

# Modeling Dynamic Vehicle Navigation in a Self-Organizing, Peer-to-Peer, Distributed Traffic Information System

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*This article presents a simulation-based framework to model the potential benefits from dynamic vehicle on-line routing in a distributed traffic information system based upon a vehicle-to-vehicle information-sharing architecture. Within this framework, certain vehicles with specific inter-vehicle communication equipment in the traffic network are capable of autonomous traffic surveillance and peer-to-peer information sharing. Based on real-time and historical traffic information, they independently optimize their routes, forming a self-organizing traffic information overlay to the existing vehicular roadway network. In-trip rerouting decisions arising from drivers' interactions with this distributed information system are modeled according both to a rational-boundary model and to a binary-logit model under the assumption that each driver is a rational entity. A path-based microscopic traffic simulation model is developed to study on-line vehicle navigation in the distributed traffic information system, testing nonrecurrent congestion cases on two different networks representing typical roadway scenarios in daily commuting. Based on simulation study results, potential benefits both for travelers with access to the traffic information system as well as for the traffic system as a whole are demonstrated.*

**Keywords** Self-Organizing Networks, Distributed, Traffic Information System, Vehicle-to-Vehicle Communication, Vehicle Navigation, On-Line Routing

The potential benefits and drawbacks accruing from advanced traffic information systems (ATIS) have been addressed by many researchers, both using analytical approaches (Ben-Akiva et al., 1991) and simulation approaches (Mahmassani and Jayakrishnan, 1991). Limited field testing of some systems has been conducted in such projects as Advanced Driver and Vehicle Advisory Navigation ConcEpt (ADVANCE) (Boyce et al., 1994) and PROgraM for European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS) (Zimmer et al., 1994) to study ATIS in large-scale networks. However, virtually all of the traffic information systems that have been either investigated (mostly through simulation) or deployed are centralized systems (Bacelo et al., 1999).

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Similarly, within the automotive telematics industry, currently all commercialized traffic information systems are centralized systems, either integrated within an in-vehicle navigation system or as a stand-alone system. These systems all require a centralized traffic information center (TIC) to process traffic information typically derived either from data collected from fixed detection stations installed in the roadways and connected to the TIC via wired cable or from “floating-car” data polled from vehicles connected to the TIC via wireless modem, with the processed data distributed to their users via wired (in-home) or wireless (in-vehicle) communication connections. Shortcomings of these centralized information systems include: the heavy capital investment needed to initiate the system, difficulty of system upgrade, vulnerability to system failures, and general lack of specific relevancy of information provided to any particular trip.

With the development of information technologies, especially those associated with intervehicle communication (IVC),

the potential for distributed traffic information systems has attracted interest both in the transportation academic community (Ziliaskopoulos and Zhang, 2003; Yang and Recker, 2004) as well as in industry where some initial field studies have also been tested (Franz et al., 2001). More recently in the US, Ford Motor Company announced in February 2004 that it was pursuing “the next-generation travel advisory system” by turning “vehicles into mobile traffic-monitoring tools” (Rajiv Vyas, Detroit Free Press, February 27, 2004). And, efforts to establish the Integrated Network of Transportation Information, currently being pursued by the Intelligent Transportation Systems Joint Program Office of the US Department of Transportation, offer the promise of “simultaneous conversations among vehicles” supported by Dedicated Short Range Communications technologies.

In contrast to centralized systems, distributed traffic information systems based on information exchange among vehicles do not require any public infrastructure installed in the network; rather, they rely only on on-board devices installed in at least some vehicles traversing the roadway network. Because such systems are totally independent of public infrastructure, they will be market-driven and self-maintained, without the noted shortcomings of centralized systems. Vehicles in the traffic network generate information, exchange information, process information, and distribute information; they are not only the users (passive beneficiaries) of the system, but also information sources (active contributors) to the system.

The “information wave” resulting from instantaneous unidirectional and bidirectional information propagation via peer-to-peer information exchange among Inter-Vehicle Communication (IVC)-equipped vehicles in the network (Jin and Recker, 2004) and noninstantaneous bidirectional information propagation (Ziliaskopoulos and Zhang, 2003) in linear traffic networks under both incident-free and incident conditions have been studied using analytical approaches. Because of the inherent complexities, simulation approaches have been used more widely than analytical methods to test information propagation under generalized conditions in one-dimensional traffic networks (Yang and Recker, 2004) and two-dimensional traffic networks (Ziliaskopoulos and Zhang, 2003).

Although intervehicle communication and information dissemination in traffic networks have been modeled both from various academic perspectives (transportation engineering, electronic engineering, and computer science) and at different levels (highly abstract, software protocols, and hardware products), no efforts have been found that systematically model and test such a distributed traffic information system based upon peer-to-peer information exchange relative to drivers’ dynamic on-line routing behaviors within it. In Yang and Recker (2004), simulation studies were performed to help determine the physical properties necessary for useful information propagation in a freeway corridor network via peer-to-peer information exchange. Results on the probability of successful IVC and traffic information propagation distance obtained from the simulation studies were generated and analyzed under incident-free and incident conditions for various roadway formats and parameter combinations. Com-

parisons between the speed of the incident information wave and the speed of the corresponding traffic shock wave due to the incident were analyzed for different scenarios as the most crucial aspect of the information propagation as a potential foundation for application in such a decentralized traffic information system. Their study stopped short of assessing drivers’ use of such information to improve their travel by rerouting around congested portions of the network.

This article focuses on detailed modeling of a self-organizing, distributed traffic information system built upon vehicle-to-vehicle information exchange, with case testing of the pretrip route-choice and en route rerouting behaviors of drivers with access to traffic information from such a peer-to-peer information system. Two different traffic networks, one comprising grid arterial streets and the other a freeway corridor, are tested with respect to different assumptions regarding drivers’ route choice behavior (including both pretrip route choice and en route rerouting behaviors) and different levels of knowledge of daily recurrent traffic patterns. Potential benefits arising from this proposed information system both for travelers with IVC and for the whole traffic system that includes all travelers with and without IVC capability are demonstrated based on simulation study results.

The remainder of this article is structured as follows. In the next section, detailed descriptions of the modeling framework for studying IVC-capable vehicle dynamic on-line routing in the proposed self-organizing, distributed traffic information systems is presented. In the third section, simulation implementations for dynamic vehicle on-line navigation for two different networks are presented in detail, and potential benefits from the distributed traffic information system are addressed based on analysis of the simulation results. The final section summarizes the findings and conclusions of this paper and presents suggestions for future modeling efforts.

## MODELING FRAMEWORK

In order to study dynamic on-line routing behavior within this complex system, the interactions among many components need to be modeled, including those between vehicles and roadway networks, those among vehicles with peer-to-peer communication capabilities, and interaction of drivers with traffic information they receive. Due to extremely complicated relationships among these components, a microsimulation approach was adopted to analyze information-sharing among vehicles via peer-to-peer communication within the traffic network.

Within the microsimulation modeling framework, those vehicles in the traffic network equipped with IVC systems (including a geographic information system, global positioning system, on-board navigation systems, and in-vehicle computing processor) generate floating car traffic information data that is exchanged with similarly-equipped vehicles through peer-to-peer communication; similarly, incoming traffic information from other IVC-equipped vehicles is processed in real-time

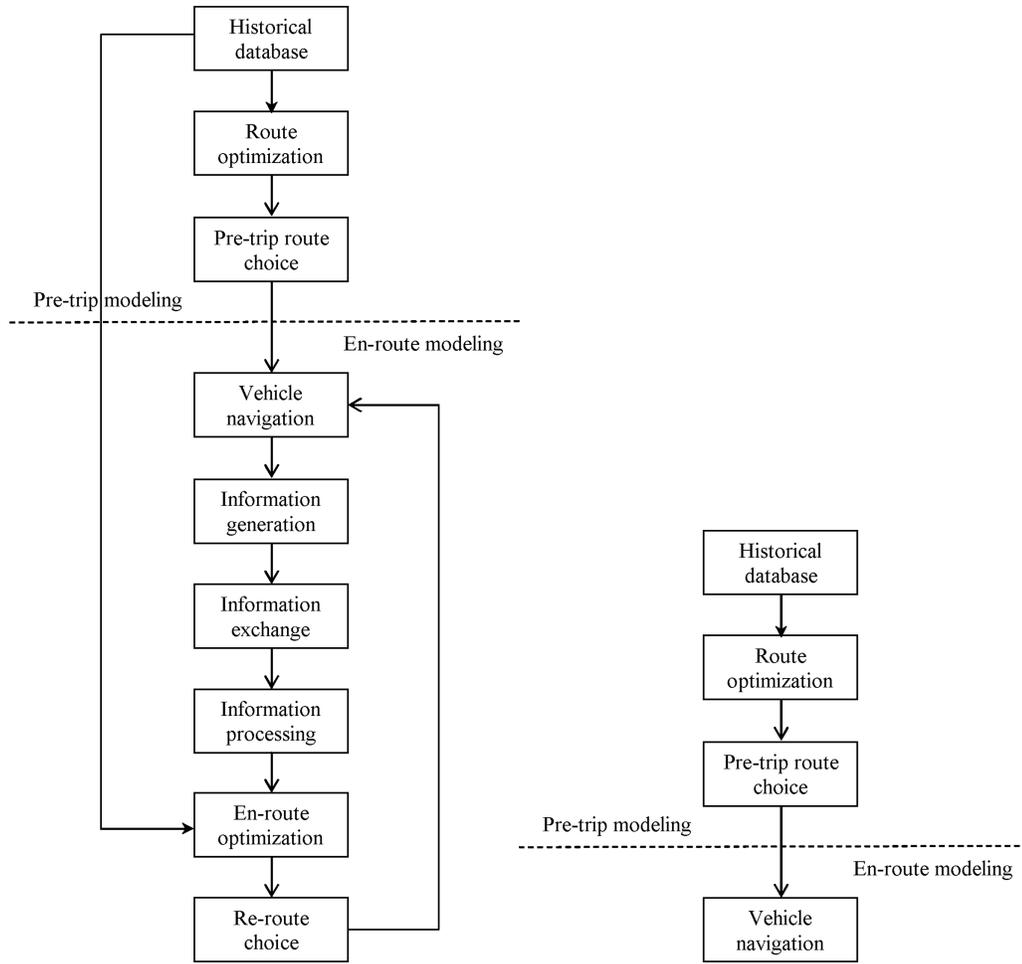


Figure 1 (a) IVC-capable vehicles (b) Non-IVC capable vehicles.

