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Simulation studies of information propagation in a self-organizing distributed traffic information system

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Abstract

This paper investigates the feasibility of a self-organizing, completely distributed traffic information system based upon vehicle-to-vehicle communication technologies. Unlike centralized traffic information systems, the proposed system does not need public infrastructure investment as a prerequisite for implementation. Due to the complexity of the proposed system, simulation is selected as the primary approach in the feasibility studies. A simulation framework is built based on an existing microscopic traffic simulation model for the simulation studies. The critical questions for building the proposed market-driven system are examined both from communication requirements and traffic engineering points of view. Traffic information propagation both in freeway and arterial networks via information exchange among IVC-equipped vehicles is tested within the simulation framework. Results on the probability of successful IVC and traffic information propagation distance obtained from the simulation studies are generated and analyzed under incident-free and incident conditions for various roadway formats and parameter combinations. Comparisons between the speed of the incident information wave and the speed of the corresponding traffic shock wave due to the incident are 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.

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1. Introduction

There has been growing interest in potential applications of the use of wireless communication between vehicles, usually referred to as inter-vehicle communication (IVC) (Varaiya, 1993). Almost all of the initial research efforts and applications in this area focus on advanced vehicle control systems (AVCS) in applications ranging from driver assistance/warning to fully autonomous driving (Aoki and Fujii, 1996; Kim and Nakagawa, 1997; Michael and Nakagawa, 1999; Tank and Linnartz, 1997; Verdone, 1997). Implementations can be found in ITS projects including RACS in Japan (Takada et al., 1989), PROMETHEUS in Europe (Catling and Belcher, 1989) and PATH in the United States (Shladover et al., 1991). A number of major automobile

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manufacturers (DaimlerChrysler, GM, Toyota, Nissan, VW, Ford, and BMW) have joined with USDOT to form a Vehicle Safety Communications Consortium to identify applications and to promote standardization of protocols in this area (National Highway Safety Administration, 2005). Similar applications in advanced transportation management systems (ATMS) and advanced transportation information systems (ATIS) have been much less well developed, but are beginning to emerge both in Europe (DaimlerChrysler AG, 2000; Definiens AG, 2001; Franz et al., 2001) and in the United States, where 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, 27 February 2004). As in the case of AVCS applications, cooperative groups are being formed to guide development and standards for ATIS applications, led by the Car 2 Car Communication Consortium (www.car-to-car.org) of European automobile manufacturers (Audi, BMW, DaimlerChrysler, FIAT, Renault, and VW).

In IVC-based ATIS, vehicles are envisioned to exchange precise position information from satellite navigation data (GPS) via IVC at low cost to optimize traffic flows and provide valuable, real-time traffic information to the drivers. The resulting network forms a decentralized autonomous system, with locally generated real-time traffic information and safety-relevant data, in which IVC-equipped vehicles are linked in a highly mobile ad hoc network to share necessary information. 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).

This paper investigates the feasibility of a distributed traffic information system based on inter-vehicle communication (IVC) technology. Specifically, using simulation modeling techniques, we determine the thresholds for some of the parameters necessary to support the systematic collection and provision of useful and in time (real-time or close to real-time) traffic information in a self-organized, distributed, *auto*nomous traffic information *net*work that is based upon the peer-to-peer information exchange among vehicles—an *autonet*.

Because mechanisms for information propagation include both ''hopping'' along vehicles moving in the same direction of flow as well as ''cross-transference'' of information to vehicles moving in the opposite direction, the system is characterized by a highly dynamic environment in which the traffic flow produces rapidly changing communication network topologies. Potential applications of this concept for traffic management and traveler information are intrinsically based on achieving information propagation throughout the traffic network; however, because penetration of the necessary technology to the fleet of vehicles can be expected to be gradual, a ''mixed'' network of IVC-capable vehicles and non-IVC capable vehicles will exist for some period of time. The concept closely follows that of SOTIS (self-organizing traffic information system) proposed by Rohling and his colleagues (Rohling and Ebner, 2001; Wischhof et al., 2003a,b; Wischhof et al., 2004).

In this paper, our focus is on the potential for the concept of IVC-based systems to serve aspects of transportation systems management; the traffic-oriented abstraction evaluation framework is developed without detailed electronic engineering and computer science modeling. We attempt to give answers to two questions: (1) What IVC equipment penetration rate is needed for information propagation to extend to a substantial part of the whole network under various traffic conditions? and (2) What IVC system requirement is needed to disseminate incident information faster than the attendant traffic/vehicle wave propagates through the network? We analyze these two issues for various possible IVC technologies and for different roadway network formats and different road traffic conditions.

2. Simulation framework

Because its complexity largely prohibits analytical modeling of any practical application, simulation typically has been used in studies of IVC, both where IVC-capable vehicles are modeled as static objects in a snapshot of moving traffic rather than as moving objects with dynamic interaction with other vehicles in the traffic network (Michael and Nakagawa, 1999; Briesemeister et al., 2000; Rohling and Ebner, 2001), as well as in studies modeling information flow combined with traffic flow, where IVC-capable vehicles are modeled as moving objects with dynamic interaction with other vehicles in the traffic network (Widodo and Hasegawa, 1998; Ziliaskopoulos and Zhang, 2003). Here, we employ microscopic simulation both for modeling vehicle movements in the traffic network, as well as for modeling inter-vehicle communication between neighboring IVC-capable vehicles. Specifically, we use PARAMICS (PARAllel MICroscopic Simulator), originally developed at EPCC (Edinburgh Parallel Computing Center) at University of Edinburgh in Scotland, as a "vehicle mover" based on its built-in car-following and lane-changing models; it functions underneath a complementary inter-vehicle communication simulation module that simulates information exchange among IVC-capable vehicles. The IVC simulation layer receives each IVC vehicle's speed and location information at each simulation time-step, and then, dependent on these speed and location data, emulates inter-vehicle communication and processes any new information received from other IVC vehicles in the simulation implementation during that time step.

Inter-vehicle communication, both via "hopping" along vehicles moving in the same direction of flow as well as via "cross-transference" of information to vehicles moving in the opposite direction, is modeled by the abstraction (Fig. 1) that neighboring IVC-capable vehicles may exchange information if the distance (D) between them is less than the communication radius range (R). This abstraction in the simulation modeling does not focus on the specific inter-vehicle wireless communication technologies in any detailed way.

