-miles over 166,000 miles of streets and highways; travel in urban areas has increased 32% in the last 10 years with a corresponding 26% increase of vehicle-hours of delay. Even so, urban freeway and arterial networks are managed based on only the coarsest of information: sparsely distributed inductance loop detectors buried in traffic lanes transmit single bits of data indicating the presence of a vehicle over wires to a traffic control center. As a result, traffic congestion is fast becoming one of the principle

---

*To whom correspondence should be addressed. E-mail: *wwrecker@uci.edu*.

Published by Blackwell Publishing, 350 Main Street, Malden, MA 02148, USA, and 9600 Garsington Road, Oxford OX4 2DQ, UK.

blocks to California and the whole country's economic development.

The emergence of digital broadband wireless communication systems, combined with advanced information technologies—geographic information systems (GIS), global positioning systems (GPS), scalable distributed computing architectures, and the Internet—may offer a gateway to a new era in transportation management. These new technologies are likely to impact every aspect of the transportation industry—automotive design, public agency management of transportation facilities, traveler services, travel behavior, traffic control, commerce, and public transit. The economic impacts from developing a better platform for sensing and managing transportation networks are thus nationally significant.

During the past 10 years or so, intelligent transportation systems (ITS) and its subarea, advanced traveler information systems (ATIS), have attracted considerable attention because of their promises to provide real-time traffic information to drivers to enable more efficient use of the existing network infrastructure. This is seen as an attractive alternative to building more roadways, an option that is becoming increasingly difficult due to both financial and environmental constraints. The typical traffic information systems proposed under ITS usually involve a central authority collecting traffic data from roadway networks via sensing detectors, then processing data and disseminating processed data to individual drivers with specific communication equipment. Some of these types of centralized systems are already provided by automakers in the market, such as OnStar system (OnStar Corp.). There are also initiatives, such as ADVANCE in Chicago, Illinois, designed to study the operation and effectiveness of such systems (Boyce et al., 1994). However, centralized traffic information systems have some serious shortcomings. The systems need substantial public investment to launch any implementation that would be effective; they are rigid, difficult to maintain and costly to upgrade; also, they are susceptible to such catastrophic events as terrorism or system failure.

In this article, we evaluate the feasibility of a fully distributed traffic information system based on information exchange among vehicles with certain wireless communication equipment. This system does not need any public infrastructure installed in the network; rather, it relies only on on-board devices installed in at least some vehicles traversing the roadway network. Because the proposed system is totally independent of any public infrastructure, it will be market-driven and self-maintained.

In the proposed system, we are faced with a very dynamic environment composed of fast-moving vehicles, which, from the communication perspective, translates into rapidly changing network topologies. In addition, the data that are exchanged between vehicles is time sensitive; therefore, it demands reliable wireless communication. The key idea of the concept arises from information propagation through the entire traffic network via the intervehicle communication (IVC) system. Applications of the information system are intrinsically based on this information propagation; however, penetration of the necessary technology to the fleet of vehicles will be gradual. A "mixed" network of IVC-capable vehicles and non-IVC-capable vehicles will exist for a long-term period. In assessing the potential of IVC in transportation management, the first question that needs to be asked is: what IVC market penetration rate among vehicles in the network is needed for information propagation to provide useful information pertaining to the whole network. The second question that should be studied is related to the communication requirements for the system; specifically, what IVC system data rate/bandwidth is needed to make dissemination of information faster than the attendant traffic/vehicle wave propagated in the network. In this article, we attempt to give some preliminary answers to these two questions based on a simulation of a real-world network.

The principal impediments to the study of the proposed system are related to two major difficulties. One is its complexity as a nonlinear and self-organizing system, which is not easily modeled analytically. Although some initial analytical and simulation results for proposed systems have recently appeared in the literature (Briesemeister et al., 2000; Rohling and Ebner, 2001; Bogenberger and Kosch, 2002; Kosch et al., 2002; Füssler et al., 2003), most of these works have arisen from the computer science/network research field and have focused on the problem of *ad hoc* routing algorithms for IVC traffic information system applications. The most comprehensive work to date on such systems arising principally from the transportation application has been due to Ziliaskopoulos and his colleagues (Ziliaskopoulos and Zhang, 2003) in America and to European investigators participating in the FleetNet project (Mauve et al., 2001; Kaesemann et al., 2002; Festag et al., 2004). The other difficulty is that because such a system does not exist currently and nor have any similar systems in real transportation systems ever existed before, it is virtually impossible to investigate the system empirically. Consequently, in this research, simulations at a microscopic level are chosen as the main approach in the entire study process: for modeling vehicle movements in the traffic network, for modeling IVC between neighboring vehicles with IVC equipments, and for modeling driver's route-choice behavior with traffic information perception via the IVC system. The relevant statistical outputs are calculated and recorded for each individual vehicle in the simulation, and then these records are aggregated and analyzed to evaluate system performance.

The objective of this article is to test the feasibility of evolving a self-organizing, distributed traffic information system based on real-time vehicle-to-vehicle information exchange. Using a microsimulation platform, we focus on several applications of the proposed system: (1) the usefulness of the real-time information to individual drivers in determining potential en-route adjustments to their travel paths, (2) the derivation of link-based traffic information for automatic incident detection algorithms based on historical and real-time information, and (3) network-wide dynamic vehicle on-line routing. Although the required microsimulation modules and their organization are not identical in each specific application, they share a common modeling assumption—vehicles with IVC capabilities generate traffic information based on their own traveling experiences, then broadcast their traffic information to their IVC-capable neighbors, who then update their own traffic information databases. In developing the communications framework, certain origin (sender) and destination (receiver) information filtering processes are developed within the simulation platform to reduce communication and information processing workload. Our focus is on the organization of the simulation modules and the scenario designs for each simulation study for various information applications to show the feasibility and the potential benefits from the proposed traffic information system.

The remainder of this article is structured as follows. In the next section, a detailed description of the overall microsimulation platform used to model IVC-based traffic information systems is given, including both pretrip and in-trip modules. In Section 3, we describe the simulation modeling of different information applications in a large-scale real-world traffic network, including investigation of path-based information collection and evaluation via intervehicle information exchange, testing link-based automatic incident detections, and studying dynamic vehicle on-line navigation in the network according to information disseminated in the information system. The final section summarizes the findings and conclusions of this article and provides suggestions for future modeling efforts.

2 MODELING A SELF-ORGANIZING DISTRIBUTED TRAFFIC INFORMATION SYSTEM

In developing a simulation framework for a traffic information system built upon a vehicle-to-vehicle information-sharing architecture, many components need to be modeled, including roadway networks, vehicles with and without information-sharing capabilities traveling in the roadway network, and drivers in moving vehicles with or without shared traffic information. The interactions among these components, including interactions between vehicles and roadway networks, interactions among vehicles with peer-to-peer communication capabilities, and interactions for drivers and their received traffic information must be included in the modeling framework to study applications based on the proposed system. Due to extremely complicated relationships among these components, simulation approaches are arguably the only practical means by which to model the information exchange system and the drivers' behaviors within this system. Because information sharing among individual vehicles is the foundation of the proposed traffic information system, vehicle representation at the individual level in the simulation environment is also highly preferred, leading to our selection of microscopic simulation to construct our modeling framework—each individual vehicle either with or without information-sharing capability is modeled as an entity in detail during its entire trip in the traffic network.

2.1 Simulation modeling framework

2.1.1 Overall framework. Within our microsimulation modeling framework, certain IVC-capable vehicles in the traffic network—those equipped with IVC systems, GIS, GPS, on-board navigation systems, and in-vehicle computing processors—generate floating car data based on their own experiences, exchange traffic information through peer-to-peer communications, and process incoming traffic information in real time using their on-board processors. In our model, such vehicles can evaluate the path information for its own path, automatically run incident algorithms to identify possible congestion resulting from incidents in the network, and dynamically navigate the network following changeable paths based upon its own reroute decisions. Vehicles without such equipment are assumed to move in the traffic network following the fixed route decided before their respective departures and without benefit of real-time information. Figure 1 shows the simulation modeling procedure (both before and during their trips) for IVC-capable vehicles/drivers; the corresponding simulation modeling procedure for non-IVC-capable vehicles/drivers is shown in Figure 2. Detailed descriptions of these modeling procedures within our simulation framework are presented in following subsections.

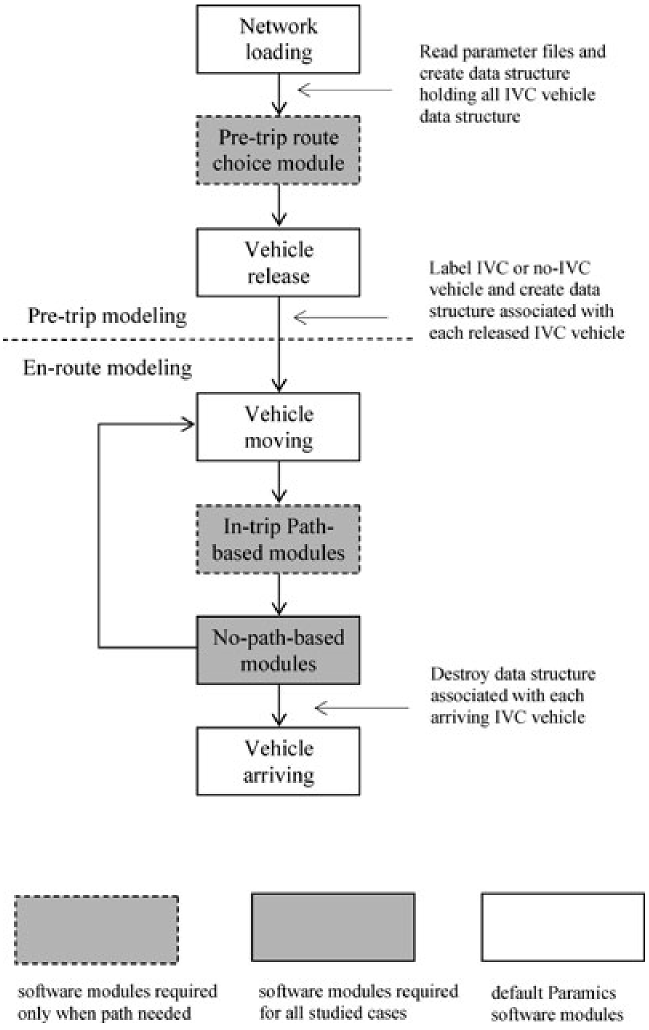


Fig. 1. Modeling procedure for IVC vehicles.