in order to “evolve” a real-time performance map of the traffic network. Each IVC-equipped vehicle within this distributed traffic information system is assumed to optimize its personal route based on information from two sources: (1) its estimation of current traffic conditions obtained from real-time traffic information propagated in the information network (if so equipped), and (2) its understanding of recurrent traffic patterns from its historical traffic information database. Vehicles with IVC capability can dynamically navigate the roadway network, follow-

ing changeable paths based upon their real-time rerouting decisions; vehicles without such equipment are constrained to follow a fixed route decided prior to their departure and based only on the historical traffic information contained in their database. Figure 1 shows the simulation modeling procedure for vehicles and drivers with cooperative equipment (GPS, GIS, IVC, on-board computer, and in-vehicle navigation system) both before and during their trips. Simulation modeling procedures for vehicles without such equipment are shown in Figure 2. The

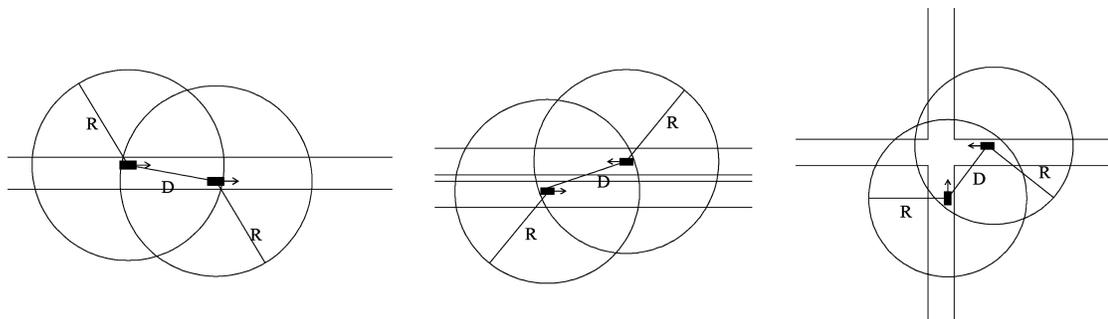


Figure 2 Inter-vehicle communication modeling abstraction.

detailed descriptions for each modeling procedure in our simulation framework are presented in following subsections.

### Historical Traffic Information Database

Depending on a traveler's familiarity (experience) with a transportation network and the frequency of the particular trip in question (e.g., a daily work trip commute vs. a recreational excursion by a vacationer), the information upon which routing decisions are made both prior to the actual commencement of the trip, as well as any rerouting decisions made during the trip, can vary. Moreover, en-route decisions based on real-time information presumably are made within the context of the driver's historical experiences (if any) traveling on the route.

In order to simulate the effect of personal experience/familiarity on rerouting behavior in the presence of real-time traffic information we constructed baseline historical traffic information databases for travelers to determine (either implicitly or explicitly) a planned route before they physically begin their trips using two approaches: (1) static-network method and (2) experiential method.

In the static-network method, link travel times are calculated based on free flow traffic conditions with modifications considering signal impacts and random errors; this assumption is applicable to situations in which little or no experiential historical information is available, for example, for newly constructed networks or for drivers unfamiliar with the network but who have had experience with similar choices. Equation (1) shows the calculation of link travel time for a given link based on the static-network method.

$$H_i = \frac{L_i}{S_i} \cdot (1 + \alpha \cdot \Delta) \quad (1)$$

where  $H_i$  is the calculated historical link travel time for link  $i$ ,  $L_i$  is the length of link  $i$ ,  $S_i$  is the free-flow speed on link  $i$ ,  $\Delta$  is a random variable (based on a specific random seed) whose value is between 0 and 1, and  $\alpha$  is a sensitivity parameter modifying the random effects. For demonstration purposes, results were obtained for two values of  $\alpha$ ,  $\alpha = 0.5, 1.0$ .

In the experiential method for generating 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 (simulated 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 (2) shows this link travel time calculation for a specific time interval for an individual link. The average values of each link travel time for whole studied time period are also calculated as shown

in Eq. (3) and stored in the historical database.

$$H_{ij} = \frac{1}{n} \sum_{k=1}^n R_{ijk} \quad (2)$$

$$H_i = \frac{1}{m} \sum_{j=1}^m H_{ij} \quad (3)$$

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  $k$ th simulation run (based on  $k$ th random seed in the simulation),  $m$  is the number of time intervals into which the study time period is divided, and  $n$  is 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, wherein historical traffic information is gleaned from the compilation of daily commute experience (trials).

### Pretrip Route Choice Behavior

In their pretrip planning phase, it is assumed that travelers select their routes based on the historical traffic information stored in their respective databases. In this pretrip phase, drivers with IVC capability are assumed not to benefit from additional real-time information as compared to drivers without IVC capability, and their pretrip route choice behavior follows the same pattern as drivers without IVC capability.

For drivers confined to rely on static-network values as their historical link travel time information, two different group random seeds are used to give two groups of values of travel time for each individual link in the network, and two shortest paths are calculated for each origin-destination pairs based on these two groups of link travel time values using the Floyd-Warshall algorithm (Floyd, 1962). Under these conditions, each driver is assumed to select a route from the two shortest routes from its origin to its destination; a binary-logit model is used to choose one route for each driver from these two possible choices (Eq. [4]).

$$P_j(1|r_j, s_j) = (1 + e^{\theta \cdot \Delta T T_{rs}})^{-1}$$

$$\Delta T T_{rs} = [T T_{rs}(1) - T T_{rs}(2)] / T T_{rs}(1) \quad (4)$$

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

For drivers with historical link travel time information databases derived from experiential data, the shortest paths for each origin-destination pair are calculated based on the average values

obtained via the repeated simulations described by Eq. (3); all such drivers choose these calculated shortest paths as their initial paths from their respective origins to destinations.

Regardless of which historical database is used for the drivers' initial route choices in their pretrip planning stages, drivers with IVC capability may change their routes at any time during their trips based on their reevaluation of the network traffic conditions reflected in real-time information obtained through peer-to-peer information exchange; however, drivers without IVC capability are restricted to follow the routes that they choose before trips begin.

### ***Path-Based Vehicle Navigation***

On-line routing of IVC-capable vehicles was accomplished through a path-based microsimulation platform in which each individual vehicle is represented as an entity traveling in the traffic network, following either the exact route it chose in pre-trip planning phase (non-IVC vehicles) or a revised route based on rerouting decisions made during its trip (IVC vehicles), until arriving at its destination. Each IVC-capable vehicle traveling on the roadway network stores its current path in its real-time database; the path can be revised at any decision point (i.e., upon approaching the ending node of current link it is traveling on) by making a decision for its next turning movement (left-turn, right-turn, or go straight ahead) based on real-time information. In addition to the stored historical link travel time of each link in the network, vehicles with IVC capability store a dynamic electronic map that is continually updated both by their own most-recent experience on these links and by real-time traffic information based upon information transmitted from other IVC-capable vehicles within communication range. 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, compared to non-IVC vehicles that are capable only of static navigation in roadway networks, following fixed routes based only on decisions made prior to starting their trips using historical traffic patterns.

### ***En-Route Traffic Information Generation***

In the distributed information system being analyzed, IVC-capable vehicles traveling on the roadways act as intelligent sensors that evolve a real-time picture of conditions in the traffic network through peer-to-peer information exchange. These vehicles continually poll other such vehicles in the traffic network, collecting raw traffic information data in real-time based both on their own travel experiences, as well as those of the vehicles polled. As each IVC-capable vehicle traverses a network link, it generates a "link-based" information packet as shown in Table 1 representing the link travel time experienced for that specific link, which then is placed in a buffer that may be probed by other vehicles.

**Table 1** Link-based information packet format

Variable name	Detailed representations	Size
Vehicle ID	ID # of the vehicle which 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 number 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

At specific time intervals (specified as a parameter in the simulation) after entering a network link, each IVC-capable vehicle estimates the link travel time for the link that it is traversing 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 the predetermined time intervals; 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 that it is traversing at one-minute intervals after entering the link, and generates a link-based information packet based on its full experience upon leaving the link.

### ***Intervehicle Communication Modeling***

Once the link-based traffic information packets are generated by vehicles according to the specific sampling policy, they are available to be passed to other IVC-capable vehicles. Vehicle-to-vehicle communication is modeled at a highly abstract level; neighboring IVC-capable vehicles have opportunity to exchange necessary information with each other if the physical distance ( $D$ ) between them is less than a predefined parameter—communication radius range ( $R$ ); no consideration is given to any specific intervehicle wireless communication technologies or to any complications arising from the relative speed between these two vehicles during their communication process. Figure 3 shows several different vehicle movements and network geometric scenarios considered.

During each communication cycle, each IVC-capable vehicle assimilates link-based information packets from neighboring IVC vehicles within communications range, then compares these newly-received packets with packets received from

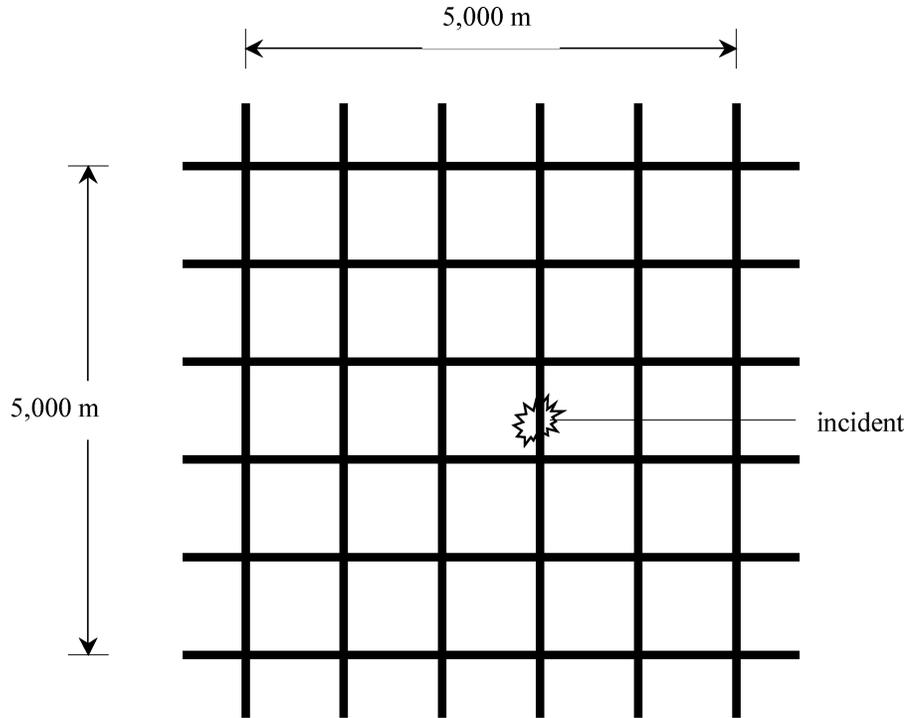


Figure 3 Grid arterial streets test network

IVC vehicles during previous communication cycles and already stored within its communication buffer. If the time stamp of a packet received during the current cycle for a specific network link is more recent than the time stamp of any packet previously received for that link, the new information packet is combined with any current link travel time information from the IVC-capable vehicle's own perspective (in its own information processing buffer) to estimate real-time traffic conditions more accurately for the link; it then stores the packet in its communication buffer to be broadcast to other IVC-capable vehicles during next communication cycle. Each IVC vehicle keeps only the most recent packets for each link in the traffic network in its communication buffer, while still maintaining the capability to estimate current traffic conditions based not only on these most recent information packets but also on link travel time information within the information processing buffer that implicitly integrates all previously received information.