In the simulations, each vehicle is released into the network according to a random distribution corresponding to a dynamic origin–destination table and is labeled randomly as being either IVC or a non-IVC capable, according to a pre-defined IVC market penetration rate (MPR) that represents the percentage of total vehicles in the traffic network with IVC capability. Once released, these vehicles distribute themselves along paths leading to their respective destinations according to car-following and lane-change protocols dependent on prevailing traffic conditions; the result is that the communications network topology is stochastic. At each simulation time step r (every $\Delta = 0.5$ s in this study)—called the communication cycle—the information content of each IVC-capable vehicle traveling in the network is updated with information from neighboring IVC vehicles within range. Information exchange is accomplished by two fundamentally different processes: (1) at any particular instant in time $t = \Delta \cdot r$, vehicles within range of each other "instantaneously" (i.e., based on the spatial distribution of IVC vehicles at that instant) exchange information in their respective buffers; and (2) at some later instant of time $t + \Delta t$, vehicles not within range of each other at time t may, through the dynamics of the traffic stream, arrive within the range of communication and exchange information (i.e., based on the evolution of the spatial distribution of vehicles at time t resulting from the dynamics of traffic). This latter mechanism of information transfer can occur both within the same stream of traffic (as a result of the dynamics of lane changing and car following principles that underlay the motion of individual vehicles) as well as between vehicles in opposing traffic streams as they pass one another (see Fig. 1).

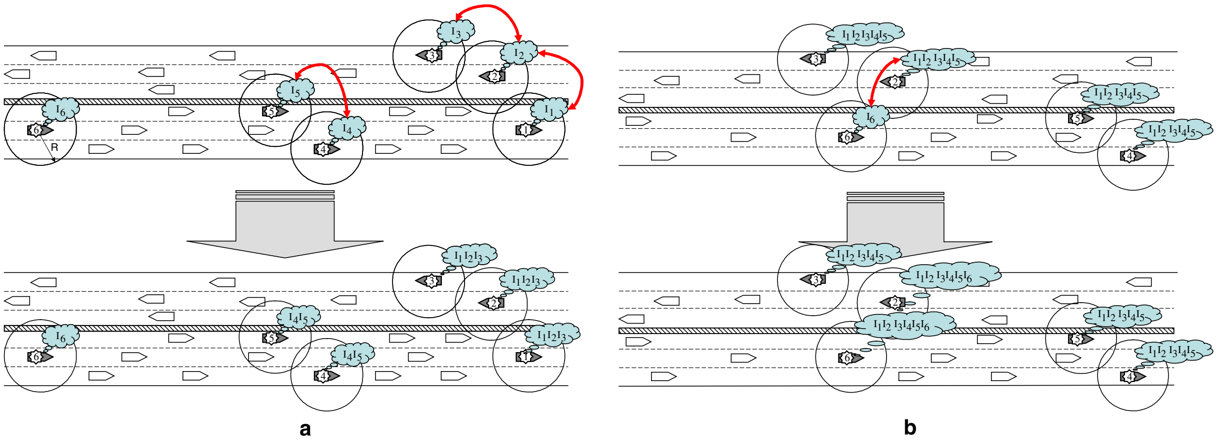


Fig. 1. Inter-vehicle communication modeling abstraction. (a) Snapshot of roadway segment at time = t. (b) Snapshot of roadway segment at time = $t + \Delta t$.

During the communication cycle, each IVC vehicle copies the contents of the information buffers of neighboring IVC vehicles into its information buffers, processes these contents, keeping useful parts and discarding non-useful parts. For non-incident cases, each IVC vehicle in the simulation network generates a packet, both for itself and for all vehicles that have communicated with that vehicle up to that time, that includes: (1) vehicle ID information, (2) message time stamp, t^*, indicating when the information was originally generated, (3) GPS location and speed of the vehicle generating information at the time of generation, (4) ID # of link on which the vehicle was traveling when it originally generated the information packet, and (5) the vehicle's travel time to traverse that link. "Incident-based" information packets are generated by IVC-capable vehicles passing by an incident location after the incident occurrence. In addition to the non-incident information described above, these packets include: (1) incident GPS location coordinates (x, y) as estimated by the IVC vehicle originally generating this incident information packet, (2) incident severity as estimated by the IVC vehicle originally generating this incident information packet, and (3) ID # of link on which incident occurs. During the communication cycle, each IVC vehicle assembles information packets from neighboring IVC vehicles within communications range into its incoming buffer, and then processes all incoming packets, together with existing packets stored in its processing buffer, according to the following criteria:

1. If the vehicle ID # in the packet is the same as its own vehicle ID #, discard it;
2. If the packet is generated by a vehicle traveling in the same direction of the roadway as current vehicle and whose location is upstream of the current vehicle location, discard it;
3. If the packet is generated by a vehicle traveling in the opposite direction of the roadway as current vehicle and whose location is downstream (relative to the point-of-view traffic moving in the opposite lanes) of the current vehicle location, discard it;
4. If the packet is from a vehicle ID # already stored in the target vehicle's processing buffer and the time stamp is newer than the one already stored, replace the old one with it; otherwise, discard it;
5. If the packet is from a vehicle ID # not previously stored in the target vehicle's processing buffer and its time stamp is newer than the current time minus the time-delay-limit parameter, keep it; otherwise, discard it.

Following this, the vehicle updates its processing buffer, cataloging travel time for each link in its map if any newly received link travel time information for that specific link is newer than that already stored in the map, and prepares to broadcasts all of the packets, including its map, at the end of that cycle.

The exchange of traffic-related information encapsulated in the packets among neighboring IVC vehicles enables individual IVC vehicles to evolve a composite picture of the traffic conditions in the network. Our primary objective in testing propagation of vehicle-based traffic information packets is to determine how far and how fast the location-sensitive traffic information can be disseminated in the traffic network based on our distributed system concept. To assist in this assessment, we focus our analysis on two outputs of the simulations: (1) *probability of IVC success*, and (2) *maximum information propagation distance*.

The *probability of IVC success*, $P_{\text{suc}}(r)$, is a measure of the percentage of IVC-equipped vehicles that successfully transmit information to one or more other so-equipped vehicles during any particular communication cycle, r. As previously discussed, the results of each simulation (for a given set of parameters) contain random fluctuations owing to the random number seeds used to generate the vehicles that enter the system as well as which of those vehicles are IVC capable. In our experimental design, thirty different random seeds are used to generate the simulation for each unique set of input parameter combinations (i.e., for each distinct set of R, MPR, and traffic flow densities); the average of all results is used for our analysis. Following an initial "warm-up" period (15 min), statistical calculations were obtained for 45 min of simulation, or a total of 5400 communication cycles for each simulation run; the 30 simulation runs for each set of parameters thus produced a total of 162,000 opportunities for IVC-capable vehicles in the network to communicate with each other. The results presented here are for an averaged value of $P_{\text{suc}}(r)$, defined as the percentage of IVC-equipped vehicles that successfully transmit potentially useful (i.e., not duplicative and with date stamp t^* within a specified tolerance of the current time; i.e., $t - t_{\text{tol}} \leqslant t^* \leqslant t$) information to one or more other so-equipped vehicles during any particular communication cycle, averaged over all communication cycles contained in the 30 simulation runs for each set of parameters. That is,

$$\overline{P}_{\text{suc}} = \frac{1}{n_{\text{c}} \cdot n_{\text{seed}}} \sum_{r=1}^{n_{\text{c}}} \sum_{s=1}^{n_{\text{seed}}} \frac{q_{rs}^{*}}{q_{rs}}$$

where q_{rs}^{*} is the number of IVC-capable vehicles that are able to transmit useful information to other such vehicles during the rth communication cycle of simulation run s, q_{rs} is the total number of IVC-capable vehicles in the network during the rth communication cycle of simulation run s, n_{c} is the total number of communication cycles in any particular simulation run (5400 in this study), n_{seed} is the total number of simulation runs for any particular set of input parameters (30 in this study).