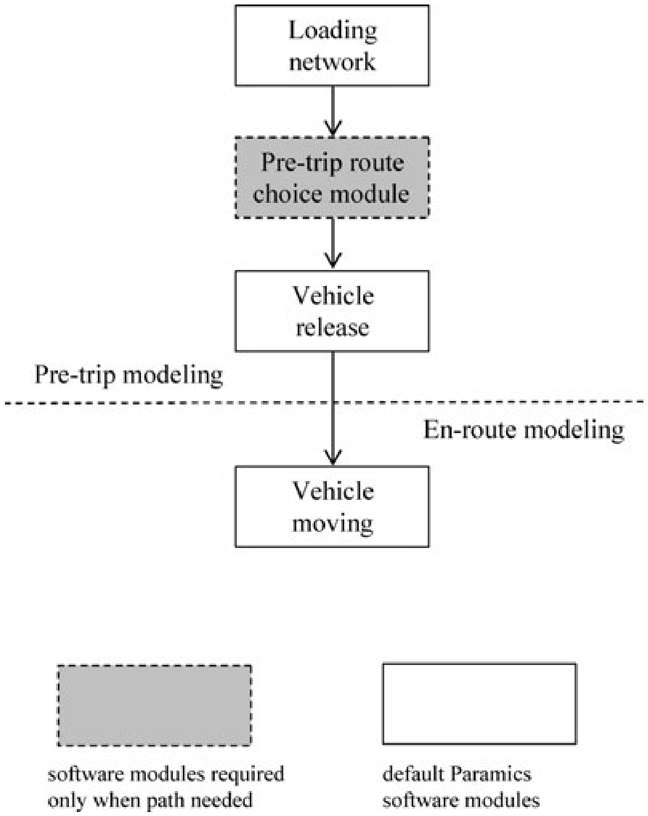


Fig. 2. Modeling procedures for non-IVC vehicles.

2.1.2 Simulation module implementations. Because the primary research goal of this study is to examine the relationship between traffic flow in a real-world traffic system and its influence on the flow of information arising from the proposed decentralized and autonomous information system, there are distinct advantages to using a widely accepted and well-calibrated simulation model over building our own simple, nonindependently validated model. Some 100 or so (either commercial or academic) microscopic traffic simulation models have been developed. Some of the more prominent recent representatives of microsimulation models are: AIMSUN2 (TSS, 2000), CORSIM (FHWA, 1996), MITSIM (Yang and Koutsopoulos, 1996), Paramics (Quadstone Ltd, 2002), and VISSIM (PTV AG, 2001). All of these microscopic models can simulate the movement of each individual vehicle in the system under the presumption that vehicle guidance does not exist. However, few can be used to test ATIS at a microscopic level because the communication between drivers and information sources cannot be modeled in most microscopic simulators without an external plug-in application programming interface (API). From among these, we chose the Paramics microsimulation model as the base simulation tool in our framework primarily because its API library facilitates customizing and extending many features of the underlying simulation model. We note that, although the algorithms developed here contain some features that are specific to Paramics, they generally can be adapted to other microsimulation platforms that support APIs with little difficulty.

In our simulation, Paramics functions only as a vehicle mover based on its built-in car-following and lane-changing models; it functions beneath a decentralized information system simulation layer that has been built based upon IVC technologies. To model the IVC traffic information system and its applications, a number of new modules were designed. These included: pre-trip static k-shortest paths calculation and route-choice behavior modules; an IVC-capable vehicle traffic information generation module; an IVC module; an IVC-capable vehicle information processing module; path evaluation modules; an incident detection module; and

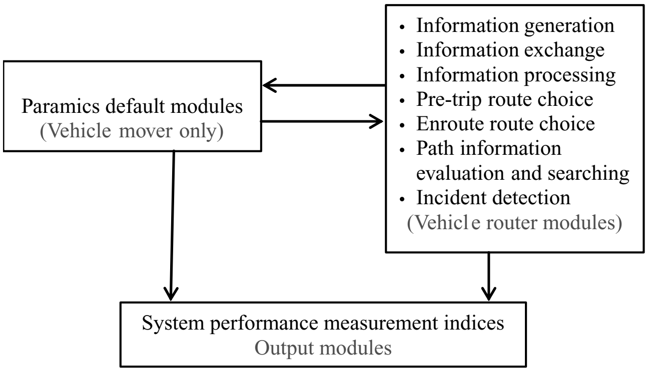


Fig. 3. Software architecture for simulation modeling framework.

enroute dynamic shortest path calculation and rerouting behavior modules. These are developed as API plug-ins to such built-in modules as the car-following and lane-changing modules. Additional new modules calculating performance measurement indices specifically for IVC applications are also developed with the API function, and integrated with the other new modules. The default traffic microsimulation model then functions as a "vehicle mover" following exact orders from these newly developed modules for route-choice decisions both before and during each trip, under the umbrella of the self-organizing, distributed traffic information system. Figure 3 shows the software architecture for these modules.

2.1.3 IVC modeling. IVC is modeled by the abstraction that neighboring IVC-capable vehicles may have opportunity to exchange traffic information with each other if the distance (D) between them is less than a predefined parameter—communication radius range (R). This abstraction in the simulation modeling does not focus on the specific intervehicle wireless communication technologies in any detailed way. Figure 4 shows a graphical representation of this abstraction for IVC modeling under different roadway scenarios considered in this article.

Each vehicle released into the network is labeled as being either IVC- or non-IVC-capable randomly, according to a predefined parameter—IVC market penetration rate—that represents the percentage of total vehicles in the traffic network with IVC capability.

At predefined time intervals—called the communication cycle—during the simulation, each IVC-capable vehicle traveling in the network probes neighboring IVC vehicles for information and processes that information, then broadcasts any processed information that it already has for possible consumption by other IVC vehicles within range. Each vehicle in the simulation updates its location and speed information only after each predefined time step interval.

Before loading the simulation program, we create a data file to store the group of combination values for all IVC parameters that are to be tested together in a single simulation run. All node coordinate values in the simulated traffic network are also read into data structures that are created by API modules for IVC modeling. In the API modules used later in the simulation, these node coordinate values are used together with each IVC vehicle's information and the link information on which that specific IVC vehicle is actually traveling, for calculating GPS coordinate values for each IVC vehicle at each simulation time step. A variable-size link list for each IVC-capable vehicle that is to be released into the traffic network in the process of the simulation is created and initialized to store all IVC vehicle data structures. Certain output files are also created by API modules to store simulation results that are calculated uniquely for IVC purposes and possible error messages.

The simulation begins with the releasing of vehicles from their respective origin zones; where and when each vehicle is released into the simulated network depends on the O/D demand input and built-in vehicle release modules. Immediately after each vehicle is released, a

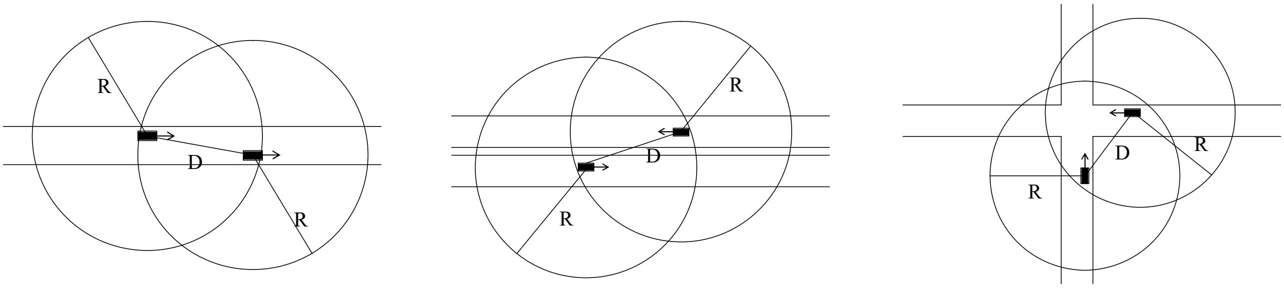


Fig. 4. Intervehicle communication modeling abstraction.

random number with value between 0 and 1.0 is generated in the API modules for IVC modeling. If this random value is less than the input value of the IVC market penetration rate, it is labeled as an IVC vehicle; otherwise, it is treated as a normal vehicle in the simulation. All API modules developed for IVC modeling deal only with IVC vehicles in the simulation; all vehicles without IVC capability in the simulation are handled by built-in modules.

For each IVC capable vehicle that is released, the IVC API modules create a data structure representing that specific IVC vehicle. All information related to this unique IVC vehicle, including: (1) vehicle ID, (2) direction in which the vehicle is moving, (3) link ID of the link through which the vehicle is just passing, (4) the total number and all vehicle IDs of IVC vehicles that are within the IVC communication radius range at this time step, and (5) information buffers to store traffic information and possible incident-related information from other IVC vehicles via peer-to-peer information exchange, are stored in this data structure. Such information stored in this data structure as vehicle ID, link ID of the link through which the vehicle is just passing can be accessed directly from the traffic microsimulation model's built-in API modules. Other information stored in the data structure, such as total number of IVC vehicles and the vehicle IDs of IVC vehicles that are in the IVC communication radius range at this time step and information buffers to store traffic information and possible incident-related information from other IVC vehicles via peer-to-peer information exchange, cannot be obtained from these built-in modules directly. This latter information is generated in our IVC API modules. This unique data structure is then inserted into the link list (created before the simulation starts) for all IVC vehicles in the simulation. Only when a particular IVC vehicle arrives at its destination, is the data structure created for this specific vehicle removed from the link list that holds data structures for all IVC vehicles currently simulated in the network.

At each time step in the simulation, we obtain the following information on each IVC vehicle moving in the network from the traffic microsimulation model's built-in API modules directly for this vehicle: (1) link ID of the link on which it is actually traveling, (2) lane number on this link on which it is currently traveling, (3) starting and ending nodes for this link, and (4) the distance from its current location to the end of this link. Because the GPS location coordinate values for each node in the simulation network are known, GPS location coordinate values can be generated easily for each IVC vehicle currently in the simulated network, and the distance between any two IVC vehicles can be calculated easily once the GPS location coordinate values for these two vehicles are known. For each individual IVC vehicle currently in the network, the calculations for the distances between itself and all other IVC vehicles are stored as members in the link list of all IVC vehicles currently in the simulated network. If the value for the distance between it and any other IVC vehicle (except itself) is less than the input value of the IVC communication radius range, the vehicle ID of that IVC vehicle is stored in the data structure of this specific IVC vehicle. The total number of IVC vehicles within IVC communication radius range is also stored into its data structure.