### Real-Time Traffic Information Processing

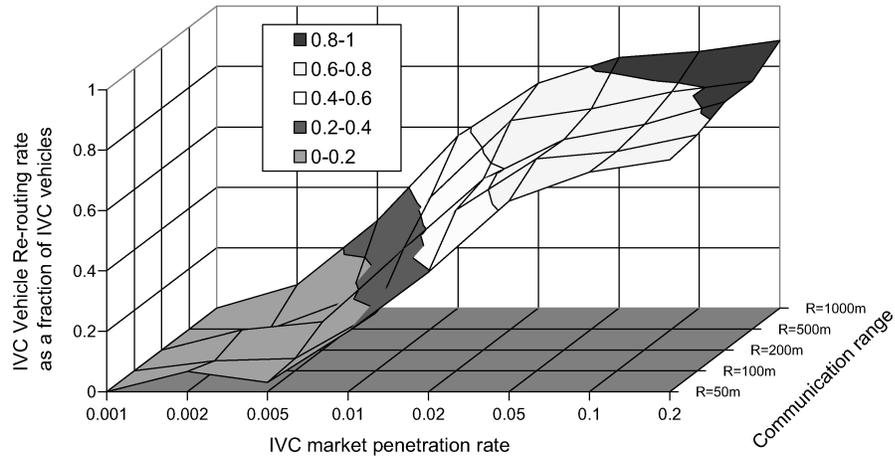
The raw travel time information generated by each IVC-capable vehicle is processed by each individual IVC vehicle in order to estimate current traffic conditions from its own perspective. Owing to variations in the distribution of IVC-capable vehicles in the network, speed distributions of IVC-capable vehicles and geometry of the roadway network, even two very closely spaced IVC vehicles at a particular time

in the traffic network, may have a totally different understanding of the current traffic situation after processing raw link-based information packets from their respective points of view.

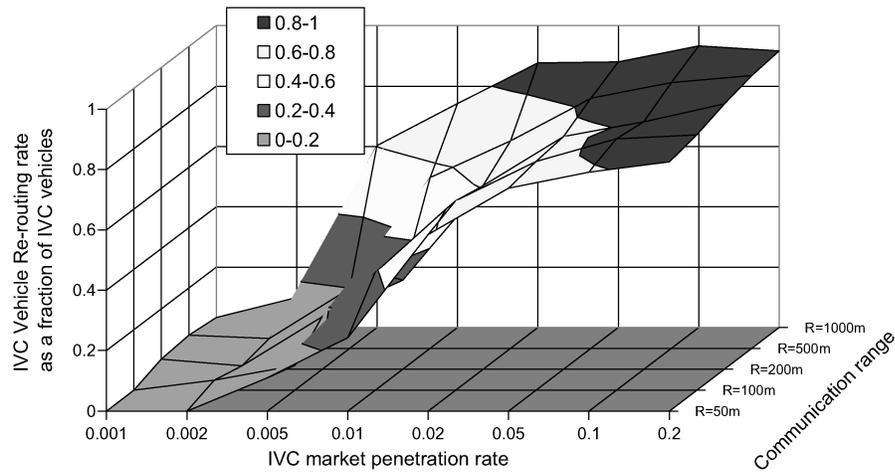
In the simulation, a modified exponential filter as shown in Eq. (5) was incorporated in each IVC vehicle to smooth estimates of link travel time values as new raw link-based information packets are received. Owing to the nature of the irregularity in the timing of reception of information packets from other vehicles (relative to current time), dynamic smoothing factors in our 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 packet last stored (i.e., the most recent up to that particular time) for the same link (see Eq. [6]). 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 estimated 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 (with historical link travel time values as backup values) in calculating the dynamic shortest path for each IVC vehicle.

$$ST_i = K_i \cdot NT_i + (1 - K_i) \cdot ST_{i-1} \quad (5)$$

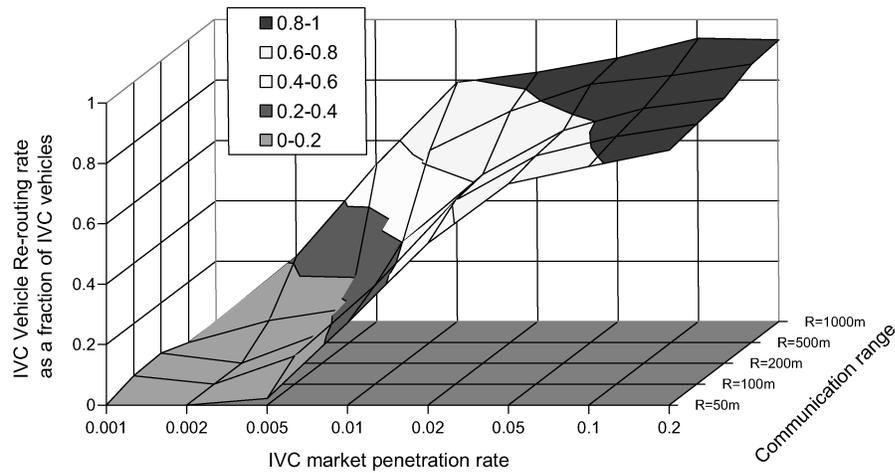
$$K_i = \begin{cases} 1; & t_i^{\text{new}} - t_i^{\text{old}} > t^* \\ -0.5 + 0.5 \cdot (t_i^{\text{new}} - t_i^{\text{old}}) / t^*; & t_i^{\text{new}} - t_i^{\text{old}} \leq t^* \end{cases} \quad (6)$$



(a)



(b)



(c)

Figure 4 IVC rerouting rate relative to IVC vehicle population (grid network). (a) Light traffic; (b) Moderate traffic; (c) Heavy traffic.

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 the last previous,  
 $K_i$  is the smoothing factor for link  $i$  in the current smoothing cycle  $t$ ,  
 $t_i^{\text{new}}$  is the time stamp of the newly received link-based information packet for link  $i$ ,  
 $t_i^{\text{old}}$  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).

### En-Route Route Optimization and Reroute Behaviors

The processed raw link-based information packets obtained via peer-to-peer communications provide IVC-capable vehicles with updated knowledge of current network traffic conditions. From this real-time link travel time information stored in the vehicle's processing buffer, each individual IVC-capable vehicle can find the shortest path from its next decision point (the ending node of current link this vehicle is traveling on) to its destination point using an on-board shortest path algorithm, for example, Dijkstra's algorithm (Dijkstra, 1959). For those links for which real-time information is not available (typically because either IVC market penetration rate is low and/or IVC communication radius is short), information drawn from the historical traffic information database within the vehicle is used as a substitute for the real-time link travel time values in the shortest path algorithm. (In the simulations reported here, historical link travel times were substituted for the estimated current link travel time value stored in IVC-capable vehicle's processing buffer when the latest estimation of a particular link lags the current time by 15 minutes or more.)

The computed shortest path based on the most recent information is compared to current path, and any rerouting decision is made according to the rerouting behavior models within our simulation framework. Two rerouting models are implemented in our simulation—the so-called rational-boundary model (Mahmassani and Jayakrishnan, 1991) and a binary-logit model (Ben-Akiva, 1985). In the case of the rational-boundary model, shown in Eq. (7), an IVC-capable driver is assumed to reoptimize the current route either when the relative difference travel time between two paths is larger than a predefined relative threshold parameter or when the absolute difference between these two paths is higher than a pre-defined absolute

threshold.

$$\delta_j(k) = \begin{cases} 1, & t_j^C(k, s) - t_j^B(k, s) > \max(\eta_j \cdot t_j^C(k, s), \tau_j) \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

where  $\delta_j(k)$  is a binary indicator variable that equals 1 when driver  $j$  (with IVC capability) switches from the path currently being followed to the best alternate based on real-time and historical link travel time information, and 0 if the current path is maintained;  $t_j^C(k, s)$  and  $t_j^B(k, s)$  are, respectively, the calculated travel time value 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;  $\eta_j$  is the relative threshold level for driver  $j$  to change from the current path to best alternate path; and  $\tau_j$  is the absolute threshold level to switch from the current path to best alternate.

In the case of the binary-logit rerouting model (Eq. [8]), the specification involves the relative differences in total travel time and total distance between the path currently being followed and the best alternate from next decision point to its destination, together with randomly generated parameters representing each driver's familiarity with the traffic network and the resistance to change the route during the trip.

$$P_j(k, s) = \left(1 + e^{(\theta_1 \cdot \Delta t_j(k, s) + \theta_2 \cdot \Delta d_j(k, s) + \theta_3 F_j + \theta_4 R)}\right)^{-1}$$

$$\Delta t_j(k, s) = (t_j^C(k, s) - t_j^B(k, s)) / t_j^C(k, s)$$

$$\Delta d_j(k, s) = (d_j^C(k, s) - d_j^B(k, s)) / d_j^C(k, s) \quad (8)$$

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  $\theta_1, \theta_2, \theta_3, \theta_4$  are model parameters. Under this particular behavioral rule, each driver 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 Eq. (8) and random value (0–1) from the random generator in the stochastic simulation process.

### Performance Measurements

A variety of traffic- and communication-related performance measures are output from the IVC-routing simulation model.

The communication performance measurement indices are intended to provide communication system-related benchmarks for specification of performance requirements of intervehicle communication technologies, algorithms and data structures for implementation of real-time peer-to-peer traffic information collection and processing. Alternatively, the traffic performance measurements are intended to be used in benefit analyses of drivers/vehicles' on-line rerouting behavior based on real-time information sharing, both for vehicles with and without IVC capability, and for the traffic system as a whole.