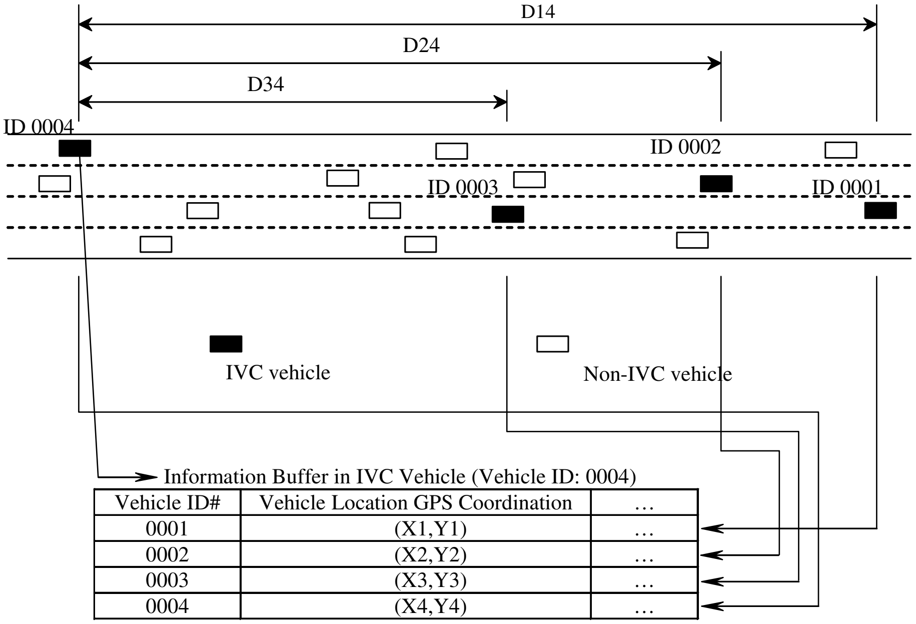
The *maximum information propagation distance*, at any time an indicator of how far the information flow has propagated in the traffic network, is a key factor in determining whether or not this information flow may potentially benefit the traffic system. For incident-free scenarios, *maximum information propagation distance*, $D_{\max}^{\text{NI}}(t)$, at any given time $t = \Delta \cdot r$ is defined as the maximum difference in distance between a IVC vehicle location and that of all of the downstream vehicles that have transmitted information packets to that particular vehicle. Formally,

$$D_{\max}^{\text{NI}}(t) = \max_{\forall v \in \mathbf{V}_{\text{IVC}}(t)} (d_j(t) - d_i(t) | \text{ID}_i \in I_j(t); d_i \leqslant d_j),$$

where $\mathbf{V}_{\text{IVC}}(t)$ is the set of all IVC-capable vehicles in the network at time t, $d_j(t)$ is the current distance of vehicle with vehicle ID # = ID_j from some arbitrary fixed point downstream, $I_j(t)$ is the current information buffer of vehicle with vehicle ID # = ID_j.

Fig. 2 shows an example of how maximum information propagation distance is calculated for each individual IVC vehicle.

For the incident scenarios, we are interested in the difference between the *maximum incident information propagation distance* and the associated distance that the traffic shock wave due to the incident has propagated; this latter distance is generated by the traffic simulation. Formally, *maximum incident information propagation distance* under incident conditions, $D_{\max}^{\text{I}}(t)$, at any time t is defined as:



Vehicle ID#	Vehicle Location GPS Coordination	…
0001	(X1,Y1)	…
0002	(X2,Y2)	…
0003	(X3,Y3)	…
0004	(X4,Y4)	…

Fig. 2. Maximum information propagation distance = $D14$. Propagation distances $D14$, $D24$ and $D34$ can be calculated based on values of (X_1, Y_1), (X_2, Y_2), (X_3, Y_3) and (X_4, Y_4) which are stored in IVC vehicle (vehicle ID:0004) information buffer. Since $D14 > D24 > D34$, $D14$ is the maximum propagation distance for this specific IVC vehicle (vehicle ID: 0004) at this specific time stamp.

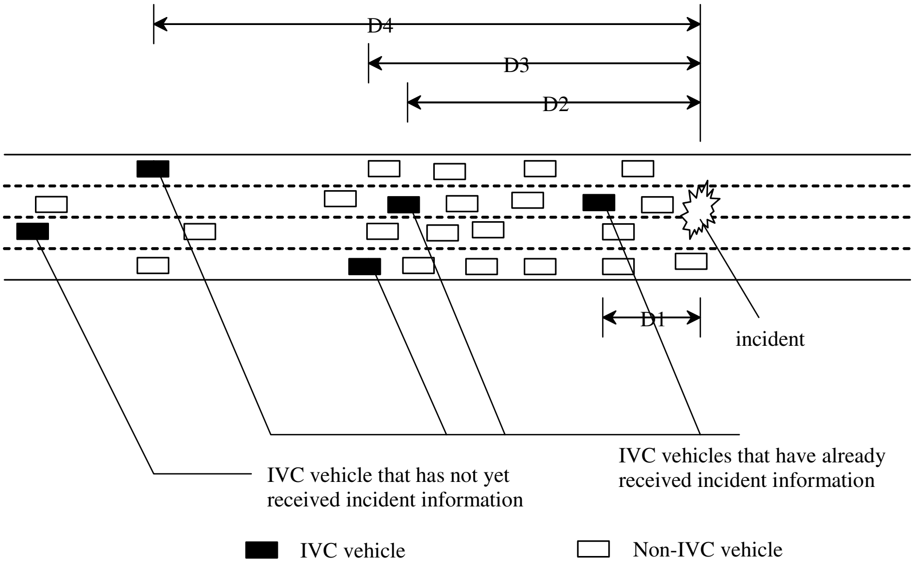


Fig. 3. Maximum incident information propagation distance = $D4$. Incident information propagation distances $D1$, $D2$, $D3$, $D4$ can be calculated based on the incident GPS location coordination values in the incident information packets which are broadcasted in the network through peer-to-peer information exchange and each individual IVC vehicle's GPS location coordination values. Since $D4 > D3 > D2 > D1$, $D4$ is the maximum incident information propagation distance for the entire network at this time step.

$$D^{\mathrm{I}}_{\max}(t) = \max_{\forall v \in \mathbf{V}_{\mathrm{IVC}}(t)} \begin{pmatrix} d_j(t) - d_{\mathrm{inc}} \ni \mathrm{ID}_i \in I_j(t); \\ \exists t^*, \mathrm{ID}_i | (x_i(t^*) - x_{\mathrm{inc}})^2 + (y_i(t^*) - y_{\mathrm{inc}})^2 \leqslant R^2_{\mathrm{inc}}, t^* \in [0, t] \end{pmatrix}$$

where d_{inc} is the distance of the location of the incident from some arbitrary fixed point downstream; x_i, y_i are the x, y coordinates of vehicle with ID # = ID_i; x_{inc}, y_{inc} are the x, y coordinates of the incident; R_{inc} is the local "broadcast" range of information emanating from the incident.