Information buffers are created for traffic information and incident-related information and initialized to "empty" immediately after an IVC vehicle is released. How these buffers store information depends on which traffic information packet format is to be evaluated in the simulation. At each simulation time step and IVC communication cycle (usually the same value), each IVC vehicle currently moving in the network finds all other IVC vehicles in the IVC communication range and obtains their information via vehicle-to-vehicle information exchange by copying the contents in their information buffers into its own information buffer, then processes these contents, keeping useful parts and discarding nonuseful parts.

2.2 Pretrip route-choice modeling

2.2.1 Historical traffic information database. As a first step, we build a historical traffic information database, to be stored in each vehicle that can be accessed during their trips; this is actually a prerequirement (either implicit or explicit) for all travelers before they physically begin their respective trips. An exponential time average method is used to generate the historical traffic information database—the collection of link travel time information for each individual link for each 15-minute time interval that is to be simulated in the study traffic network.

To generate historical link travel time information, repeated simulations were run over the study network under both noncongested and recurrent congestion conditions and the travel times for each vehicle (via microscopic simulation) for each individual link for the studied time period (divided into many time intervals) was recorded. From these multiple runs, the average link travel time based on all (simulated) experiences from different days for same time interval for each individual link in the traffic network were calculated and stored in the historical database as the historical link travel time information for that specific time interval. Equation (1) shows this link travel time calculation for a specific time interval for an individual link. The average values of each link travel time for the whole studied time period are also calculated as shown in Equation (2) and stored in the historical database.

$$H_{ij} = \frac{1}{n}\sum_{k=1}^{n} R_{ijk} \tag{1}$$

$$H_i = \frac{1}{m}\sum_{j=1}^{m} H_{ij} \tag{2}$$

where H_i is the historical link travel time for link i during the study period, H_{ij} is the calculated historical link travel time for link i in time interval j, R_{ijk} is average value of all recorded vehicle travel times for link i in time interval j for the kth simulation run (based on kth random seed in the simulation), m is the number of time intervals into which the study time period is divided, and n is the total number of simulation runs under various random seeds for the same O/D demand and test network. Base network travel time information derived in this manner is meant to synthetically mimic the real-world experience, in which historical traffic information is gleaned from the compilation of daily commute experience (trials).

2.2.2 Pretrip link-based k-shortest path algorithm. After loading the network and before initiating the simulation, time-dependent (dynamic) shortest paths ($k = 2$ in the results reported here; that is, the best and the second best) from each origin zone to each destination zone for a specific departure time period (15 minutes interval) are calculated for all simulation time periods based upon historical link travel time for all links in this specific time interval and turning costs for all possible turning movements in the network. Each vehicle selects one of these paths as its initial path to follow when it is released into the network in the simulation.[1] The historical link travel time in the kth shortest path search process is obviously not identical for each time interval and may not be the same for each simulation run. A modified link-based Dijkstra label-setting algorithm is implemented in which the previous link is labeled in the search process rather than the previous node as in the node-based Dijkstra algorithm.

2.2.3 Pretrip binary logit route-choice model. All travelers are assumed to optimize their individual routes based on the same historical traffic information before their trips begin, under the assumption that each individual traveler has equal opportunity to assess historical traffic information in order to develop an understanding of the traffic patterns under congestion-free and recurrent congestion conditions in their pretrip planning phases. In other words, drivers with IVC capabilities do not have any extra capabilities to guide their behavior before their trip begins.

The shortest and the second shortest paths are calculated for each origin–destination pair based on loaded historical link travel time values. A binary logit model is used to select one route from these two possible choices. Equation (3) shows the binary logit model used, yielding probability values for each individual driver to choose one route from two choices. In the simulation, each driver/vehicle selects one route as its initial route according to a random number generated in the simulation process based on the calculated probability value from Equation (3). Drivers with IVC capabilities may change their routes at any time during their trips based on their estimation of network traffic conditions gleaned from real-time information through peer-to-peer information exchange; drivers without IVC capability can follow only the initial routes that they chose before their trips begin.

$$\begin{aligned} P_j(1 \mid r_j, s_j) &= \left(1 + e^{\theta \cdot \Delta TT_{rs}}\right)^{-1} \\ \Delta TT_{rs} &= [TT_{rs}(1) - TT_{rs}(2)]/TT_{rs}(1) \end{aligned} \tag{3}$$

where $P_j(1 \mid r_j, s_j)$ is probability of driver j taking path 1 from its origin r to destination s, θ is a constant parameter, $TT_{rs}(1)$ is total travel time for shortest path 1 from origin r to destination s based on link travel time values from the first group random seeds, and $TT_{rs}(2)$ is total travel time for shortest path 2 based on link travel time values from the second group random seeds.

2.3 Enroute modeling

2.3.1 Path-based vehicle navigation. To model enroute decisions, a path-based microsimulation algorithm was developed, in which each individual vehicle is represented as an entity traveling in the traffic network, following either the exact route it selected in the pretrip planning phase (non-IVC vehicles are so restricted) or a revised route based on rerouting decisions made during its trip, until arriving at its destination (available only to IVC vehicles). Vehicles with IVC capability store a dynamic electronic map consisting of their most current traffic information for these links, which is continually updated by real-time traffic information based upon information transmitted from other IVC-capable vehicles within communication range. At each decision point (the ending node of current link it is traveling on) each IVC-capable vehicle makes a decision for its next turning movement (left-turn, right-turn, or go straight ahead) based both on the stored historical link travel time of the links in the network and on this real-time

Table 1
Link-based information packet format

Variable name	*Detailed representations*	*Size*
Vehicle ID	ID of the vehicle that originally generated this information packet	16 bits
Message time stamp	Time when this information packet was originally generated by the generating vehicle	32 bits
Vehicle GPS location	Vehicle GPS location coordination (X, Y) when it originally generated this information packet	32 × 2 bits
Vehicle speed	Vehicle speed when it originally generated this information packet	32 bits
Link ID	ID of link passing through when it originally generated this information packet	16 bits
Link travel time	Vehicle travel time for the link represented by link ID	32 bits

information. IVC-equipped vehicles are thus capable of dynamically navigating in the traffic networks, changing their routes during trips based on estimations of the latest traffic conditions as compared to non-IVC vehicles that are capable only of static navigation in roadway networks, following fixed routes based only on decisions made before starting their trips using historical traffic patterns.

2.3.2 Enroute traffic information generation. IVC-capable vehicles traveling on the roadways act as intelligent sensors in the traffic network and are the major traffic information source in the proposed peer-to-peer information exchange system. All vehicles with such equipment poll vehicles in the traffic network, as well as collect raw real-time traffic information data based on their own traveling experiences. In our simulation, each IVC-capable vehicle generates a link-based packet (see Table 1 for details) during its trip either immediately after passing the link or while it is still traveling on the link.

There are two different modes for IVC-capable vehicles to sample roadway traffic conditions and generate link-based information packets based upon their own experience: (1) *link basis mode*, in which an IVC-capable vehicle calculates link travel time from its own full experience on this specific link and generates an information packet for that link when it reaches the end of the link; and (2) *time basis mode*, in which the vehicle estimates link travel time for the link on which it is traveling based on its partial experience for that link (extending this partial experience to the whole link) and generates a link-based information packet for this specific link at certain time intervals, defined as a parameter in the simulation.

At specific time intervals after entering a specific network link, each IVC-capable vehicle estimates link travel time for the link on which it is traveling based on its partial experience for that link (extending this partial experience to the whole link); upon reaching the end of a link, it calculates link travel time and generates a link-based information packet based on its full experience. In this way, under congested traffic conditions in which vehicles may take an extended period of time to traverse a given link, updated conditions on that link will be guaranteed to be generated at intervals no greater than the sampling rate. In the simulations reported here, each IVC-capable vehicle generates a link-based information packet for the link it is traveling at 1-minute intervals after entering the link, and generates a link-based information packet based on its full experience upon leaving the link.

2.3.3 Real-time traffic information processing. In order to estimate current traffic conditions for each link in the traffic network more accurately, a modified exponential filter module, as shown in Equation (4), was incorporated in each IVC vehicle to smooth estimates of link travel time values as new raw link-based information packets are received. Owing to the nature of the irregularity in the timing of reception of information packets from other vehicles (relative to current time), dynamic smoothing factors in the modified exponential filter are calculated based on differences between the time stamp of the most recent packet to be used in this smoothing cycle and the time stamp of the last stored packet (i.e., the most recent, up to that particular time) for the same link (see Equation (4)). If this time difference is more than a prespecified threshold value (15 minutes is used in the cases reported here), only the newly received packet is considered in the smoothing filter to compute the estimation of link travel time for that specific link. The smoothed values of link travel time for every link in the traffic network are stored in each IVC vehicle's information processing buffer and are used as the primary source for link travel time values for all of our information applications.

$$ST_i = K_i NT_i + (1 - K_i) ST_{i-1} \tag{4}$$

$$K_i = \begin{cases} 1;\ t_i^{\mathrm{new}} - t_i^{\mathrm{old}} > t^* \\ -0.5 + 0.5\left(t_i^{\mathrm{new}} - t_i^{\mathrm{old}}\right)/t^*;\ t_i^{\mathrm{new}} - t_i^{\mathrm{old}} \le t^* \end{cases} \tag{5}$$

where

ST_i is the smoothed link travel time value for link i in the current cycle t

ST_{i-1} is the smoothed link travel time value for link i in previous smoothing cycle $t-1$

NT is the raw link travel time value for link i in the newly received link-based information packet whose time stamp is newer than that of the packet currently stored

K_i is the smoothing factor for link i in the current smoothing cycle t

t_i^{new} is the time stamp of the newly received link-based information packet for link i,

t_i^{old} is the time stamp of the link-based information packet last previously received and used in the last smoothing cycle for link I, and

t^* is a parameter (15 minutes in the results shown in this article).

3 TEST APPLICATIONS OF THE PROPOSED SELF-ORGANIZING DISTRIBUTED TRAFFIC INFORMATION SYSTEM

The traffic information system introduced above has been shown to have the potential to propagate traffic information to each driver/vehicle with IVC capability under a broad range of circumstances, even for relatively low IVC market penetration rates (Yang and Recker, 2006; Jin and Recker, 2006; Recker et al., 2008). However, any benefit achieved from such propagation depends on how the traffic information is used. In this section, we examine three applications of the proposed IVC-based traffic information system. These applications are tested both in incident-free and in incident scenarios in a large-scale real-world traffic network to investigate potential benefits from the proposed information system to its users as well as to the whole system.