Although the performance measures can be monitored at specific time intervals to analyze performance variations with time, in the results reported here the total simulation period (excluding the warm-up period) was used to estimate average performance. We do not focus on communication technologies, but rather present results on three traffic-related performance measurement indices: (1) vehicle reroute rate, (2) average travel time for different classes of vehicles, and (3) total vehicle travel time for the whole system. Vehicle re-route rate, defined as the percentage of IVC-capable vehicles who change their routes at least once during their trips, is a measure of the population of vehicles that re-route (relative either to all IVC-capable vehicles or to all vehicles) under the influence of accessibility to real-time information. Average travel time comparisons between different groups of vehicles with and without IVC capabilities are used to investigate potential benefits accrued from peer-to-peer information exchange. The potential for accrual of benefits to the whole system (IVC- and non-IVC-capable vehicles) is captured by examining the total system travel time under the various scenarios. We examine these measures across a range of specific technology and adoption parameters (communication range and market penetration) and traffic conditions (light through congested), and under different assumptions regarding drivers' re-routing behavior.

### **SIMULATION IMPLEMENTATIONS AND ANALYSIS**

The base simulation tool used to implement our modeling framework is Paramics, a commercially available microscopic time-step traffic simulation model (Quadstone, 2004) in which each individual driver/vehicles is modeled as a driver-vehicle-unit and updates its location in the traffic networks at every time-step. The default Paramics model does not contain any built-in modules for procedures that are required to simulate dynamic on-line vehicle routing based on peer-to-peer information exchange. Using the application programming interface feature of Paramics, a series of new "plug in" modules were developed in order to model IVC-capable vehicle dynamic on-line routing: pretrip static shortest path calculation and route choice behavior modules; an IVC-capable vehicle traffic information generation module; an intervehicle communication module; an IVC-capable vehicle information processing module; in-trip dynamic shortest path calculation and reroute behavior modules; and performance measurement modules. These new modules were integrated with the default Paramics models to dictate route choices

**Table 2** O/D Demands for grid arterial street network

O/D Demand	Average speed (mph)	Density (veh/km)
Light	25	20
Moderate	17	42
Heavy	10	68

(both pretrip and en-route) under the proposed distributed traffic information system.

### **Simulation Results for Nonrecurrent Congestion on an Arterial Street Grid Network**

The test case reported here concerned nonrecurrent congestion scenarios on the 5,000 m × 5,000 m grid network of equally spaced two-lane local street roadways with speed limit of 45 mph shown in Figure 3. The distance between any two neighboring signalized intersections is 1 km. In the simulation, each direction of the roadway segments between any two intersections is further decomposed into two individual links, each 500 m long (a total of 288 one-direction links in the network).

In the scenario, an incident is simulated on a link close to the center of the study grid network 15 minutes into the simulation and lasts for 30 minutes. This incident is assumed to cause passing vehicles to reduce speed to 5 mph in the direction of the roadway in which the incident occurs and to 10 mph in the opposite direction of the roadway (due to speculator slowing).

Three levels of uniform O/D demand (shown in Table 2) are used to generate light, moderate and heavy traffic flow conditions in the network; these conditions correspond to traffic volumes that, under nonincident conditions, produce Levels-of-Service (LOS) A, C, and E, respectively.

The total simulation time is 1 hour, with the first 15 minutes used as "warm-up" in the simulation; statistical calculations for the performance measure results are for the final 45 minutes of the simulation only. For each unique input parameter combination, the average of results obtained using 30 different random seeds are used for analysis.

### **Behavioral Assumptions**

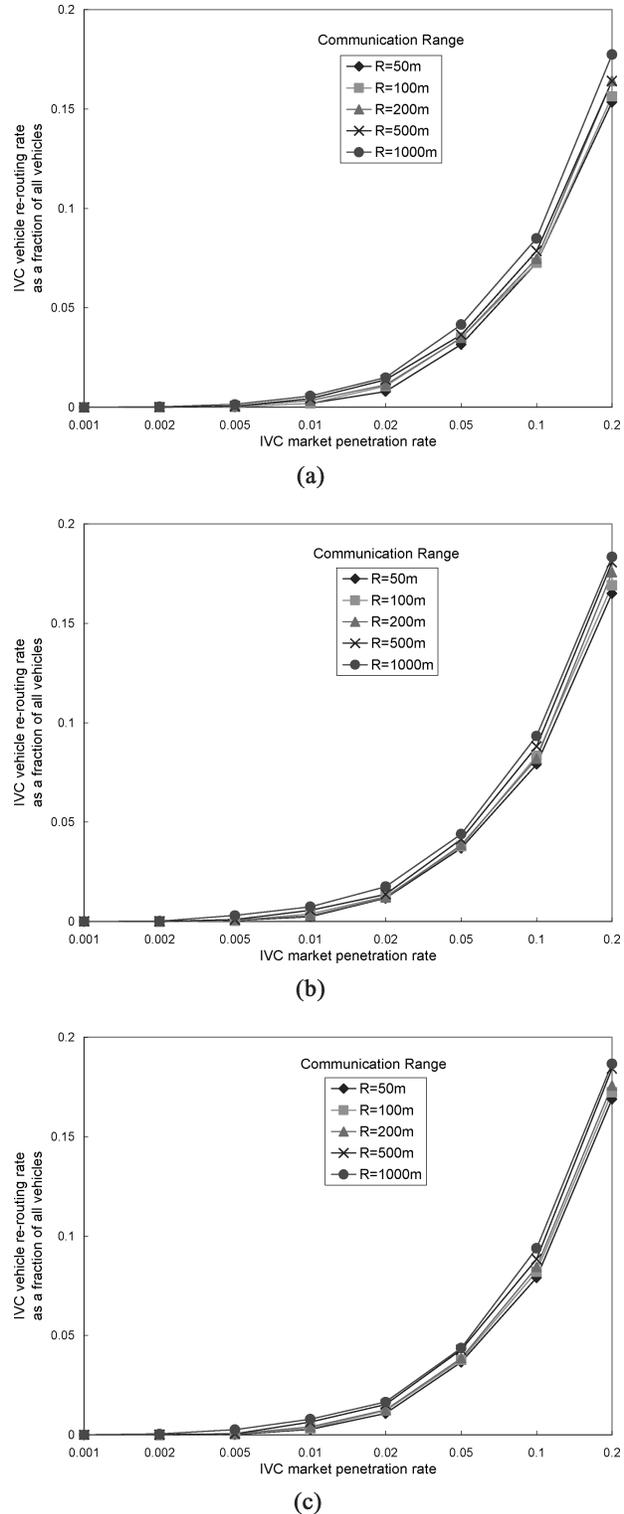
Owing to the multiplicity of routes between origin/destination pairs in this grid network, it was assumed that drivers' familiarity with the network was restricted to base-level information (exclusive of actual experiential knowledge); correspondingly, the static-network method was used to generate the pretrip routes selected by the individual travelers. Specifically, two groups of link travel time values for each individual link in the network using Eq. (1) and two random number seeds, and two shortest paths are calculated based on these link travel time values for each origin/destination pair. Then, each vehicle was assigned to one of these two calculated paths from its origin to its destination as its initial, "pretrip," path according to the binary-logit route choice model presented in Eq. (4).

In the simulation, vehicles without IVC capability are constrained to follow their initial paths from their origins to their destinations. Alternatively, each individual IVC-capable vehicle acts as a polling vehicle in the traffic network, collecting both link travel time information (based on either full or partial experience on the links that it traverses) as well as incident information. These vehicles exchange link-based information packets through the IVC system; each updates the shortest route from current location to its destination based on the most recent link travel time information and, for those links not represented in its real-time data buffer, from its historical traffic information database loaded within the vehicle. At each decision point along its path, each IVC vehicle is capable of a rerouting decision that switches the vehicle to a new shortest path if it differs from its current path. For demonstration purposes in this example the rational-boundary model in Eq. (7) is used to model the rerouting decision behavior.

Shown in Figures 4 and 5 are rerouting rates for IVC-capable vehicles whose initial paths include the link (in either direction) on which the incident occurs. Figure 4 presents these results relative to the population of IVC-capable vehicles, Figure 5 relative to the total population of vehicles. As expected, the rates increase with IVC market penetration rate and communication radius range under all traffic conditions considered; the former results in more IVC-capable vehicles acting as polling vehicles in the traffic network, while the latter results in an increase in the extent of the two-dimensional grid roadway network that can be reached through intervehicle information exchange. The greater the frequency with which raw traffic information is generated and the faster the information propagation the easier it is for each IVC-capable driver to estimate real-time traffic conditions in time to take advantage of rerouting options to escape heavy congestion locations affected by the incident.