That is, the maximum distance between the current location of an IVC vehicle at any time in upstream traffic that has already received incident information via incident format packets generated by downstream vehicles and the location of the incident (Fig. 3).

As with the case of *probability of IVC success*, this measure, for any time t, is averaged over 30 different simulation runs for each parameter combination; i.e., the results presented are for

$$\overline{D}^m_{\max}(t) = \frac{1}{n_{\mathrm{seed}}} \sum_{s=1}^{n_{\mathrm{seed}}} \left[D^m_{\max}(t)\right]_s; \quad m = \mathrm{NI}, I$$

where $[D^m_{\max}(t)]_s = D^m_{\max}(t)$ obtained for the sth simulation run.

Because our research focus is on a feasibility analysis for the emergence of an Autonet-like system, we limit our investigation to the range of relatively low IVC market penetration rates (0.01–0.2) that might be experienced during the nascent period of the evolution of such a system. No particular IVC technology is specified in the simulation studies; 1000 m is specified as the maximum value for IVC communication radius based on specifying an upper limit that would include the communication range of DSRC under perfect conditions.

3. Information propagation in highway traffic via uni-directional exchange

We first present the results of simulation studies of one-way information propagation, i.e., information can be exchanged and propagated (upstream and/or downstream) only through IVC vehicles moving in the same direction. Our principal interest in presenting this case is twofold: (1) to establish a base for demonstrating the gains (if any) in information transmission efficiency provided by the flow of opposing traffic in the two-directional case considered in the next section, and (2) to compare the simulation results to theoretical results obtained for the idealized case of instantaneous propagation (in which the flow of traffic is irrelevant to the process).

Table 1
O/D demands for one-way 4-lane freeway

O/D demand level	Flow rate (veh/h)	Density (veh/km)
Light	2600	23
Moderate	6192	55
Heavy	9200	90

The roadway investigated in this case is one direction of an 8-lane (4 lanes in each direction) freeway with speed limit of 65 mph. Three levels of O/D demand, based on level of service (LOS) A, C and E for freeways from the Highway Capacity Manual (FHWA, 1996), are used in the simulation to generate "light", "moderate" and "heavy" traffic flow conditions, respectively, in the network; values of the related vehicle densities in the simulation are shown in Table 1.

The network simulated is 20 km in length; to avoid marginal effects from the boundaries of the network, statistical calculations are performed only when vehicles are within the 10-km long middle portion of the network. The simulations are intended to provide a preliminary vision of a system in which each IVC-equipped vehicle tries to maintain and update a real-time map containing the detailed traffic status of the network.

3.1. Uni-directional information propagation under incident-free conditions

The results of the simulations indicate that for uni-directional information propagation the flow of useful information will exist only when the IVC success probability either equals or is very close to 1. That is, the average *maximum information propagation distance* will be greater than the IVC communication radius range only if the *IVC success probability* at each time instant equals or is very close to 1 across the entire system; such conditions can arise either through sufficiently dense distributions of IVC vehicles in stable traffic streams or through less dense distributions in sufficiently turbulent traffic flow conditions to result in IVC vehicles having many different "neighbors" as they progress through the traffic stream (or a combination of these conditions). Strictly speaking, that every individual IVC-equipped vehicle can find another IVC vehicle among its neighboring vehicles within IVC communication radius range at any time is a practical pre-requisite in this case for the information chain not to be broken so as to allow information flow. Thus, in the one-direction propagation case, IVC equipment market penetration rate and vehicle density in the network must be above a relatively high threshold to support the proposed information system. For values of IVC communication radius range R less than 100 m, a market penetration as great as 0.2 is insufficient to achieve an *IVC success*

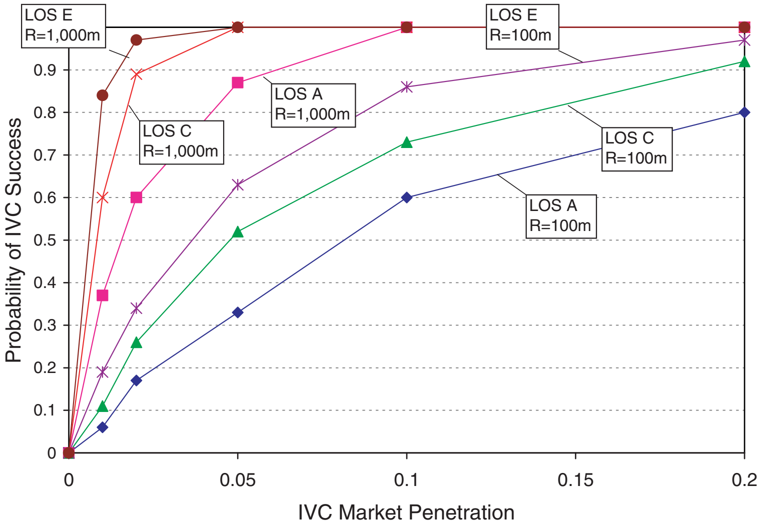


Fig. 4. Likelihood of successful information chain.

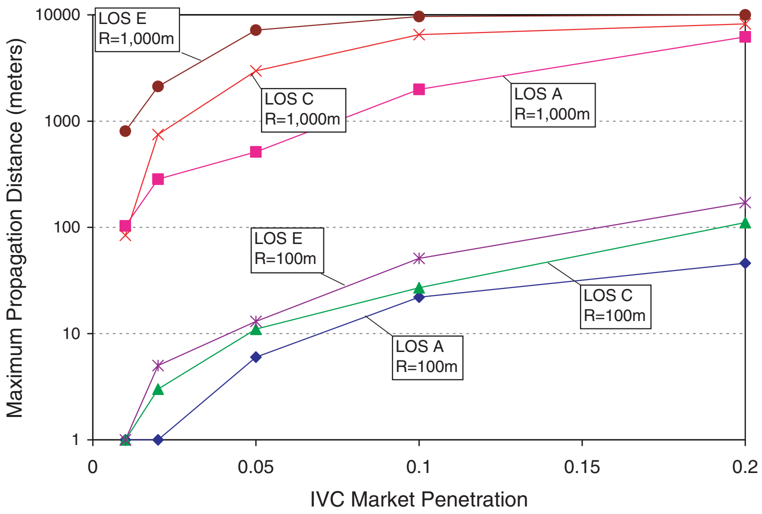


Fig. 5. Average maximum information propagation distance (60-s delay tolerance).

probability close to 1 (Fig. 4) even for dense traffic conditions (e.g., LOS E); consequently, under such conditions, average maximum traffic information propagation distances are less than the communications range (Fig. 5), which means that information flow is not achievable. (It is noted that the results for LOS E, $R = 1000$ m, in Fig. 5 are bounded by the 10,000 m limit to eliminate boundary effects in the calculation of statistics for the simulation.)