3.1 Test network and scenarios

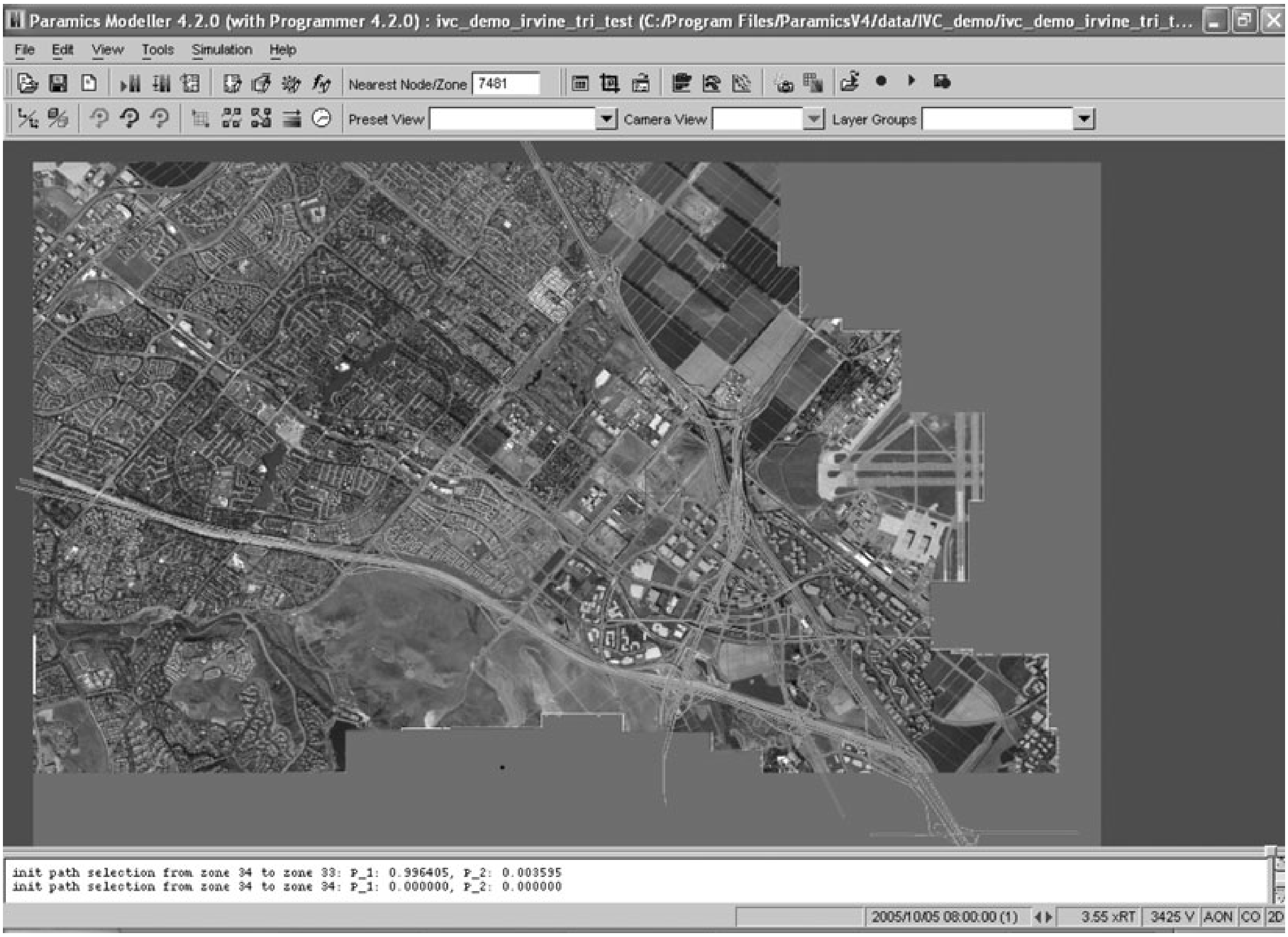
A network covering an area of approximately 100 km^2 located in the city of Irvine in Central Orange County, California, which includes three major freeways and several major arterial streets, is investigated in our application studies. The coded network consists of 582 one-direction links with a total distance of 162.3 km, including 154 one-direction freeway links with a total distance of 62.2 km and 372 one-direction arterial street links with a total distance of 100.1 km. The speed limit on the three freeways is 65 mph and the speed limit on the arterial streets ranges from 25 mph to 50 mph. Dynamic O/D demands (in 15-minute intervals) comprising approximately 30,000 vehicle trips between 34 origin and destination zone pairs for the morning peak hours (8:00–10:00 AM), used in our simulation studies, generate medium-to-heavy traffic flow conditions in the test network. For each unique input IVC parameter combination, 30 different random seeds are used in the simulation studies, and the average of all results is calculated for our analysis. For incident cases, an incident is generated on a freeway entirely blocking one direction of the freeway, reducing passing vehicle speed to 5 mph. The test network is shown in Figure 5.

In the simulation, a historical traffic information database, comprising all link travel time values for each simulation time interval for every 15-minute O/D time slice, was generated using the exponential time-average method discussed in Section 2.2.1. Based on historical link travel time information and turning costs for all possible movements in the network, a modified link-based Dijkstra label-setting *k*th shortest path algorithm was implemented searching for the two best shortest paths for each O/D pair in the network.

We employ two indices to measure the communication performance of the peer-to-peer traffic information system: *IVC success probability*, representing the average chance that an individual IVC-equipped vehicle can find other IVC vehicles in the communication radius range and communicate successfully in the traffic network at any particular time, that is, the percentage of IVC-equipped vehicles that successfully transmit information to one or more other so-equipped vehicles during any particular communications cycle; and *communication bandwidth*, indicating the average maximum amount of data that need to be transmitted by each IVC vehicle in the traffic network, defining the basic software and hardware requirements for successful implementation of the proposed system. Details of the definitions of these indices for each test application are given in the following subsections.

3.2 Path-based traffic information evaluation

Understandably, individual drivers are expected to be more interested in traffic information regarding the links on their respective paths rather than that associated with links irrelevant to their respective trips. In evaluating the potential usefulness of individual path-related information we focus on the age of link-based information along the individual routes traveled by IVC-capable vehicles from origin to destination.



Nearest Node/Zone 7481

```
init path selection from zone 34 to zone 33: P_1: 0.996405, P_2: 0.003595
init path selection from zone 34 to zone 34: P_1: 0.000000, P_2: 0.000000
```

```
2005/10/05 08:00:00 (1)   3.55 xRT   3425 V   AON   CO   2D
```

Fig. 5. Irvine triangle network in the simulation studies.

3.2.1 Incident-free case. Under incident-free conditions, each vehicle begins to navigate the roadway networks, following the fixed route decided before its departure. At decision points moving from one link into the next link in its path, each IVC vehicle evaluates all link traffic information pertinent to links on its path from its current location to its destination that are available from other IVC-capable vehicles that have passed within its communication range, and which have been stored in its dynamically updated database. From this information, we calculate an index of the "path information age" that measures the age of the traffic information (relative to current time) available for the remaining path that this specific IVC vehicle still needs to traverse to its destination; this is computed as the summation of age of the traffic information for all links on the path from current location to the destination weighted by the link length (see Equation 5). During the simulation, all IVC vehicles' respective path information ages calculated at all decision points are recorded. The average values of these performance indices are calculated based on 30 simulation runs using different random seeds. These average values are further disaggregated into three groups based on an index, path road type (see Equation 6), that measures the portion of freeways on the path to identify any variance in IVC performance between IVC vehicles traveling on freeways versus those traveling on urban surface streets.

$$\text{Path\_info\_age} = \Sigma(\text{link\_info\_age} * \text{link\_length}) / \Sigma\text{link\_length} \tag{5}$$

where link_info_age = current time − time stamp of the newest available link-based information packet in the vehicle's database

$$\text{Path\_road\_type\_index} = \Sigma(\text{link\_type\_index} * \text{link\_length}) / \Sigma\text{link\_length} \tag{6}$$

where link_type_index = 1 if freeway, link_type_index = 0 if urban street.

Table 2
Path categories

Path category	*Path road type index*	*Average trip distance*
Predominantly freeway	>0.9	4,930 m
Mixed	>0.5 and <0.9	5,350 m
Predominantly urban street	<0.5	1,720 m

Table 2 shows the average trip distances for each path category road type and categorization standards. Results of path information evaluation from the simulation studies are shown in Figures 6–13.

The results in Figure 6 demonstrate that the probability that any two IVC-capable vehicles can successfully transfer traffic information during a given communications cycle (or, IVC success rate) dramatically increases beyond market penetration rates of 0.01, reaching near certainty for market penetration greater than 0.10, even for communication ranges on the order of 500 m (well within the range of current technology).

The results in Figure 7, which displays the average age (with real time = 0 minutes) of traffic information available to IVC-capable vehicles pertaining to their respective paths to destination not yet traversed (i.e., Path_info_age as calculated from Equation 5 above), indicate that link travel times that are accurate to within 5 minutes of current conditions can be achieved with currently available communications technology (communications ranges ≤ 1,000 m) with IVC market penetration as low as 1%. Expectedly, this performance varies somewhat depending on the types of roadways traversed (Figures 8–9). The results indicate that, under the same IVC market penetration rate and communication radius and similar traffic demand, path information ages are more current along freeway paths than on paths that are predominantly on urban street paths. The probable explanation is that vehicle density on freeways is higher than on urban streets in both time domain (due to higher vehicle flow rates and much higher relative speeds between vehicles moving in opposite directions on the freeway carrying and passing traffic information during the IVC process) and space domain (usually more lanes and vehicles on freeways than on urban streets), both leading to faster dissemination of information.

However, achieving this level of performance is not without cost. As Figure 10 shows, the bandwidth required to support the IVC traffic information system also increases dramatically with increasing market penetration. The indication here is that the architecture of the information buffers and their probing may require significant "intelligent" design to filter the broadcasting of marginally useful information.