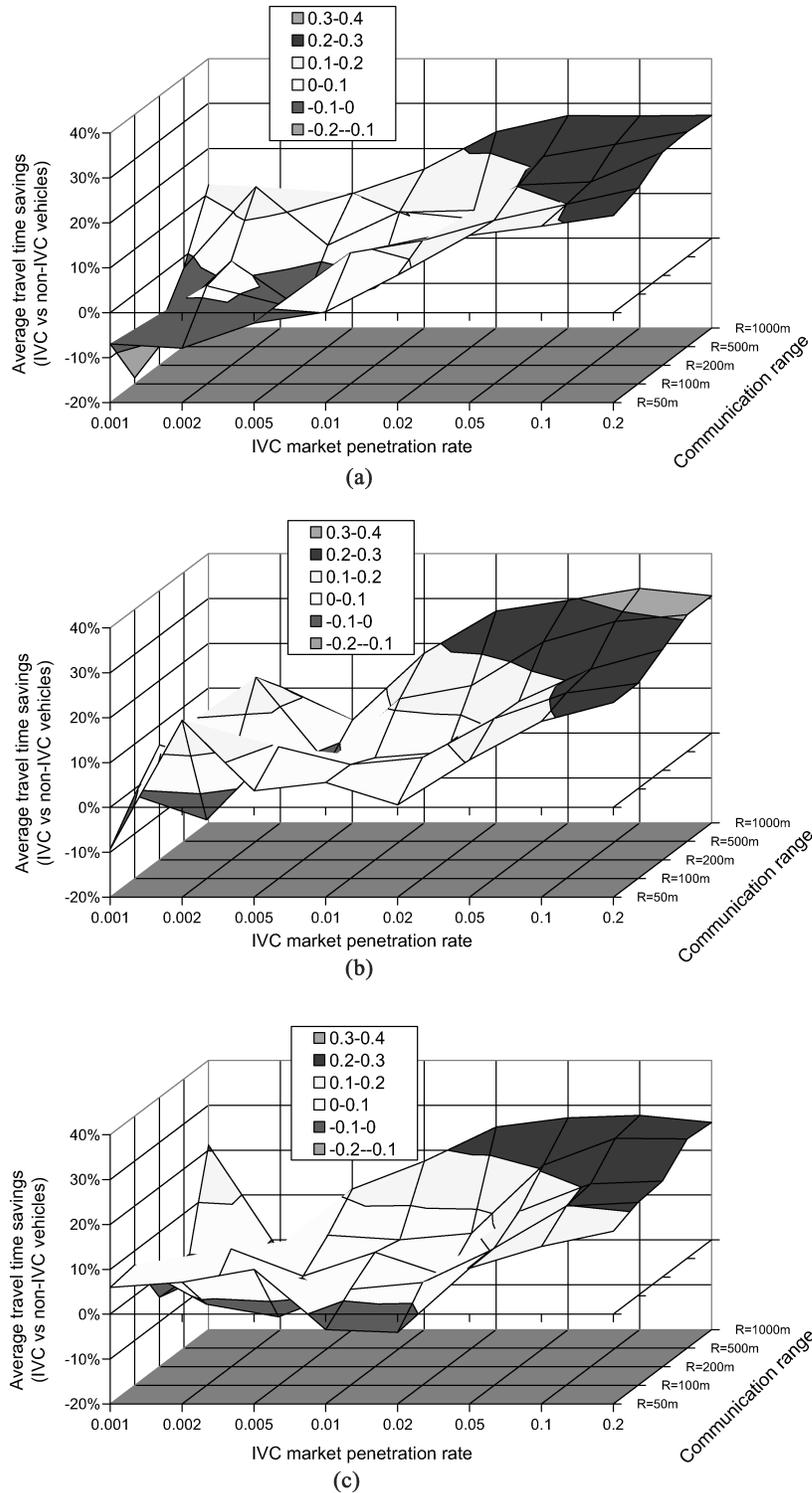
**Results**

Shown in Figure 6 are results for average travel time comparisons between IVC- and non-IVC-capable vehicles whose initial paths include the link (in either direction) where the incident occurs. The results indicate that the IVC-capable vehicles require less time to complete their trips than do vehicles restricted to following their initial paths for all demand levels considered when the IVC market penetration rates are higher than a threshold value of approximately 1%–2%. Consistent with the observations noted above regarding the correlation of rerouting rates with market penetration and communications range, we find similar correspondence for the relative travel time saving values for re-routed IVC-capable vehicles vs. vehicles without rerouting behavior. However, because of the increasing number of IVC-capable vehicles taking rerouting actions under higher IVC market penetration rates, the marginal benefits accrued by IVC-capable vehicles rerouting can decrease with increasing market penetration (and even decrease in absolute terms) as shown in these figures; as greater numbers of vehicles migrate from their initial paths to preferred paths, thereby both



**Figure 5** IVC rerouting rate relative to total vehicle population (grid network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

decreasing the performance of the paths to which they rerouted while lessening the impact of the incident on the paths they vacated (which includes the link on which the incident occurs). This result is consistent with those found by other researchers



**Figure 6** Relative time savings of IVC vehicles (grid network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

in assessing the “optimal” information penetration rate for system performance (Ben-Akiva et al., 1991; Mahmassani and Chen, 1991; Mahmassani and Jayakrishnan, 1991; Watling and Van Vuren, 1993).

Because only IVC-capable vehicles have capabilities to dynamically navigate based on real-time traffic information, it is

intuitive that travelers with IVC have a travel time advantage over travelers without IVC capabilities; this presuming that there is sufficient opportunity for IVC interaction. As shown in Figure 7, only when IVC market penetration rates are higher than some threshold values (roughly around 2%, but which vary for different communication radius ranges and demand levels) is

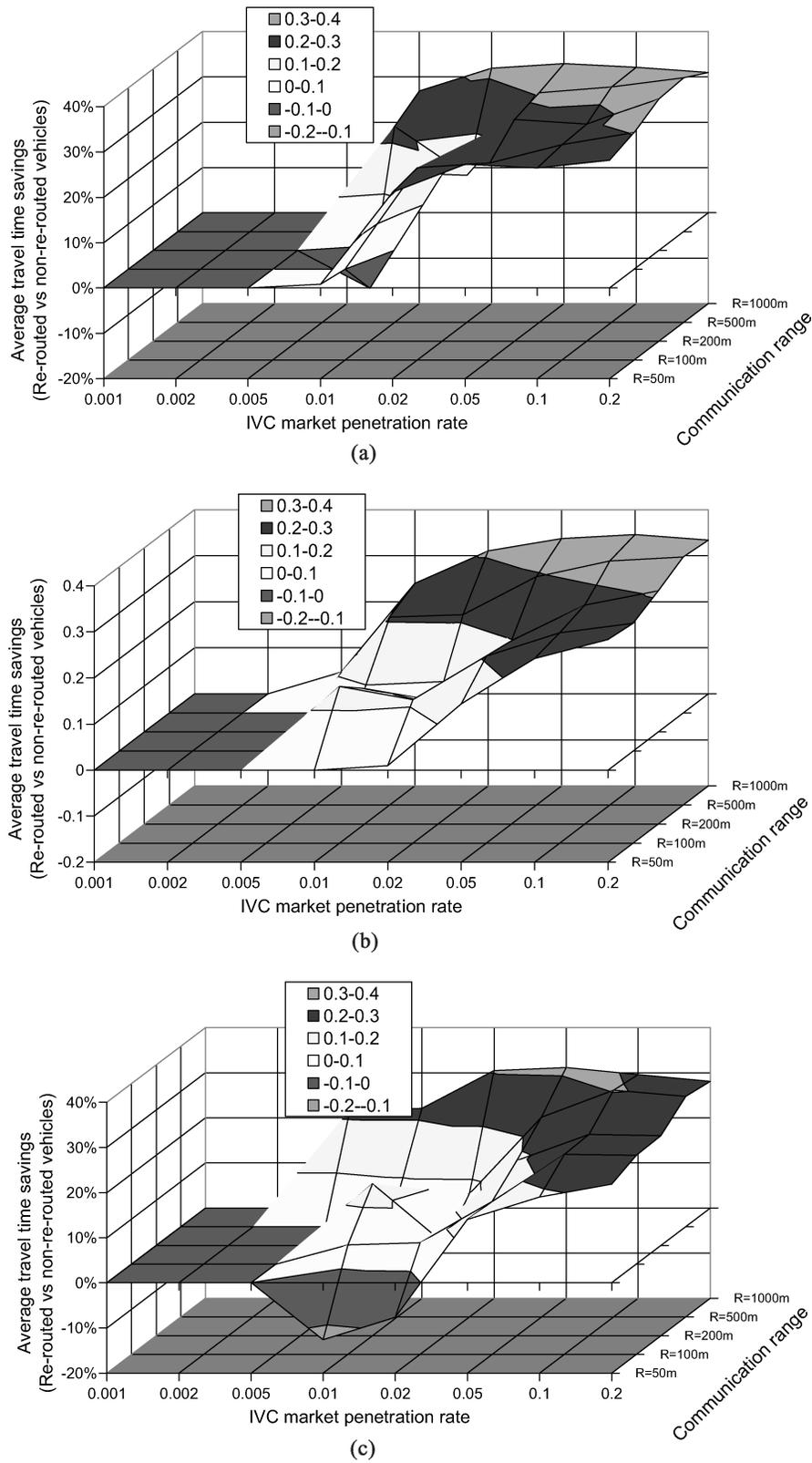


Figure 7 Relative time savings of rerouted IVC vehicles (grid network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

the average travel time for IVC-capable vehicles generally less than that for non-IVC vehicles. Near these threshold values, there is a compensatory relationship between market penetration and communications range. Expectedly, travel time savings for IVC-capable vehicles compared to non-IVC vehicles increase with higher IVC market penetration rates and longer communication radius range until reaching maximal values, and then decrease as the increasing rerouting results in reduced marginal benefit.

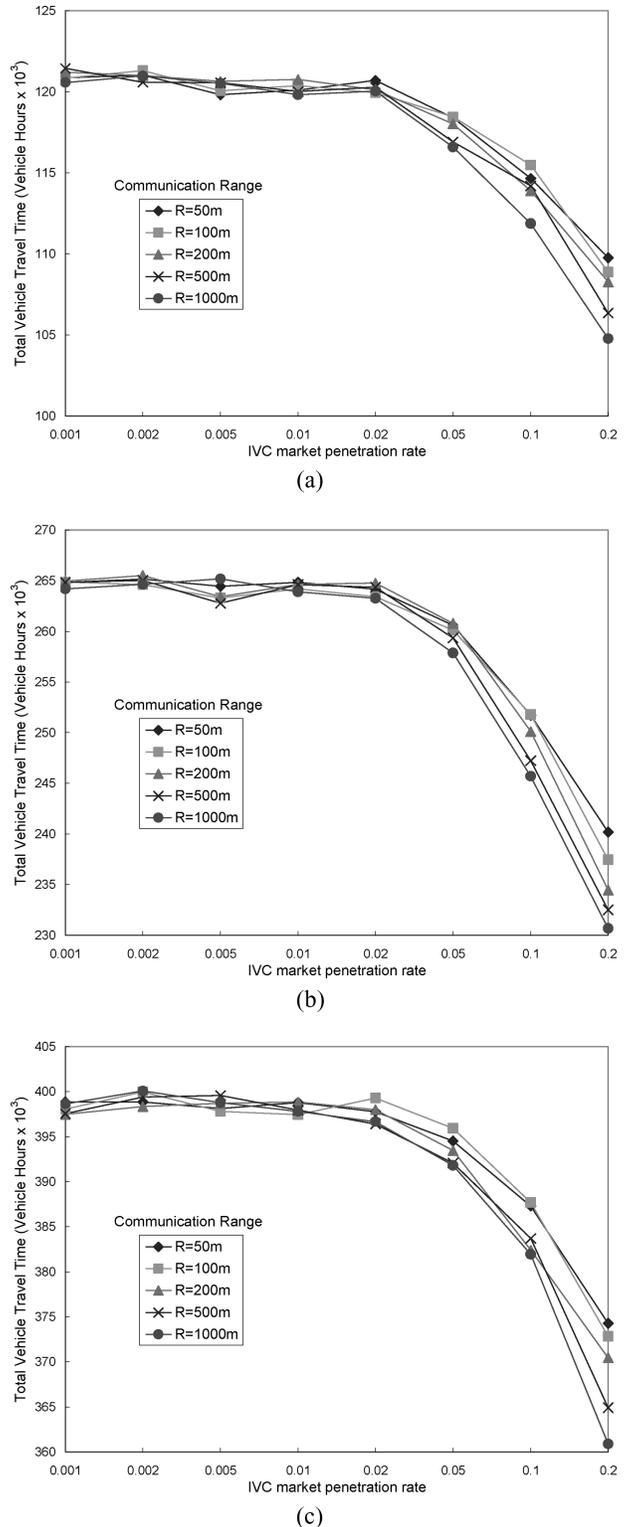
Figure 8 presents performance results for the whole traffic system, including travelers with and without IVC capability. Beyond thresholds for market penetration rates and communication range identified above, total vehicle travel time decreases with increasing penetration and communications range for all traffic demand levels considered. This is an outcome of the IVC-capable vehicles' travel time savings from rerouting and the travel time savings for non-IVC vehicles whose paths include the incident link (now with less demand as a result of IVC-capable vehicles rerouting) being greater than the increased travel time on the links comprising the IVC-capable vehicles' rerouting paths. Under heavy demand levels, reduction in unused network capacities needed to accommodate IVC-capable vehicles on their rerouted paths produces less dramatic system performance improvements.