The results imply that it would be practically impossible to launch such vehicle-to-vehicle traffic information sharing systems at a low market penetration rate (less than 0.2) and with a limited communication range (e.g., on the order of 100 m) in traffic networks in which IVC is possible only between vehicles moving in the same direction. This result is easily explained by the nature of uni-directional information propagation. The information system in this case is just an overlay to the traffic flow that progresses from upstream to downstream. Since the direction of flow of information is reverse to the traffic flow direction, these two flows do not reinforce each other; rather, they combine to make useful information flow even weaker and slower.

The simulation results for this case can be compared (albeit somewhat loosely) to theoretical results obtained for the case of instantaneous information propagation in uniform traffic. Jin and Recker (in press) have shown that for multi-hop instantaneous information propagation on an infinitely long road a uniform stream of traffic with density ρ, a lower bound on the success rate for information to travel beyond the kth vehicle in cell c (where the length of a cell is defined as equal to the communications range) at h hops, is given by

$$s(c,k) = \max_{h} S(c,k;h)$$

where

$$S(c,k;h) = \sum_{(d,i)=(c,k)}^{(h,n)} P(d,i;h),$$

where $P(d,i;h)$ is determined from the recursive relationship

$$P(c+1,k;h+1) = \sum_{i=1}^{k-1}\sum_{j=1}^{i}\left(P(c,i;h-1) - \sum_{l=j}^{i-1} Q(c,l,i;h-1)\right)\mu^2 v^{n+i-k} + \sum_{i=k}^{n}\left(P(c,i;h) - \sum_{l=k}^{i-1} Q(c,l,i;h)\right)\mu v^{i-k}$$

with

$$P(1,k;1) = \mu\upsilon^{n-k}$$

where

$$Q(c+1,j,k;h+1) = \sum_{i=j}^{k-1}\left(P(c,i;h-1) - \sum_{l=j}^{i-1} Q(c,l,i;h-1)\right)\mu^2\upsilon^{n+i-k}$$

with

$$Q(1,l,i;1) = 0,$$

and where μ $(0 \leqslant \mu \leqslant 1)$ is the penetration rate of equipped vehicles, and $\upsilon \equiv 1 - \mu$.

Although the outputs of the simulation experiments are not directly comparable to these theoretical results, both because of the assumptions of uniform traffic and instantaneous propagation (relative to the traffic motion) as well as because the simulation is a realization of the probabilities rather than the probabilities themselves, we can nonetheless get a qualitative comparison of the general agreement between the theoretical values for the ideal case and the simulated. Displayed in Fig. 6 is a comparison of the simulation results relative to the maximum propagation distance cumulative probabilities predicted by the theoretical model for instantaneous propagation in uniform traffic for moderate traffic density (55 vehicles/km) and market penetration of 0.10. (This corresponds to one of the example scenarios contained in Jin and Recker, in press.) In the figure, the dotted lines correspond to the theoretical cumulative probabilities of the propagation distance, while the solid lines represent the distribution of the average (over all IVC-capable vehicles in the simulation) propagation distance obtained from 100 simulation runs. There is general agreement between these results; it is noted that the cumulative distribution for the simulation results have distinctly smaller variance owing to it being derived from the means of the maximum propagation distance from many vehicles in the traffic stream (each IVC-capable vehicle in the simulation produces a corresponding maximum distance for the extent of its information dissemination) while the theoretical results pertain to a single vehicle.

Another useful comparison to the idealized uniform instantaneous case that this simple uni-directional case affords involves the relationship between the probability of establishing an information chain and the interstitial distance between the limits of the communications range between successive IVC-capable vehicles. For uniformly distributed IVC-capable vehicles in a stream of uniformly spaced vehicles, at any instant the interstitial distance d^* between the limits of the communications range between successive IVC-capable vehicles (i.e., the distance between the trailing and leading edges of the communication ranges of two successive

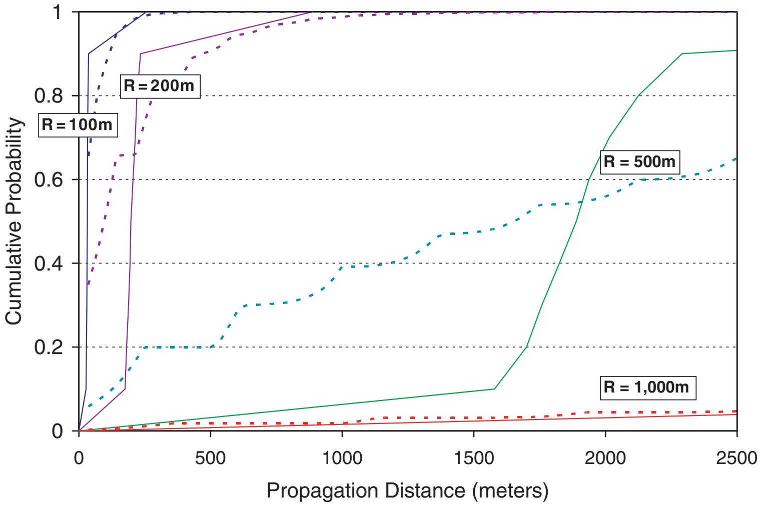


Fig. 6. Comparison of simulation results to theoretical estimates.

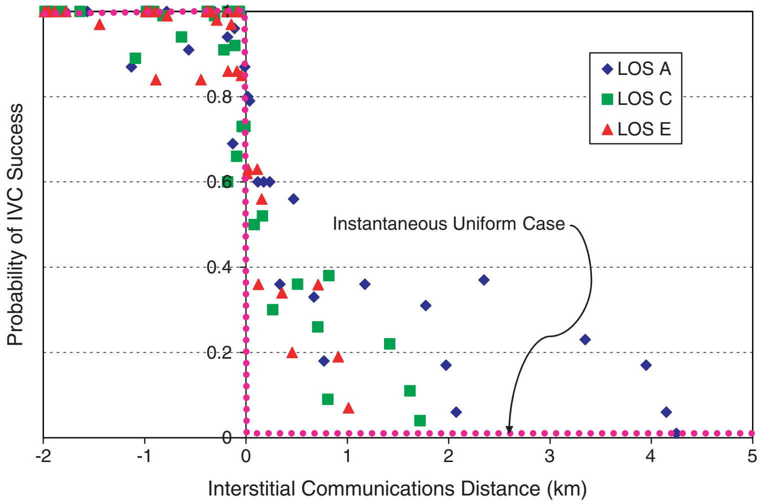


Fig. 7. Variation of probability of success with interstitial communications distance.