The simulation results (not shown) indicate that path information age decreases approximately linearly with higher IVC success rate; for IVC success rate values

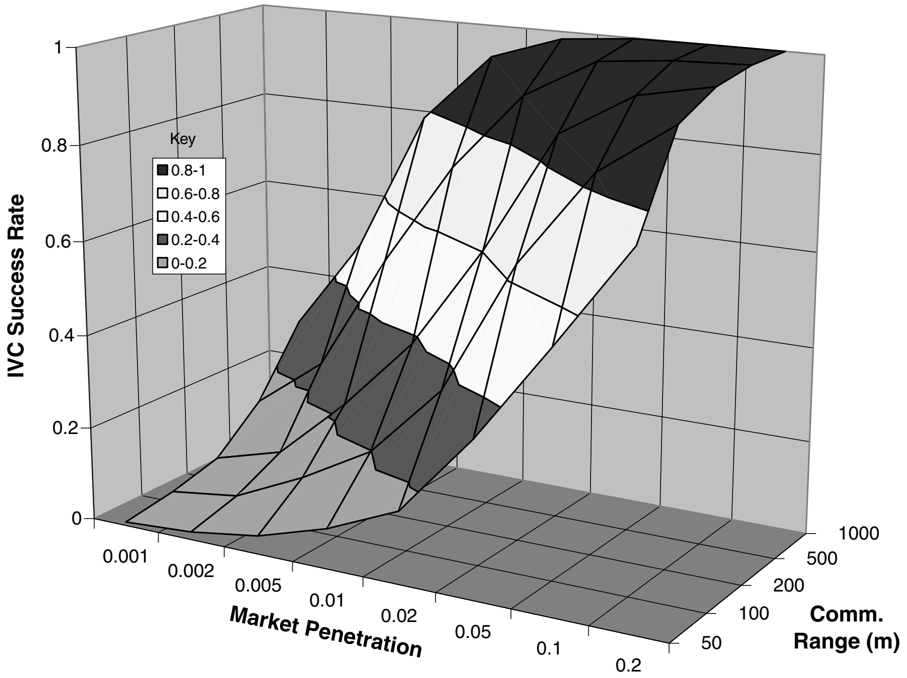


Fig. 6. Probability of successful IVC communication (IVC success rate) during any single communication cycle.

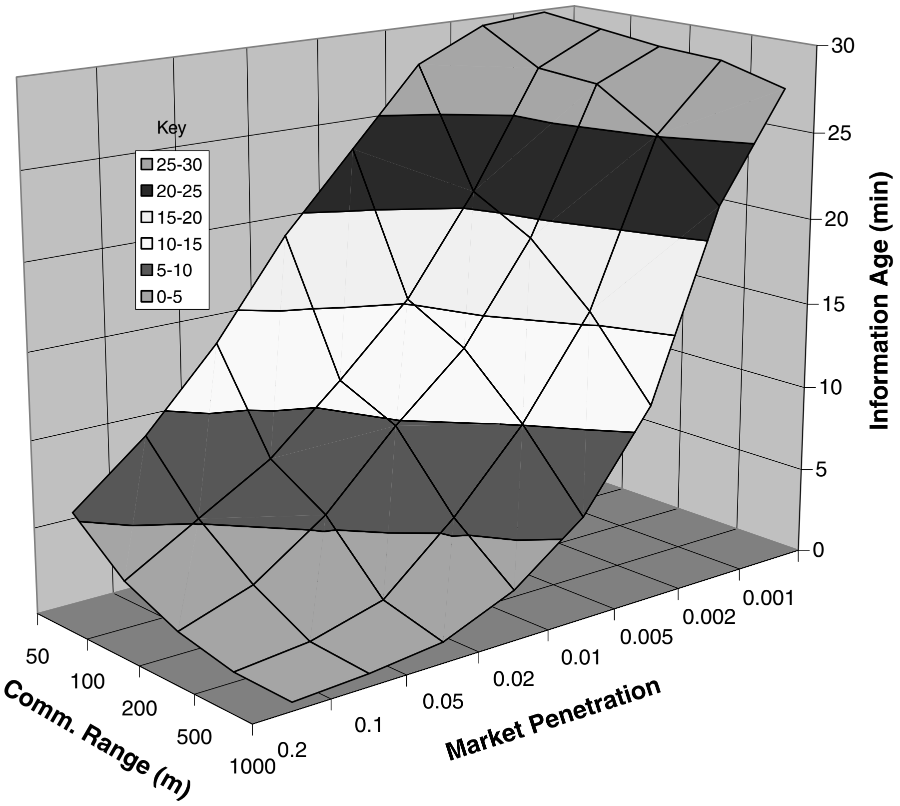


Fig. 7. Average path information age for all trips on network.

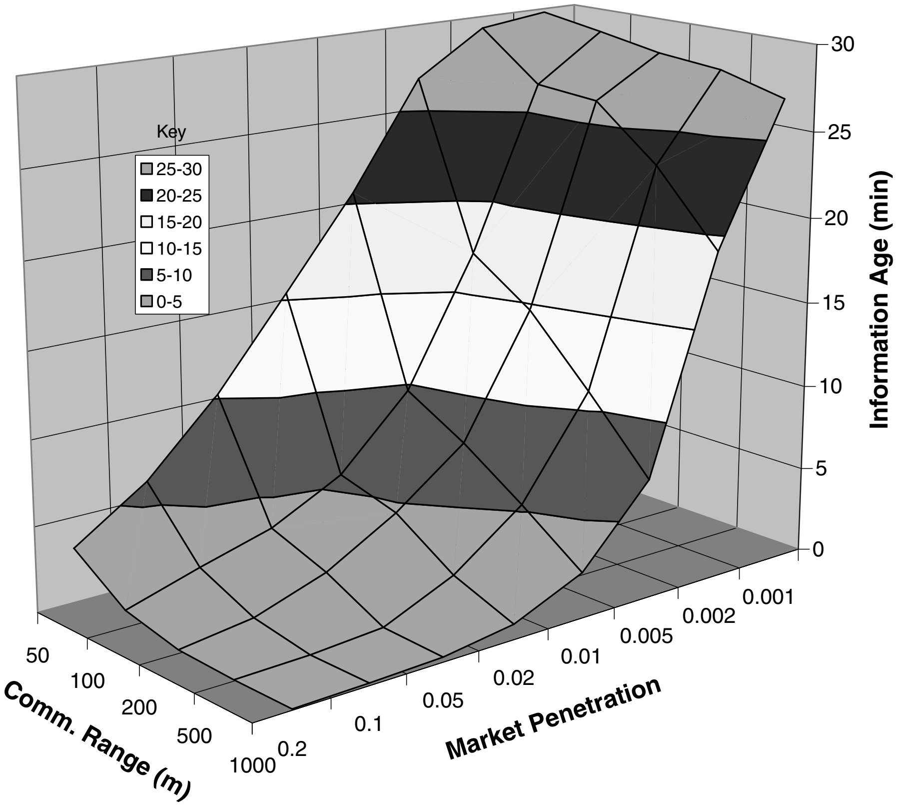


Fig. 8. Average path information age for trips on network that comprise primarily freeway travel.

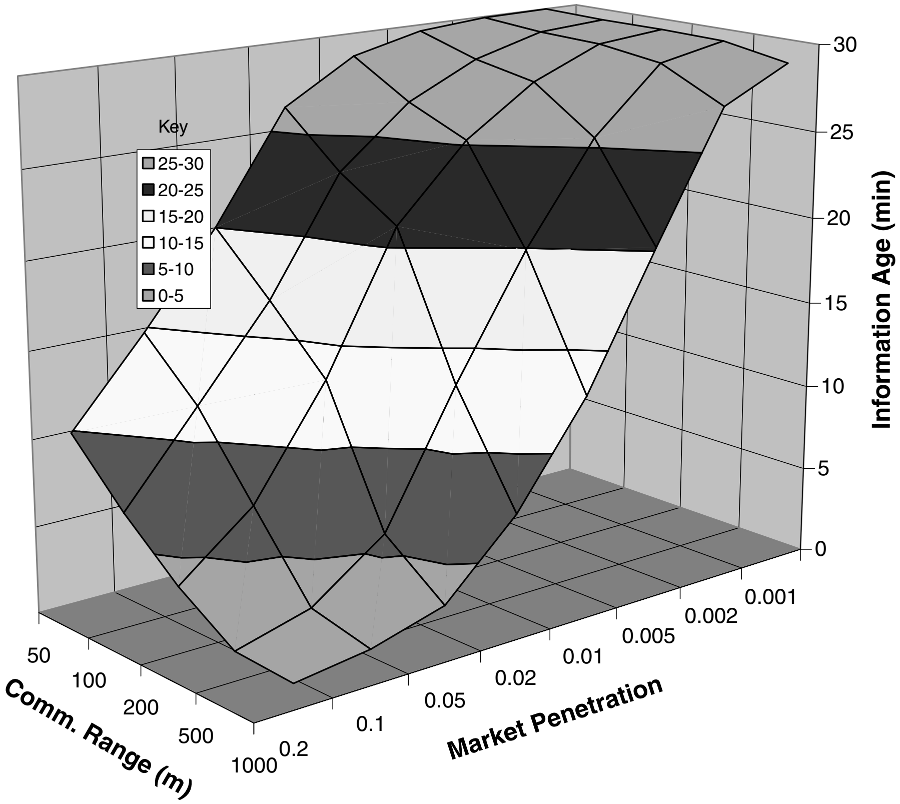


Fig. 9. Average path information age for trips on network that comprise primarily travel on urban streets and arterials.

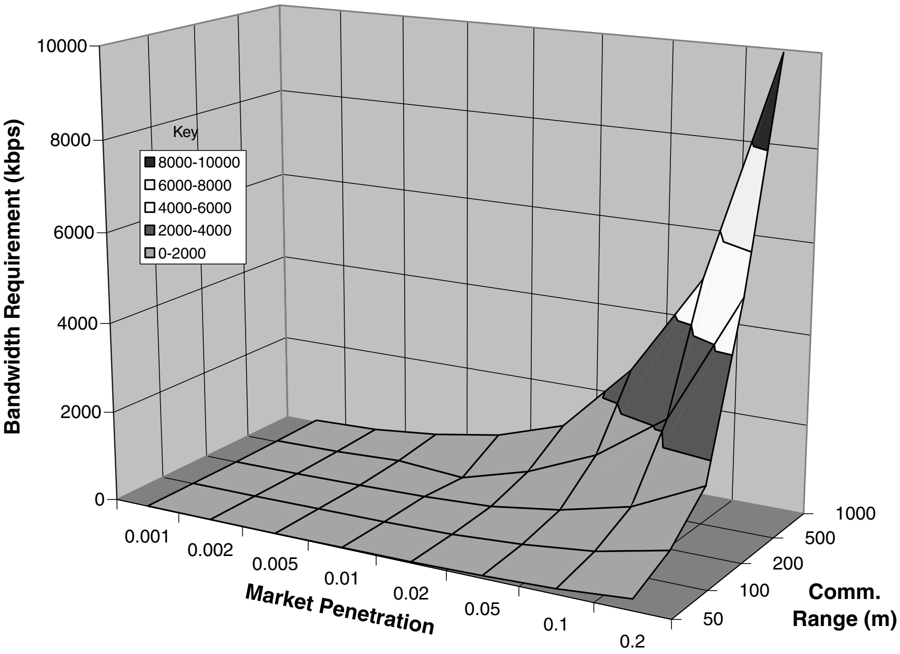


Fig. 10. IVC communication bandwidth required during any single communication cycle.