**Simulation Results for Nonrecurrent Congestion on a Freeway Corridor Network**

A second test case considers nonrecurrent congestion scenarios along the freeway corridor with a neighboring alternative arterial street shown in Figure 9. The test network is comprised of an eight-lane freeway with four lanes in each direction and speed limit of 65 mph, and a four-lane arterial street parallel to the freeway with two lanes in each direction and speed limit of 45 mph. The eight-lane freeway and four-lane arterial are each 20 km long; the distance between the freeway and its alternative parallel arterial streets is 1.5 km. Both freeway and arterial streets are segmented into 500-m long links. The freeway and parallel arterial street are connected by other arterial streets running perpendicular to the freeway and freeway on/off ramps spaced at 2000-m intervals.

In the simulation, an incident 4000 m from the far end of the network occurs 30 min into the simulation and lasts for 30 min; owing to the blockage caused by the incident, vehicle speed in that direction is reduced to 5 mph near incident location. (See Figure 10 for details.) Three levels of O/D demand (shown in Table 3) are used to generate light, moderate, and heavy traffic flow conditions (corresponding to LOS A, C, and E, respectively), both for the freeway and the arterials.

The time period simulated varies for different levels of O/D demand, based on the time needed to clear the traffic jam and return traffic conditions back to normal after the incident: 1 h and 15 min for light traffic conditions, 1 h and 30 min for moderate traffic conditions, and 1 h and 45 min for heavy traffic conditions.



**Figure 8** Impact of IVC on total system travel time (grid network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

As in the previous case, the first 30 min of the simulation is treated as a “warm-up” time period; statistical calculations are only for the time period following this warm-up period. For each unique input parameter combination, 30 different random

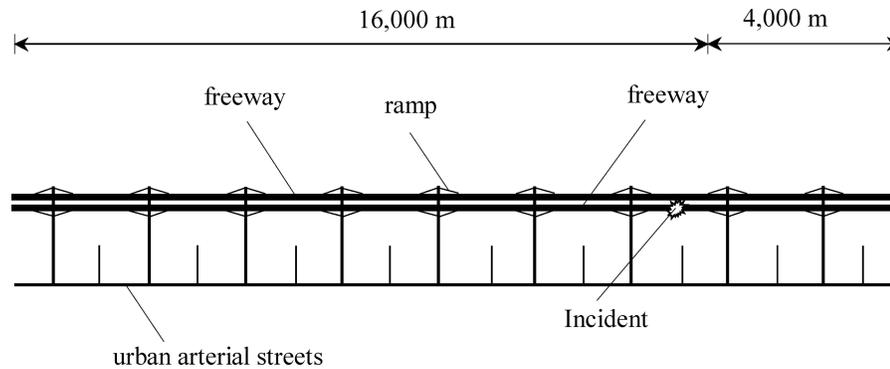


Figure 9 Freeway corridor test network.

seeds are used and our analysis is based on the average of all results.

### Behavioral Assumptions

For demonstration purposes, we assume conditions loosely associated with traffic arising from a daily commute period; we assume that the overwhelming proportion of drivers have familiarity with the network based on actual experience. As such, during the pretrip planning phase, routes are selected based upon the shortest path between each origin/destination pair, calculated using the experiential method for generating the historical traffic information database. Any rerouting decisions made by individual IVC-capable vehicles are according to a random number generated by the simulation at every decision point based on the calculated probability value from in-trip reroute binary-logit model specified by Eq. (8).

### Results

Rerouting rates for IVC-capable vehicles (relative to all vehicles), who are either directly (i.e., with routes that contain links on which the incident occurs) or indirectly (i.e., on routes that contain links that are impacted either by spillback or rerouted traffic) affected by the incident on the freeway, increase with higher IVC market penetration rates and longer communication radius ranges under all traffic conditions, as shown in Figure 10. Although in absolute numbers more vehicles with IVC capability reroute during their trips as IVC market penetration rate and communication ranges increase, rerouting rates for IVC-capable vehicles as a percentage of all IVC-capable vehicles decrease after reaching a maximal value, as shown in Figure 11.

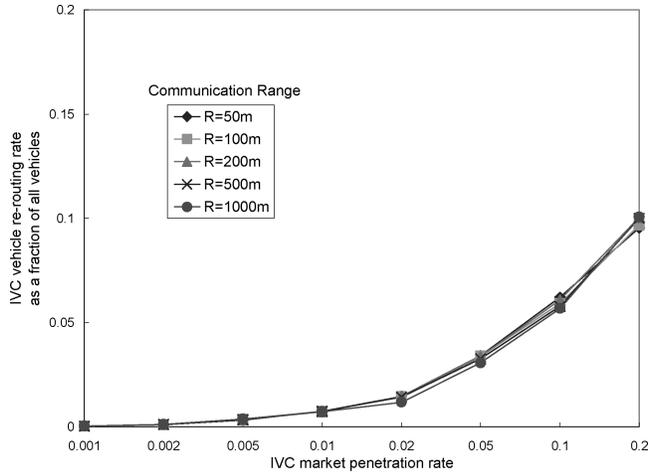
While increasing values of IVC market penetration rate and communication range generally result in more frequent raw traffic information generation and faster information propagation, ostensibly providing each driver with IVC capability greater opportunity to identify alternative paths with less congestion, the greater percentage of IVC-capable vehicles acting on this information produces fewer and fewer benefits for rerouting due to worsening of traffic conditions on their possible rerouting paths. Consequently, there is asymptotic behavior among IVC-capable drivers as the marginal benefits of rerouting approach a limit.

Figures 12 and 13 show results for average travel time comparisons between all IVC-capable vehicles (Figure 13), the subset of IVC-capable vehicles that rerouted (Figure 12) and non-IVC-capable vehicles traveling either on the freeway or arterial streets in the direction impacted by the incident. The results indicate that the rerouted IVC-capable vehicles generally (and expectedly) take less time to complete their trips than do vehicles confined to their initial paths; this result holds for all demand levels when the IVC market penetration rates are higher than a threshold value (approximately 0.2–0.5%; Figure 13), except for the combination of heavy demand and high market penetration (0.20). Results shown in these figures also indicate that the relative travel time savings for rerouted IVC-capable vehicles continuously increase with IVC market penetration rate and communication range to maximal values, decreasing thereafter. These results stem from the opposing effects of better and faster traffic condition estimation by which to optimize new routes with the higher IVC market rates and longer communication ranges and the deterioration of traffic conditions on possible alternative paths due to rerouted traffic (and the corresponding improvement on the initial paths resulting from the diversion).

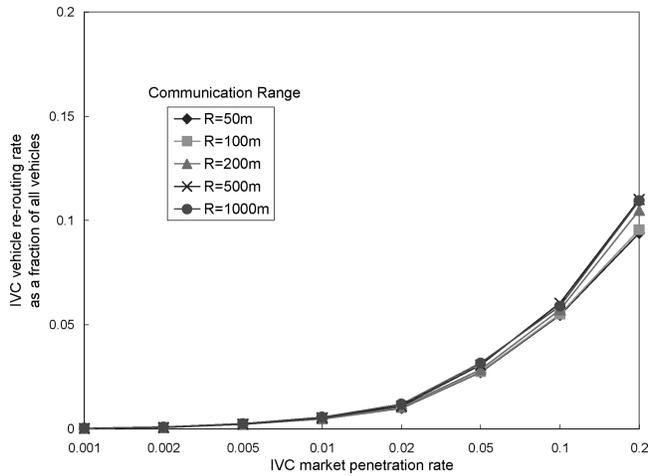
Total system performance as measured by the vehicle travel time for all vehicles potentially impacted by the incident over the entire simulation period (excluding the warm-up period) is shown in Figure 14. The results indicate that the impact of the real-time information provided IVC-capable vehicles is greatest under conditions of light to moderate traffic, during which there is sufficient excess system capacity to redistribute impacted IVC-vehicle traffic in a manner that moves the entire

Table 3 O/D Demands for Freeway Corridor Network

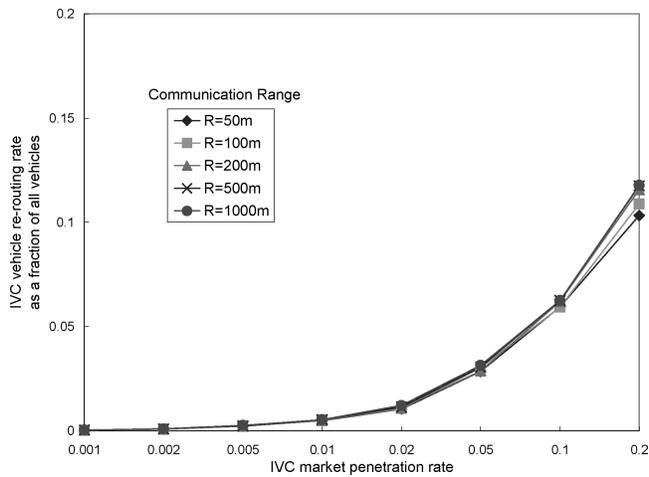
O/D Demand level	Freeway mainline flow rate (vehicles/hour)	Arterial streets flow rate (vehicles/hour)
Light	3000	500
Moderate	6000	750
Heavy	9000	1000



(a)

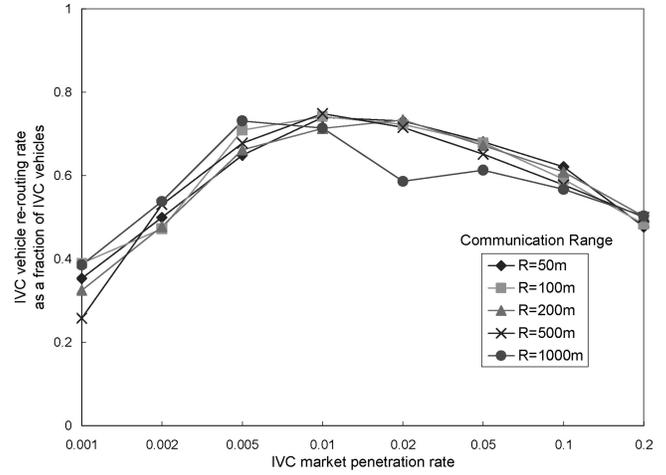


(b)