IVC-capable vehicles) is given by $d^* = (\text{traffic density} \cdot \text{MPR})^{-1} - 2R$. (The minimum value of d^*, -2, represents the case where two such vehicles are coincident.) Under the deterministic instantaneous uniform assumption, success in establishing an information chain obviously requires $d^* \leqslant 0$. Shown in Fig. 7 are the corresponding results from the simulation runs for the uni-directional case as a function of d^*; the extent to which these results deviate from the instantaneous deterministic case (shown by the dotted line) indicate the influences of stochasticity and traffic flow.

It is noted that as traffic density increases, the positive effects of traffic flow on information flow decrease; under heavy traffic conditions (LOS E), the simulation results approach the limiting instantaneous case, while under light traffic conditions (LOS A), the flow of traffic provides a mechanism whereby a vehicle's information can be "carried" to neighboring vehicles beyond the instantaneous interstitial distance.

3.2. Uni-directional information propagation under incident conditions

In this sub-section, we examine peer-to-peer information sharing and associated information propagation under incident conditions. For demonstration purposes, we present results for the simulation of an incident that totally blocks the roadway, rendering roadway capacity close to zero, occurs 4000 m from the downstream end of the network at 15 min after simulation begins and lasts for 30 min. After the incident occurs, and until the incident is cleared, any upstream IVC-equipped vehicles that are less than $R_{\text{inc}} = 50$ m from the incident location will generate an incident information packet and send out that packet. The practical question that needs to be answered for information propagation under incident conditions is whether or not the incident information wave propagates faster than the traffic shock wave propagates; there is not much value in a driver getting traffic information of an incident downstream if the driver is already stuck in the traffic congestion due to that incident and/or has already passed the critical point to make any re-routing decisions.

In order to estimate the location of the traffic shock wave at any time in our simulations, we divide the roadway into 100 m-long sections from the incident location to the end of the roadway in the upstream traffic direction. At each time step, the vehicle densities and average speed are compared for every neighboring upstream and downstream section. For purposes of this study, if the value of vehicle density in downstream section is greater than twice of the value of vehicle density in next to upstream section, and the value of average speed of vehicles in upstream section is greater than twice of the value of average speed of vehicles in next to downstream section, the traffic shock wave is determined to have arrived at the border between these two neighboring sections. Linear interpolation is used to estimate the traffic shock wave propagation distance at the specific time point at which the statistical information is calculated.

In the simulation, we compare the difference between the maximum incident information packet propagation distance, $D^{\mathrm{I}}_{\max}(t)$, and the location of the traffic shock wave at the same time (at $t = 1$, 5 and 15 min after the incident occurs). The results of the simulation are shown in Figs. 8a–8c, for three traffic conditions (LOS A, LOS C, and LOS E). Positive values of the difference between propagation distance of the incident information wave and the traffic shock wave indicate that the average information propagation speed (to that point in time) is greater than the traffic shock wave speed, and vice versa. The results indicate that, under the restriction of information being passed along vehicles moving in the same direction, it is only under heavy traffic conditions (LOS E) that information regarding the incident propagates at a pace to be potentially useful to upstream vehicles under even low market penetration rates (MPR). The results for $R = 1000$ m and MPR $\geqslant 0.10$ reveal a case of almost instantaneous propagation, and are not shown in the figure. Under moderate traffic densities (LOS C), a market penetration on the order of 0.10 is required (as in the case noted above, almost instantaneous propagation is achieved under LOS C for $R = 1000$ m and MPR $= 0.20$ and results are not shown in the figure), and under low densities (LOS A), a penetration rate on the order of 0.20 is needed. For moderate traffic and market penetrations below 0.10, and for light traffic and market penetrations below 0.20, the information wave front barely outpaces the traffic shock wave. The results also indi-

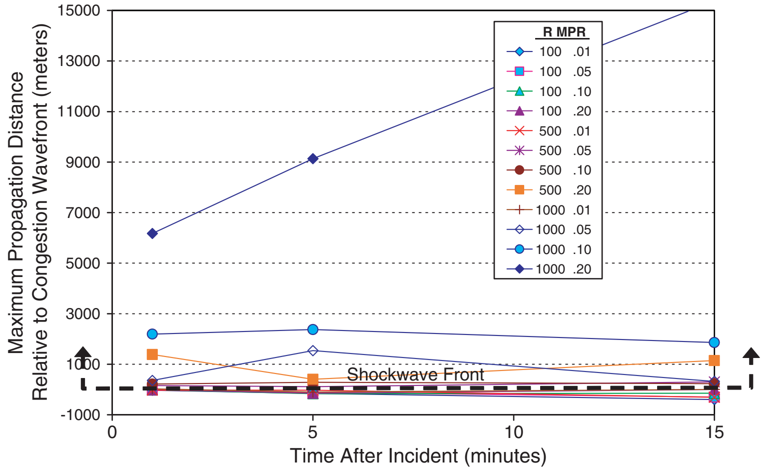


Fig. 8a. Difference between information wave front and traffic shockwave front (light traffic LOS A).

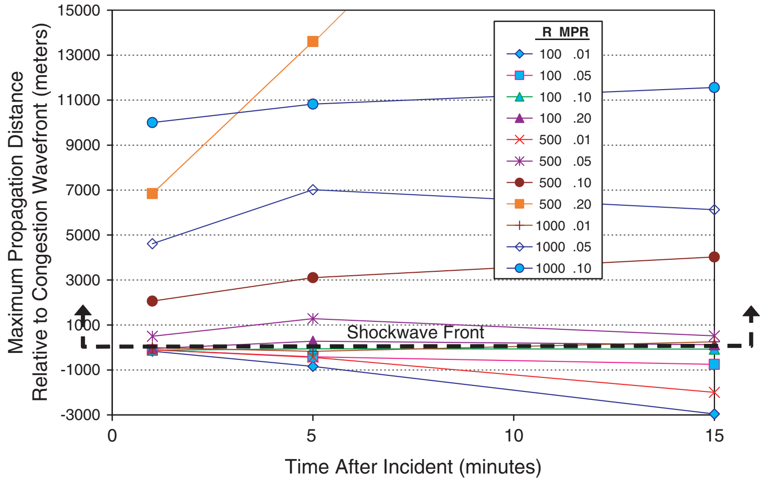


Fig. 8b. Difference between information wave front and traffic shockwave front (moderate traffic LOS C).

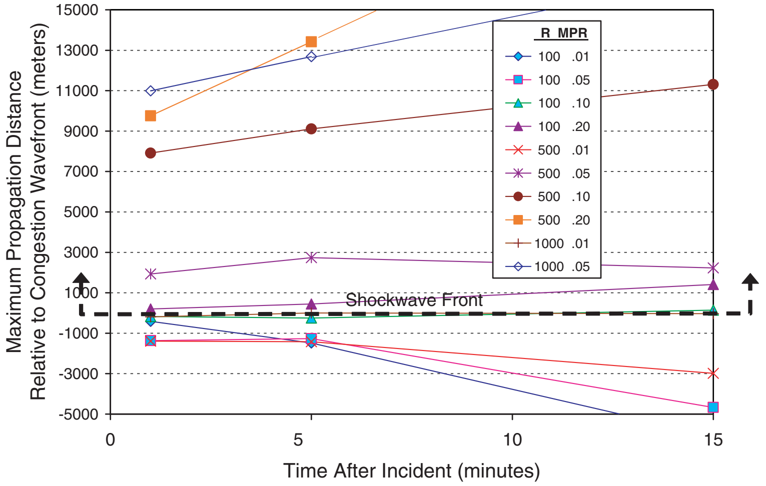


Fig. 8c. Difference between information wave front and traffic shockwave front (heavy traffic LOS E).

cate that if the IVC communication radius range is less than 500 m and market penetration rate is less than 0.2, the traffic shock wave caused by the incident travels faster than the incident information wave. The results virtually prohibit the evolution of the self-organizing, distributed traffic information system on networks in which vehicle information exchange can travel only between vehicles traveling in the same direction.