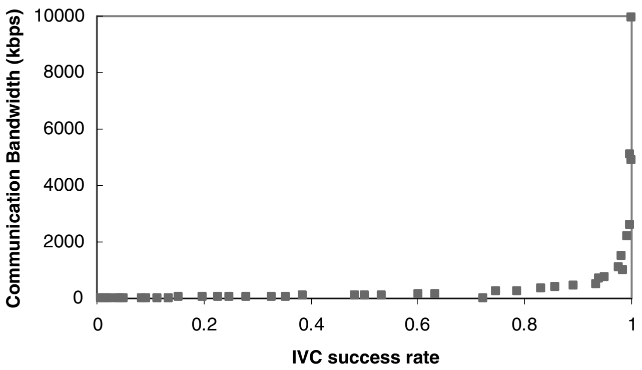


Fig. 11. Relationship between IVC success rate and communication bandwidth.

approaching 1.0, information delays from one IVC vehicle to another vehicle virtually disappears. However, the IVC bandwidth requirement generally increases exponentially with IVC success rate, approaching 10,000 kbps for IVC success rate values approaching 1.0 (Figure 11).

We conclude from these simulation results that near real-time path information transference among IVC-capable vehicles can be achieved in a network such as that typified by that in the "Irvine triangle" with only modest levels of adoption of the system, indicating that such a system could evolve from an early prototype—one in which early adopters might number as few as 0.5% of the vehicle population. However, the bandwidth required to support a mature system may be formidable.

3.2.2 Link-based incident detection algorithm. The value of real-time traffic information undoubtedly increases under conditions in which incidents substantially distort travel times and conditions gleaned from historical experience. Here we evaluate our proposed traffic information system relative to its potential to alert travelers to incidents that may affect their travel. In the simulation, each IVC vehicle runs an automatic incident detection algorithm based on both historical link travel time information stored in its historical information database and real-time link travel time information received from its IVC-capable neighbors. The automatic incident detection algorithm implemented in our application is executed by each IVC vehicle at 10-second intervals, and is confined to freeway links only. Unlike the typical incident detection algorithms currently implemented in centralized Transportation Management Centers, which usually use occupancy/volume/speed values from loop detectors in the field, the basic algorithm implemented here compares link travel time value differences between each upstream and downstream link in the freeway, as obtained from IVC; it then compares this difference to those stored in its historical base, checking these values against a user-defined threshold.

In the simulation, an incident is generated in one direction of freeway reducing passing speed to 5 mph in this direction of the freeway. There are two major performance measurement indices for this application: (1) the time lag from the time of the incident and the time at which each IVC vehicle in the network detects the incident; and (2) the percentage of IVC vehicles in the network that have detected the incident within 5/10/15 minutes after the incident occurs. The results shown in Figures 12 and 13 are averages of the values of these performance indices calculated from 30 simulation runs based on difference random seeds. The simulation results for the time lag to first detection are shown in Figure 12; they indicate that there is a precipitous improvement in performance for market penetrations greater than about 1% of vehicles—for values above this threshold, average time to detection is relatively constant (across the spectrum of communication ranges) at about 5 to 10 minutes.

Expectedly, we find that the values of detection rates 5/10/15 minutes after the incident occurs increase with higher IVC market penetration rate and greater communication ranges as shown in Figures 13a and b, which can be easily explained that with more IVC polling vehicles in the network and relatively long communication ranges, more accurate information representing real traffic conditions in the network can be disseminated faster for better automatic incident algorithm performance. However, we note that it is only for the highest market penetration rates (0.20) and communications ranges ($R = 1{,}000$ m) tested that a majority of the IVC-capable vehicles within our test network receive incident notification within 15 minutes of occurrence. The apparent anomaly of a drop in the percentage of IVC-capable vehicles with incident information near market penetration rates of about 10% (followed by rapid growth to near 100% of all such vehicles under a market penetration of about 20%) evidenced in Figure 13b bears explanation. First, although not shown, this effect was evident (to some degree) in the simulations for communication ranges between 200 m and 1,000 m; because of the large number of simulations (using different random number seeds) from which these average results are drawn, we conclude that rather than an anomaly, this effect is more likely a property of the system. A plausible (but certainly not definitive) explanation lay in the observation that this phenomenon occurs precisely when conditions also lead to a very rapid increase in the number of IVC-capable vehicles

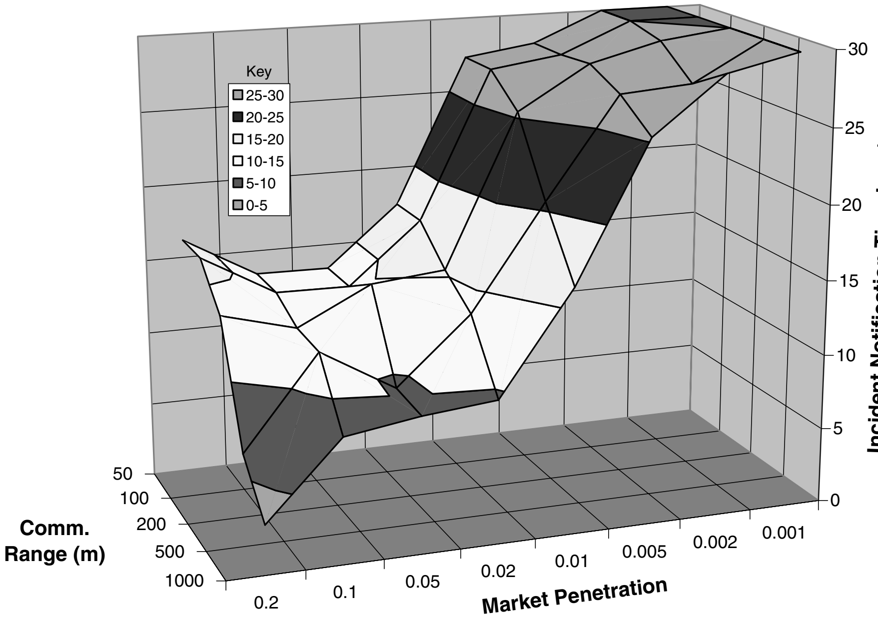


Fig. 12. Average time to incident detection.

that reroute to paths not affected by the incident (as can be seen in Figure 15 in the next section)—the interpretation is that the movement of IVC-capable vehicles away from the vicinity of the incident creates a local depression in the density of such vehicles within communication range of vehicles that could also benefit from the information; that is, the rerouting of these IVC-capable vehicles creates an "apparent" market penetration rate in the vicinity of the incident that is significantly less than the system-wide average. This effect is ultimately overcome as the market penetration rate increases beyond the 10% level. Certainly, further testing is needed before this plausibility can be confirmed.

From Figure 14, we can conclude that it is only when IVC success rates approach 1.0 that first detection time values decrease dramatically—at a rate much faster than linear.

The communication bandwidth requirements for incident notification (not shown) are similar to those for path-based information in Figure 11.

From these simulation results we conclude that although it is feasible for IVC-capable vehicles to automatically identify the incident in the network based upon the proposed IVC-based distributed traffic information system, the performance in this application is heavily dependent on IVC market penetration rates and communication ranges; relatively high penetration rates and long communication ranges are required for acceptable performance, but much more bandwidth is needed to achieve this performance.

3.3 Dynamic vehicle on-line routing

In this application, IVC-capable vehicles that receive link-based traffic information may use such information to reconsider any portion of the path remaining in their routes to destination. This potentially can benefit these vehicles as well as vehicles without IVC capability, the latter due to benefits to the overall system arising from redirecting a portion of the traffic from an incident site. In the application, each IVC-capable vehicle optimizes its personal route based on its estimation of current traffic conditions from real-time traffic information propagated in the information network and its understanding of recurrent traffic patterns from its historical traffic information database. From the real-time link travel time information stored in the vehicle's processing buffer, each IVC-capable vehicle finds the shortest path from its next decision point (the ending node of current link this vehicle is traveling on) to its destination point using the modified link-based Dijkstra's label-setting algorithm identified previously. The outputs of the shortest path algorithm include all links (in order) on the path from current location to destination, distance for this path, travel time for this path, and path information age calculated based on Equation (5). Any rerouting decision is made according to the binary logit rerouting model shown in Equation (7).

$$\begin{aligned} P_j(k,s) &= \left(1 + e^{(\theta_1 \Delta t_j(k,s) + \theta_2 \Delta d_j(k,s) + \theta_3 F_j + \theta_4 R)}\right)^{-1} \\ \Delta t_j(k,s) &= \left(t_j^C(k,s) - t_j^B(k,s)\right) \big/ t_j^C(k,s) \\ \Delta d_j(k,s) &= \left(d_j^C(k,s) - d_j^B(k,s)\right) \big/ d_j^C(k,s) \end{aligned} \tag{7}$$