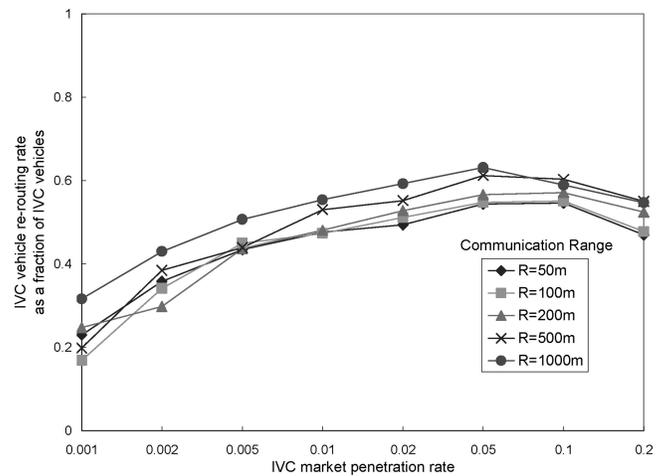


(c)

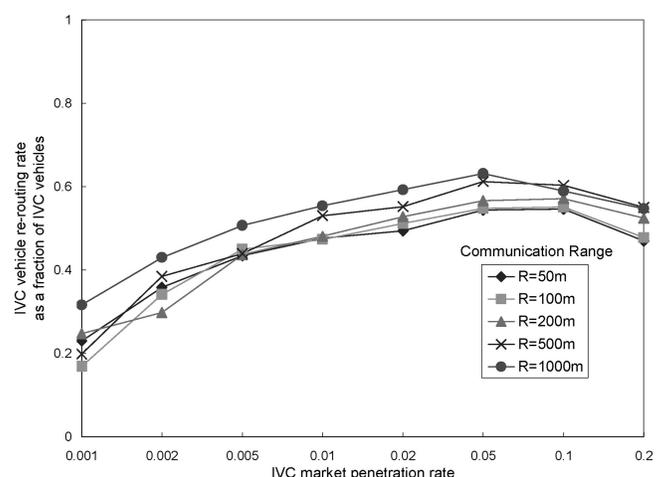
**Figure 10** IVC rerouting rate relative to total vehicle population (freeway network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.



(a)



(b)



(c)

**Figure 11** IVC rerouting rate relative to IVC vehicle population (freeway network) (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

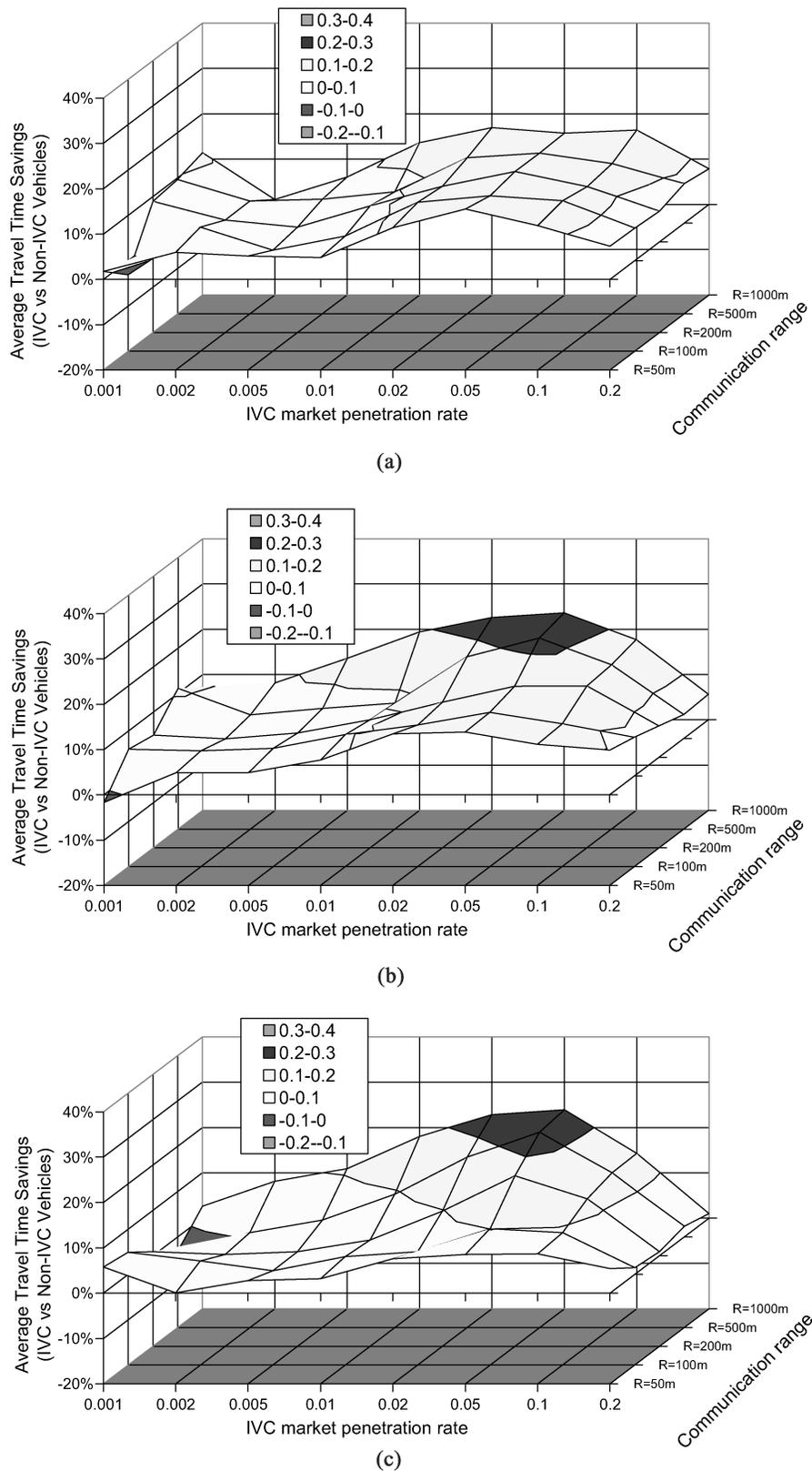
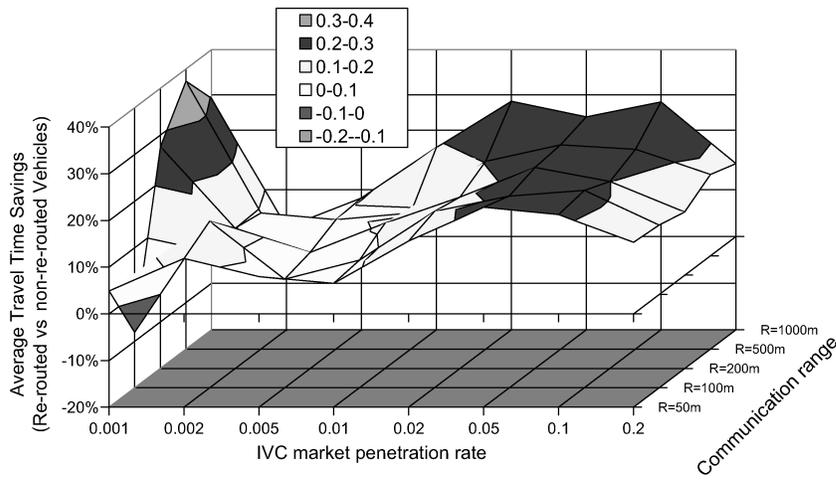
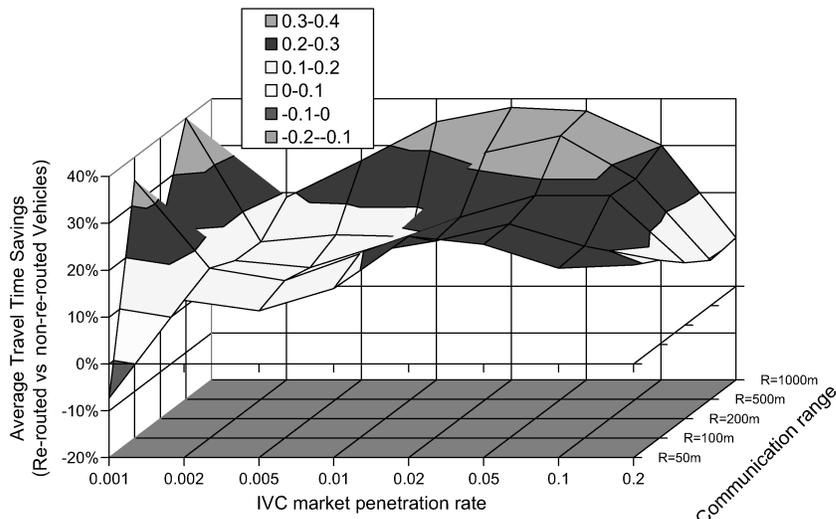


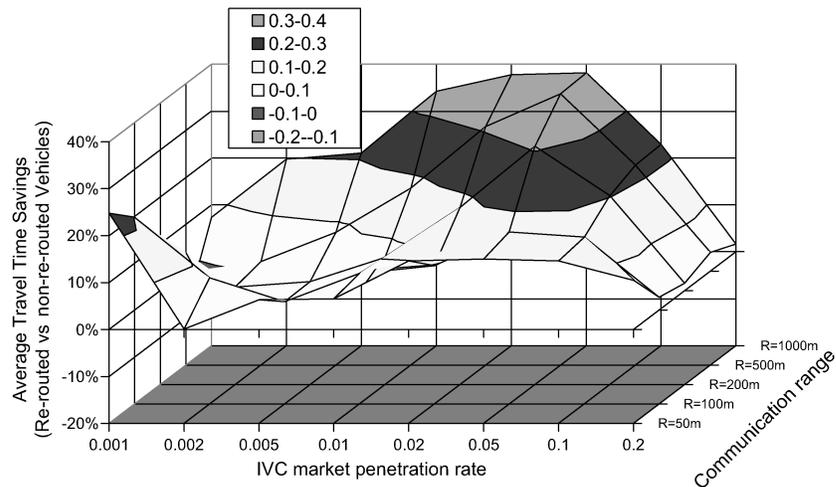
Figure 12 Relative time savings of IVC vehicles (freeway network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.