4. Information propagation in highway traffic via bi-directional exchange

We next investigate information propagation in freeway network in which the IVC-equipped vehicles moving in the same as well as in the opposite direction on the roadway exchange information. The roadway in this example is assumed to be a freeway with four lanes in each direction and speed limit of 65 mph; all other conditions for the simulations were identical to the uni-directional case described previously, with the slight modification in that we define maximum information propagation distance as the maximum difference in distance between the current IVC vehicle location and the locations of all other IVC vehicles, *moving in the same direction as*, *and downstream of*, *the current IVC vehicle* that generated vehicle-based packets contained in any particular IVC vehicle's data base, at the time of generation of their respective packets.

4.1. Bi-directional information propagation under incident-free conditions

In bi-directional information propagation, we are interested in the information propagation only from IVC vehicles in the downstream traffic to upstream IVC vehicles traveling in the same direction of the roadway (even though this information may be passed through vehicles moving in the opposite direction). In the simulation, once the IVC vehicle receives information packets from its neighboring IVC vehicles, it keeps and sends the information based on the location and time sensitivity criteria defined previously. Each IVC vehicle will keep information emanating from two sources: (1) information from IVC vehicles in the downstream of the same roadway direction, and (2) information from IVC vehicles in the upstream of the opposite roadway direction.

Compared to information propagation employing information exchange only among vehicles in the same stream of traffic, efficiencies and effectiveness of bi-directional propagation systems built upon inter-vehicle communication technology are significantly easier to achieve. Unlike the one-dimensional flow case, where each IVC-equipped vehicle has to find other IVC vehicles among a set of neighboring vehicles within IVC communication radius range moving at approximately the same speed in stable traffic (i.e., the topology of neighboring vehicles at all times is virtually constant) as a prerequisite for the information chain not to be broken, information flow in bi-directional propagation cases is aided by a rapidly changing mix of vehicles

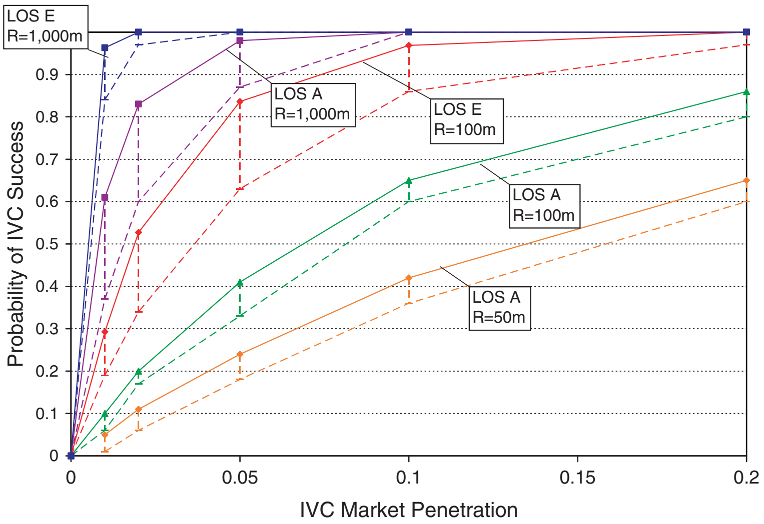


Fig. 9. Probability of successful IVC during any particular communication cycle.

passing the target vehicle in the opposite direction, virtually all of which are within IVC communication radius range, if only for a brief time. Thus, in the bi-directional propagation case, the threshold of IVC equipment market penetration rate and vehicle density in the network to support the inter-vehicle information system is expected be much lower compared to uni-directional propagation cases. This is a particularly important attribute since having a relatively low threshold for IVC equipment market penetration rate required to support such a decentralized and self-organizing system is critical to evolving the system. In marked contrast to the one-direction roadway case, here the two flows of traffic, moving in opposite directions, effectively increase the vehicle density in time domain in the bi-directional information propagation cases; traffic flow actually helps, rather than hinders, information flow to accelerate its propagation.

The results indicate that, although bi-directional information exchange increases the probability of successful communication during any particular communication cycle only marginally (Fig. 9), the average maximum information propagation distance in general will be much greater than the IVC communication radius range even if IVC success probability value is significantly less than 1.0 for the whole system (Fig. 10, for a delay tolerance of 60 s.). (For reference, in Figs. 9 and 10 the corresponding values for the uni-directional case are shown by the dashed lines.) This means that, by virtue of inter-stream transference, the information chain is not easily broken even if IVC equipment market penetration rate and vehicle density values in bi-directional freeway traffic networks are relatively low.

For IVC communication radius range value of 50 m, which is the smallest value used in our simulation studies, and IVC market penetration rate of 0.01, which is the smallest value that we tested in our studies, IVC success probability is much less than 1 (see Fig. 9) for any traffic conditions; yet, the traffic information propagation distance (see Fig. 10, where again the 10,000 m asymptote for some cases is an artifact of the limits of statistical calculation) is much longer than the communication radius range, making information flow possible in the traffic network. All results imply that it is quite possible that a vehicle-to-vehicle information sharing based traffic information system could be functional at the low market penetration rate (less than 0.02) even if the IVC technology only allows neighboring IVC-equipped vehicles exchange information when the distance between them is less than 50 m.