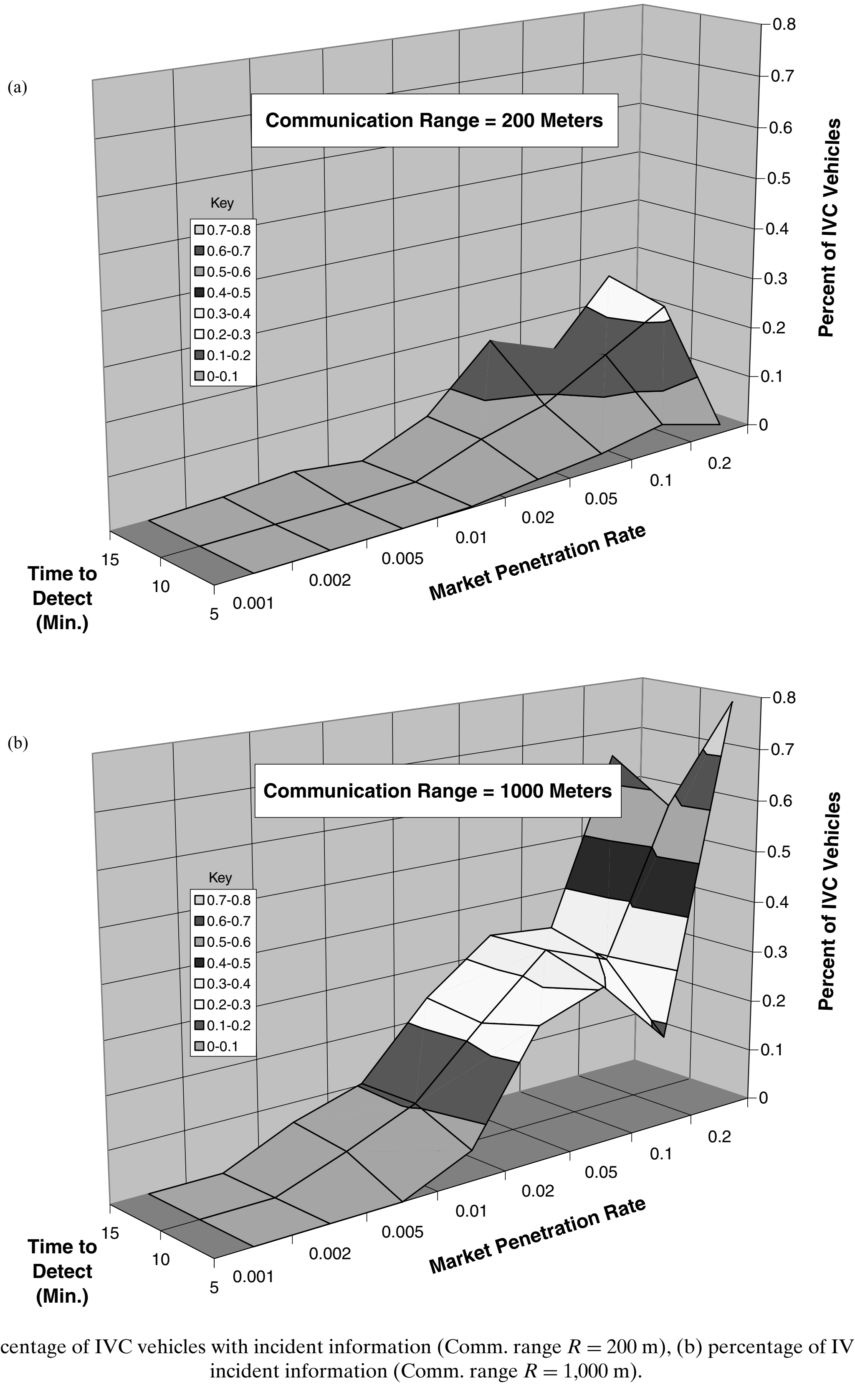


Fig. 13. (a) Percentage of IVC vehicles with incident information (Comm. range $R = 200$ m), (b) percentage of IVC vehicles with incident information (Comm. range $R = 1{,}000$ m).

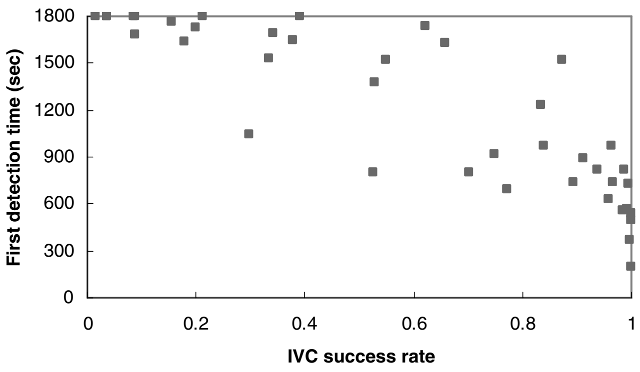


Fig. 14. Relationship between first incident detection time and IVC success rate.

where $P_j(k, s)$ is the probability for driver j (with IVC capability) to switch from the current path to destination s to the best alternative shortest path at the next node k; $\Delta t_j(k, s)$ and $\Delta d_j(k, s)$ are, respectively, the relative differences in the calculated travel times and distances between the current path and best alternative path from next node k to destination s based on real-time and historical link travel time information; $d_j^C(k, s)$ and $d_j^B(k, s)$ are, respectively, the calculated travel distance from the next node k to destination s for driver j on the path currently being followed and on the shortest path based on real-time and historical link travel time information; $t_j^C(k, s)$ and $t_j^B(k, s)$ are as previously defined; F_j is a positive integer variable representing driver's familiarity with the network; R is a positive integer variable representing the drivers' (common) resistance to change their initial routes during their trips due to human being's inertia; and θ_1, θ_2, θ_3, θ_4 are model parameters. Under this particular behavioral rule, each vehicle with IVC capability makes its reroute decision according to two values: a probability value to change its current following path to newly found shortest path calculated from binary logit model in Equation (7) and a random value (0–1) from the random generator in the stochastic simulation process.

We apply this dynamic vehicle on-line routing example to the test network and conditions defined for incident detection application discussed in the last subsection; that is, one in which an incident is generated in one direction of a freeway reducing passing speed to 5 mph in this direction of the freeway and lasting for 30 minutes. Two major performance measurement indices are examined: (1) IVC vehicle rerouting rates for IVC-capable vehicles with original paths that traverse the incident spot and those that do not, and (2) travel time comparisons for IVC-capable vehicles, non-IVC vehicles, and all vehicles. Statistics are calculated for a period encompassing 30 minutes after the incident has been cleared. Results are shown in Figures 15 through 18.

In general, rerouting rates of IVC-capable vehicles, as natural reactions to dynamic traffic conditions in the network, increase with higher IVC market penetration rates and longer communication ranges, regardless of whether or not the initial paths of these IVC vehicles are scheduled to pass the incident location as shown in Figures 15 and 16. The faster information dissemination due to the

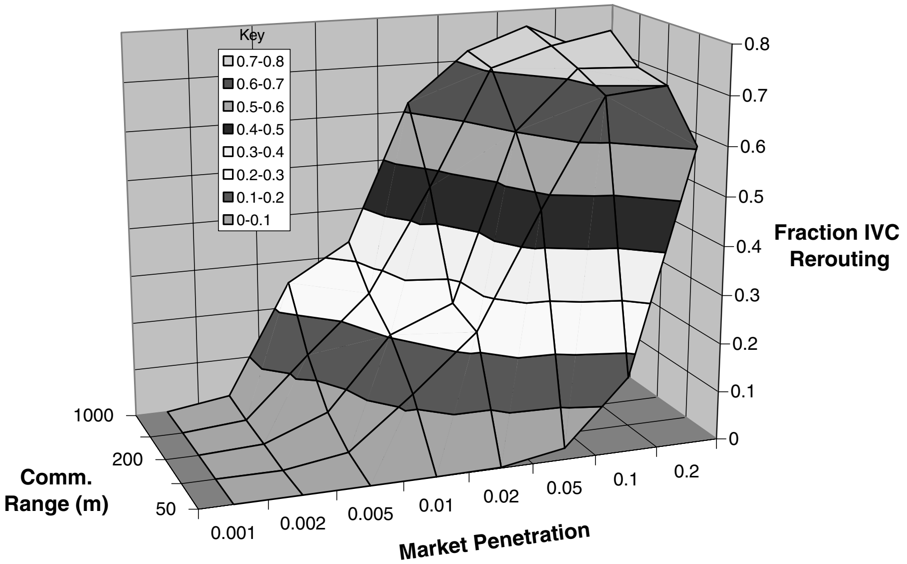


Fig. 15. Rerouting behavior of IVC-capable vehicles with travel paths that utilize link directly affected by incident.

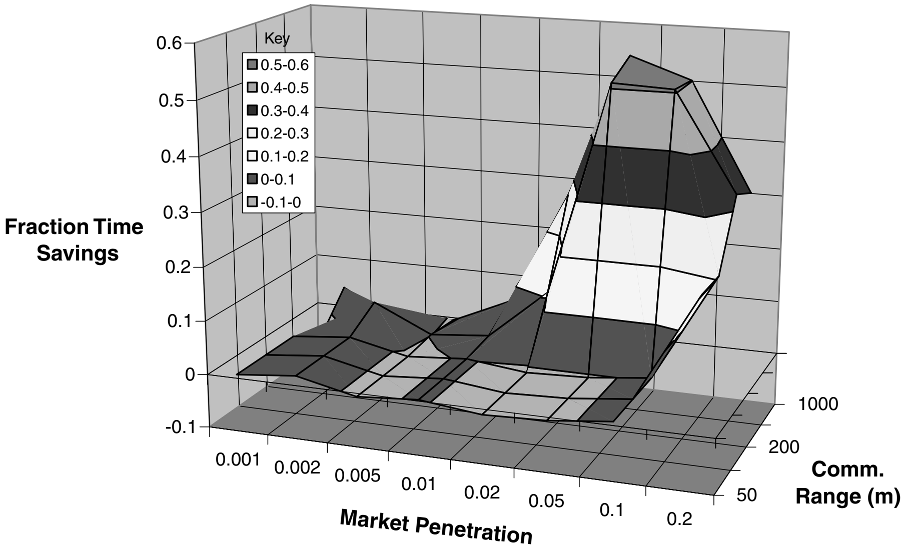


Fig. 16. Fractional time savings of rerouted IVC-capable vehicles with travel paths that utilize link directly affected by incident.

presence of more polling vehicles generating traffic information under higher IVC market penetration rates and greater communication ranges result in IVC-capable vehicles having a clearer picture of real-time network traffic conditions that leads to both more accurate as well as more timely dynamic alternative shortest path searching, in turn resulting in more IVC vehicles changing their paths during their trips. This is particularly the case when the paths of these vehicles are destined to traverse the link on which the incident occurs. Figure 15 shows a dramatic increase in the percentage of vehicles that are able to use peer-to-peer information exchange regarding a breakdown of traffic on their respective routes to reroute around the incident for market penetration rates greater than about 0.10, reaching a maximum of about 70% for market penetration greater than about 0.2 for all but the shortest communication ranges. There is correspondingly significant travel time savings for these vehicles, as shown in Figure 16. The results are, understandably, much less dramatic, both in fraction of vehicles rerouting and in fractional time savings for IVC vehicles not directly affected by the incident; rerouting percentages were found to remain relatively minimal (less than 10%) for most combinations of communication range and market penetration tested, rising above 10% only for combinations of communication range greater than 200 m and market penetration greater than 10%, reaching a maximum of slightly less than 20% for a market penetration of 20% and a range of 1,000 m. Average fractional travel time savings for such vehicles, although measurable, were no greater than 10% even under the most favorable conditions tested.