(a)



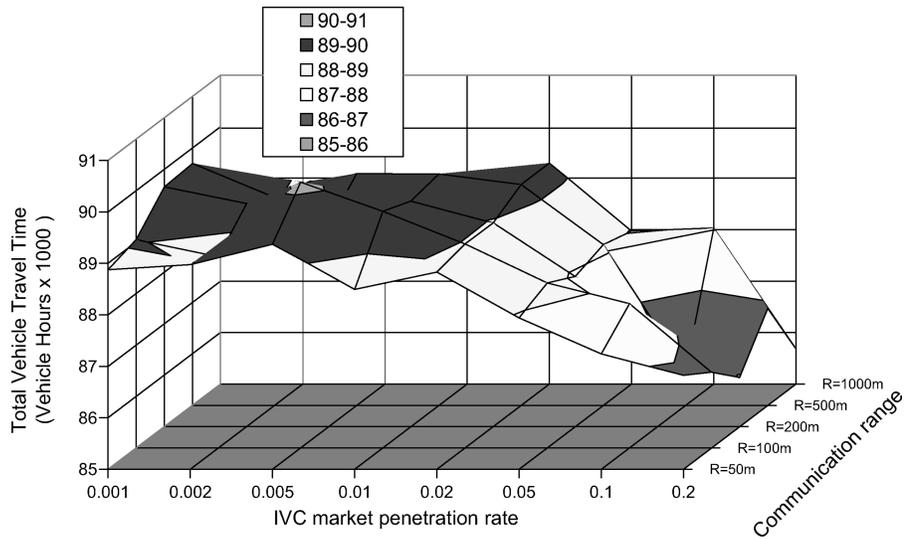
(b)



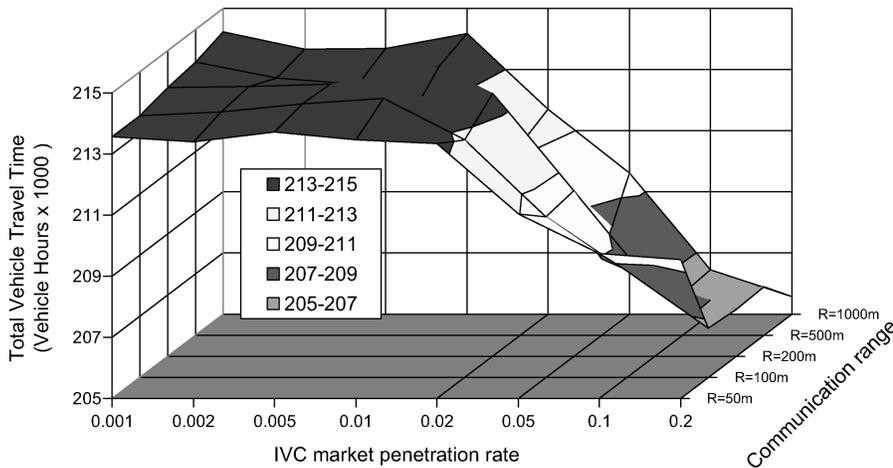
(c)

Figure 13 Relative time savings of rerouted IVC vehicles (freeway network) (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

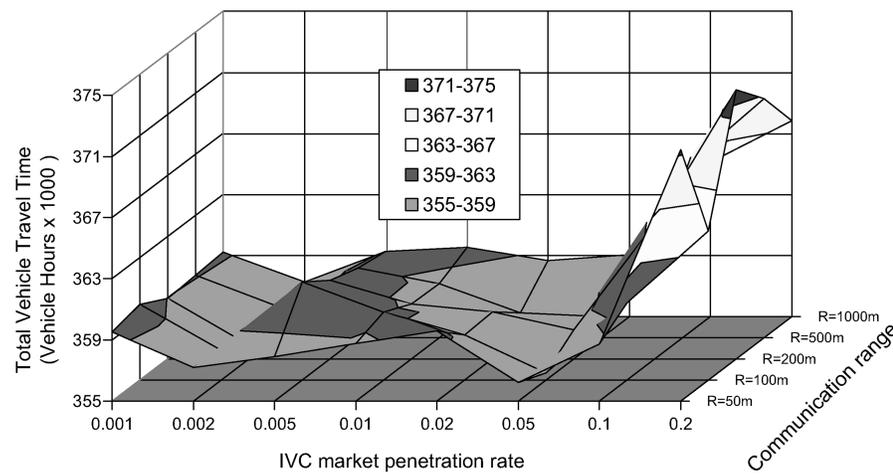
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(a)



(b)



(c)

Figure 14 Impact of IVC on total system travel time (freeway network). (a) Light traffic (b) Moderate traffic (c) Heavy traffic.

system toward system optimal conditions. Even at the higher IVC market penetration rates and longer communication ranges under light and moderate demand levels the travel time savings from rerouting is greater than the increase in travel time for vehicles not directly affected by the incident owing to the worsening of traffic conditions on the arterial streets on the rerouting paths. However, under heavy demand, less unused capacity exists on the arterial streets to accommodate rerouted vehicles, and system performance is not noticeably better and actually can become worse with high IVC market penetration rates and long communication ranges, as seen in Figure 14.

For most cases in the freeway corridor network, as increasing numbers of drivers have accessibility to real-time traffic information from intervehicle information exchange, the redistribution of IVC-capable vehicles enables the system to move toward user equilibrium. The characteristics of this freeway corridor network are such that a traveler has significantly fewer choices than in the grid arterial streets network (actually only having two basic choices—taking either the freeway or arterial streets from its origin to destination). Under normal traffic conditions the freeway system typically has much more capacity and a better level of service than its surface street alternative, leading to many more vehicles choosing to use the freeway system under these conditions; thus, even a relatively small amount of IVC-capable vehicles' rerouting from the freeway to arterial streets may dramatically worsen the traffic conditions on the arterial streets, resulting in a general worsening of system performance under heavy demand.

## CONCLUSIONS

Although dynamic on-line routing based upon advanced traffic information systems has been studied by researchers dating back to 1990, attention has been focused on centralized systems. Alternatively, the focus of this article is on modeling dynamic vehicle navigation in a distributed traffic information system built on vehicle-to-vehicle information exchange using a microsimulation modeling framework.

In our simulation modeling framework, two methods—static-network method and experiential method—are used to calculate link travel time values from which shortest paths from each origin to each destination are found that comprise the historical traffic information database. Drivers' pretrip route choices are modeled according to either a pretrip binary logit model or simply based on shortest-path selection in their trip planning phases. A path-based microscopic traffic simulation model is constructed to model vehicle navigation in the traffic network. During its trip, each IVC-capable vehicle generates link travel time information embedded in traffic information packets from its own full or partial traveling experience, following a roadway traffic condition sampling policy that combines both a time ba-

sis mode and a link basis mode. A modified exponential filter is used to smooth raw link travel time values to estimate current traffic conditions after each IVC-capable vehicles receives link-based information packets from any neighboring IVC-capable vehicles through peer-to-peer information exchange. In the simulation, each IVC-capable vehicle optimizes its own path based on its estimate of current traffic conditions and historical recurrent traffic congestion information, taking rerouting actions according to either a rational boundary model or binary logit model.

Some preliminary, demonstration, results on the potential efficacy of IVC are given for two networks—grid arterial streets network and freeway corridor network—under conditions representing non-recurrent congestion scenarios under various demand levels. Results from these cases help identify the conditions under which travelers with IVC capability to accurately estimate real-time traffic conditions can be expected to achieve time-savings through dynamic routing.

From our simulation demonstration under nonrecurrent congestion scenarios in the grid arterial streets network, we find that only when IVC market penetration rate is higher than some threshold value can IVC-capable vehicles make sufficiently accurate estimations of real-time traffic conditions to take rerouting actions. This threshold value is relatively high compared to freeway networks due to the dimensional characteristics of grid arterial networks compared to freeways. Although the relative travel time saving benefits for IVC-capable vehicles from rerouting decrease after reaching maximum values, the population of IVC-capable vehicles consistently maintains an advantage compared to their counterparts and total system performance generally improves by their re-routing. (Owing to the random terms in both the route-choice model and the traffic simulation model, it is certainly possible that a particular IVC vehicle could worsen its situation.) This result may be more representative of an upper bound in that in the pretrip route choice behavior model implemented for this grid arterial streets network, each vehicle (IVC-capable or non-IVC) can select the path from its origin to destination from a set of only two possible choices. In this particular grid test network, multiple similar route choices exist between each origin and destination, and each individual link in the network has a similar capacity. Because there are only two selectable choices in the simulation from possible multiple routes (mostly more than two) from each origin to destination, neither system optimum nor user equilibrium can be achieved generally under these conditions. Moreover, neither may be truly achievable in real-world transportation systems; however, the simulation results indicate that rerouting behavior enabled by IVC can move performance toward system optimal.

The results from the simulation of dynamic on-line routing under nonrecurrent congestion scenarios in the freeway corridor network indicate that even under relatively low IVC market penetration rates, IVC-capable vehicles can make sufficiently accurate estimations of real-time traffic conditions to take effective

rerouting actions. Traffic information dissemination along the freeway is greatly assisted by IVC-capable vehicles' movements in opposing lanes of the freeway and the "coverage" is universal in the sense that even a single vehicle will generally come in contact with every other IVC-capable vehicle in the lanes upstream of an incident. By way of contrast, in the two-dimensional grid arterial streets network, the intersection of any two IVC-capable vehicles' communication range is a function of the paths taken by the respective vehicles that are distributed in two-dimensional space rather than being confined to a single, linear path that virtually ensures the opportunity to communicate with opposing traffic.

Since rerouting decisions are based on the most recent link times in the IVC vehicles "real-time" data buffer, rather than on a "forecast" of future travel times on those links, over-response can occur if sufficient numbers of vehicles reroute and over-capacitate a link from which there is only limited opportunity to divert. This happens, for example, in the freeway corridor case for high market penetration under heavy traffic. Basically, upon receiving information of the freeway incident, IVC vehicles exit to the surface street alternative based on the current (or most recent) link times there; the surface streets become over-capacitated and, although further diversion to the surface street is limited to those vehicles that have older information based on the pre-congested state, the surface street system does not recover. As referenced in the text, this system behavior has been noted in other simulation studies and is verified here. Theoretically, this limitation can be overcome with incorporation of a traffic forecasting algorithm to accompany the real-time data; however, development of such an algorithm that would be robust enough to address the myriad of situations that might produce nonrecurrent congestion is likely a daunting task.

Except under heavy demand levels for the freeway corridor network noted above, overall system performance is shown to improve with dynamic rerouting as IVC market penetration rate and communication range increase. The results indicate that a distributed traffic information system built upon autonomously polling of vehicles as a means for traffic surveillance has the potential to not only bring benefits to travelers within the IVC information system, but also to benefit the traffic system as a whole in most cases.

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