As shown in Figures 17 and 18, travel time for IVC vehicles, either directly/indirectly impacted by the incident or not affected by the incident, is generally significantly less than that for the system-wide average travel time for all vehicles, for all ranges tested; however, it must be pointed out that only when IVC market penetration rates and communication ranges are above certain thresholds are travel time savings for IVC vehicles compared to their non-IVC counterparts significant. Furthermore, although these relative saving values increase with higher IVC market penetration rates and greater communication distances, they level off and even begin to decrease after reaching maximal values. This is easy to explain in that dynamic IVC vehicle on-line routing based on the proposed IVC system brings benefits to the rerouted IVC vehicles only if the information is accurate and timely. As greater numbers of IVC vehicles reroute to alternative routes that were reported as being noncongested at some lagged time, benefits for rerouting IVC vehicles become less and less because other diverted IVC vehicles (acting on the same information) make traffic conditions on the alternative paths worse. Nonetheless, the rerouting leads to better performance for the whole system, as shown in Figure 18.

From these simulation results for dynamic IVC vehicle on-line routing in a real-world traffic network, we conclude that the distributed traffic information system proposed can provide significant benefit

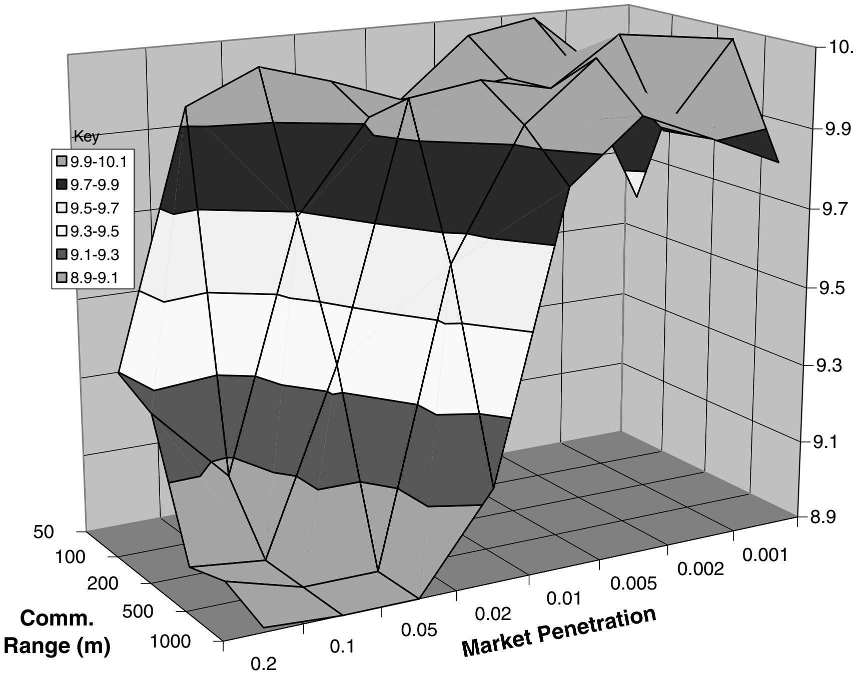


Fig. 17. Average travel time savings for IVC-capable vehicles.

to drivers/vehicles with IVC capabilities, provided that IVC market penetration rates and communication ranges are above minimal threshold values. In general, those IVC vehicles that are directly affected by an incident get greater advantage than do IVC vehicles not directly affected, and both have an advantage over their non-IVC counterparts. However, an underlying user equilibrium principle leads to non-IVC vehicles also

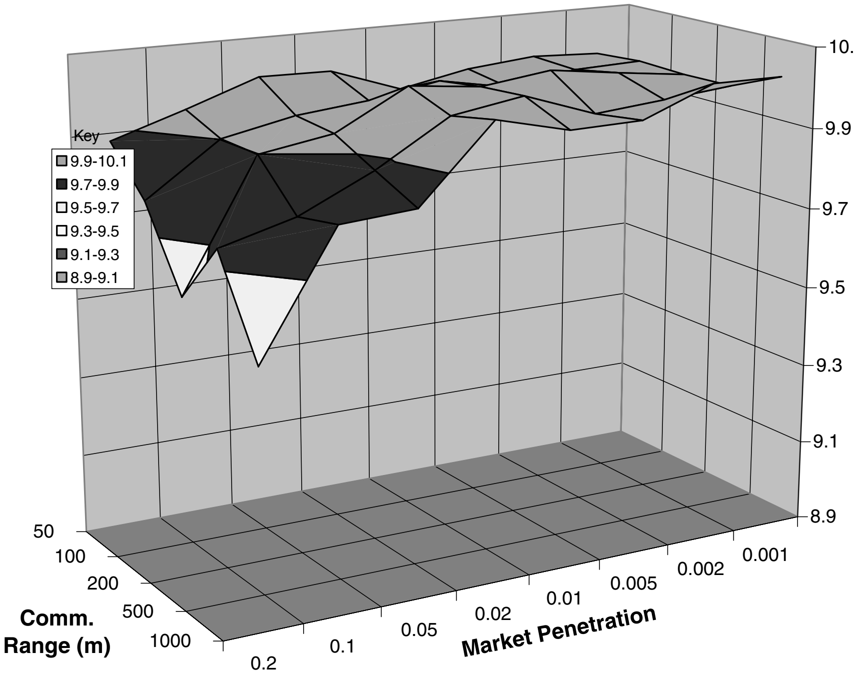


Fig. 18. Average system-wide travel time savings.

benefiting from the fact that the rerouted IVC vehicles better distribute themselves on less-congested alternative links, leading to an improvement of traffic conditions on these congested links.

4 SUMMARY AND CONCLUSIONS

Traffic information systems and their applications have been studied since the early 1990s; however, the preponderance of these are centralized systems and their applications are based on centralized processing. The purpose of this article is to test some information applications based upon a self-organizing, distributed traffic information system built on vehicle-to-vehicle information exchange among these vehicles with specific intervehicle communication equipment. A specific microsimulation modeling framework has been constructed that models: the historical traffic information database, drivers' pretrip route-choices behavior, raw traffic information generation from in-trip IVC-capable vehicles, information exchange among IVC-capable vehicles, and information processing within each IVC-capable vehicle. In the article, three information applications based on the proposed IVC-based traffic information system are tested in the simulation studies for a large-scale real-world network covering both freeways and local arterial streets in central Orange County, California. The first application—path information collection and evaluation based on the proposed information system—investigates IVC vehicles' path information delay for different categories of path (freeway, mixed, and urban street paths) under various IVC market penetration rates and communication ranges in incident-free conditions. The second application—automatic incident detection—focuses on the performance of identifying incidents in the network in terms of first detection time and detections rates 5/10/15 minutes after the incident occurs. The third application—IVC-capable vehicles dynamic on-line routing—investigates rerouting actions in terms of both travel time comparisons between different driver/vehicle groups and total vehicle time for the whole system.

The information applications tested lend some initial credence to the feasibility of a real-time traffic information system built upon autonomously polling vehicles' traffic surveillance, intervehicle information exchange, self-data processing, and optimization. The results are generally consistent with significant benefits being accrued both to IVC-capable vehicles as well as to the system as a whole for relatively low market penetration rates that would be expected during the early stages of adoption.

NOTE

1. The turning cost for each specific turning movement in the *k*-shortest path search algorithm is assigned according to the signal plan for the intersection and link types of both upstream and downstream links for this specific movement.

REFERENCES

Bogenberger, R. & Kosch, T. (2002), Ad-hoc peer-to-peer communication-webs on the street, *9th World Congress on Intelligent Transport Systems, ITS 2002*, Chicago, USA.

Boyce, D. E., Kirson, A. M. & Schofer, J. L. (1994), ADVANCE—the Illinois dynamic navigation and route guidance demonstration program, in I. Catling (ed.), *Advanced Technology for Road Transport: IVHS and ATT*, Artech House, Norwood, MA, pp. 247–70.

Briesemeister, L., Schafers, L. & Hommel, G. (2000), Disseminating messages among highly mobile hosts based on inter-vehicle communication, *IEEE Intelligent Vehicle Symposium,* Detroit, MI.

Federal Highway Administration (FHWA), US-DOT. (1996), *CORSIM User Guide*, Technical Report Version 1.0.

Festag, A., Füssler, H., Hartenstein, H., Sarma, A. & Schmitz, R. (2004), FleetNet: bringing car-to-car communication into the real world, in *Proceedings of the 11th World Congress on ITS*, Nagoya, Japan, October, 2004.

Füssler, H., Mauve, M., Hartenstein, H., Kasemann, M. & Vollmer, D. (2003), *A Comparison of Routing Strategies for Vehicular Ad Hoc Networks*, Technical Report Nr. TR-02-003, University of Mannheim, Germany.

Jin, W. & Recker, W. W. (2006), Instantaneous information propagation in a traffic stream through inter-vehicle communication, *Transportation Research, Part B: Methodological*, **40**(3), 230–50.

Kaesemann, M., Hartenstein, H., Füssler, H. & Mauve, M. (2002), A simulation study of a location service for position-based routing in mobile ad hoc networks, Technical Report Nr. TR-02-007, University of Mannheim, Germany.

Kosch, T., Schwingenschloegl, C. & Ai, L. (2002), Information dissemination in multihop inter-vehicle networks, in *The IEEE 5th International Conference on Intelligent Transportation Systems*, Singapore.

Mauve, M., Widmer, J. & Hartenstein, H. (2001), A survey of position-based routing in mobile ad-hoc networks, *IEEE Network*, **15**(6), 30–39.

PTV AG. (2001), VISSIM 3.60 user manual.

Quadstone Ltd. (2002), Paramics V4.0 modeller user guide.

Recker, W., Jin, W.-L., Yang, X. & Marca, J. (2008), Autonet: inter-vehicle communication and network vehicular traffic, *International Journal of Vehicle Information and Communication Systems*, in press.

Rohling, H. & Ebner, A. (2001), Self-organized digital radio network for automotive applications, in *Proceedings of the 8th World Congress on Intelligent Transportation Systems*, Sydney, Australia, October 2001.

TSS-Transport Simulation Systems S. L. (2000), AIMSUN2/GETRAM user manual.

Yang, Q. & Koutsopoulos, H. N. (1996), A microscopic traffic simulator for evaluation of dynamic traffic management systems, *Transportation Research Part C, Emerging Technologies*, **4**(3), 113–29.

Yang, X. & Recker, W. (2006), Simulation studies of information propagation in a self-organizing distributed traffic information system, *Transportation Research, Part C: Emerging Technologies*, **13**(5–6), 370–90.

Ziliaskopoulos, A. K. & Zhang, J. (2003), *A Zero Public Infrastructure Vehicle Based Traffic Information System, 2003*, TRB Annual Meeting, Washington, DC.