4.2. Bi-directional information propagation under incident conditions

The results for incident information wave propagation vs. traffic shockwave propagation under incident conditions in bi-directional freeway show trends similar to those obtained in the initial analysis under incident-free conditions. We get the similar conclusion that, compared to one-direction information propagation

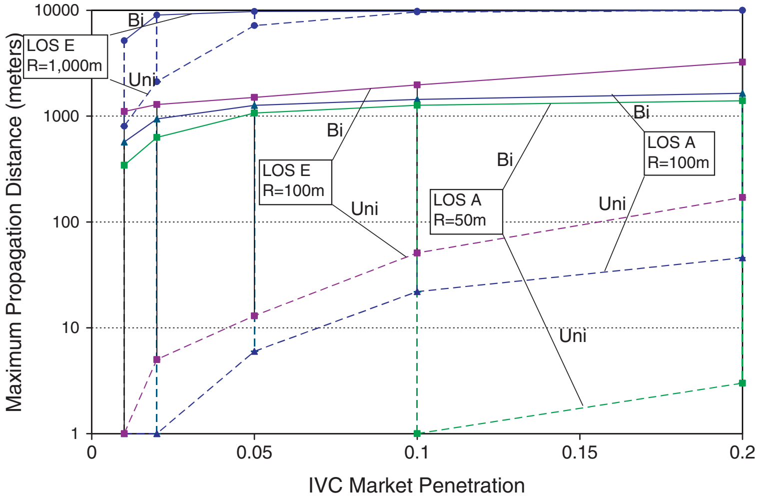


Fig. 10. Maximum propagation distance under bi-directional communication.

cases, it is much easier to achieve a functional Autonet system at a low market penetration rate (equal to 0.01) even if the IVC technology allows neighboring IVC-equipped vehicles to exchange information when the distance between them is no greater than 50 m (provided that information exchange includes vehicles moving in opposite directions). As shown in Figs. 11a–11c, in which the propagation distance differences between the incident information wave and traffic shock wave are plotted for various levels of market penetration (MPR), communications range (*R*), and traffic density in the freeway lanes opposite to the incident (XLOS), the values of propagation distance differences for incident information wave and traffic shock wave are significantly greater than zero for IVC communication radius range as small as 50 m and marker penetration rate as low as 0.01. (*Note:* In Fig. 11a, the corresponding results for the unidirectional case with $R = 1000$ m and MPR $= 0.2$ are provided for comparative purposes; for unidirectional cases involving LOS C and E, the information propagation is essentially instantaneous for $R = 1000$ m and MPR $= 0.2$ and are not shown.)

In the bi-directional case, the two opposite traffic flows not only effectively increase the vehicle density in the time domain, but also allow IVC vehicles in the direction of the roadway impacted by the incident to get incident information through IVC vehicles in the other direction of the roadway not impacted by the inci-

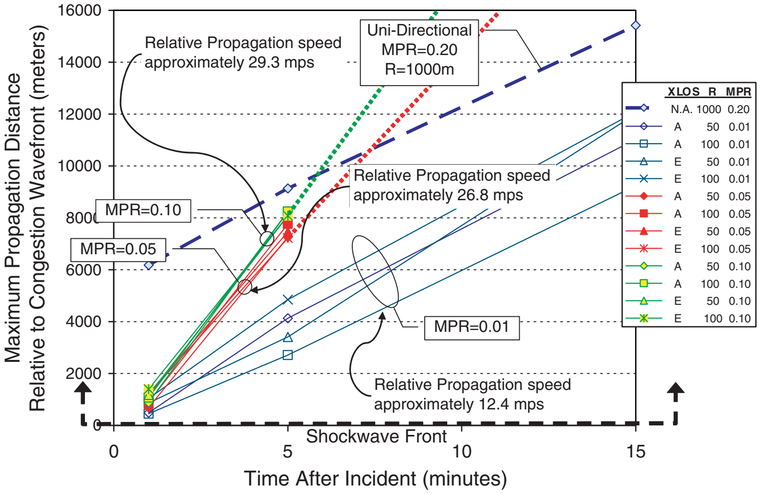


Fig. 11a. Difference between information wave front and traffic shockwave front (light traffic LOS A).

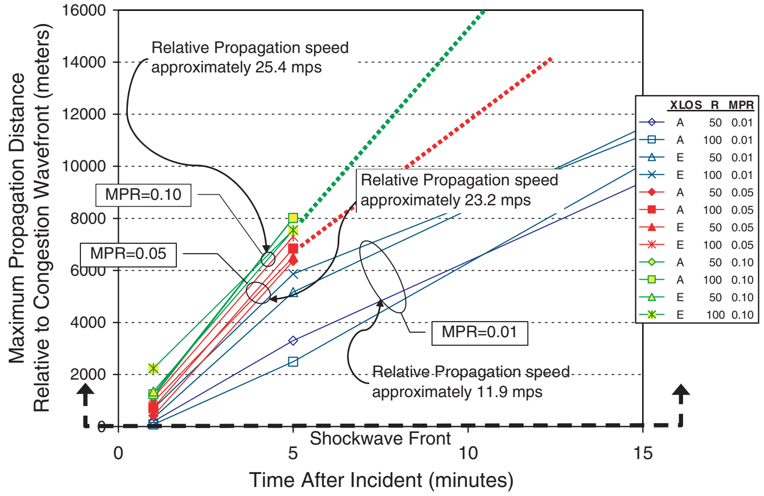


Fig. 11b. Difference between information wave front and traffic shockwave front (moderate traffic LOS C).

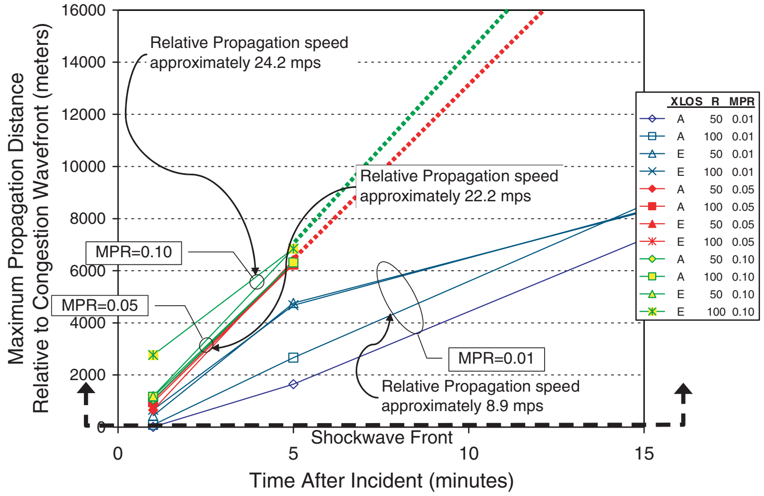


Fig. 11c. Difference between information wave front and traffic shockwave front (heavy traffic LOS E).

dent. In this way, traffic flow helps information flow to accelerate its propagation speed under incident conditions.

For communications ranges greater than 100 m, the propagation of incident information relative to the congestion shockwave front is virtually instantaneous for all market penetration rates considered. For conditions displayed in Figs. 11a–11c (i.e., relatively low market penetration coupled with relatively short communications range), the relative speed of propagation of the incident information depends on the directional traffic conditions (LOS and XLOS), as reflected by the probability of successful communication between two vehicles. The speed itself is influenced both by any delay in the observation of the incident (e.g., caused by the chance arrival of an IVC-capable vehicle in the opposite lanes of traffic) and the actual propagation of the information via either multi-hop along the traffic queued behind the incident or through the "carrying" of the information upstream by vehicles in the opposing lanes of traffic (or a combination of the two). For combinations of low market penetration rates and light traffic in the opposing lanes, the observation delay can be significant—roughly speaking, observation delay = 1/(flow rate ∗ IVC (%)). Correspondingly, the information packet propagation is mostly affected by the probability of successful IVC. At sufficiently high levels of the probability of success (e.g., combinations of high market penetration, large communications radius, and dense

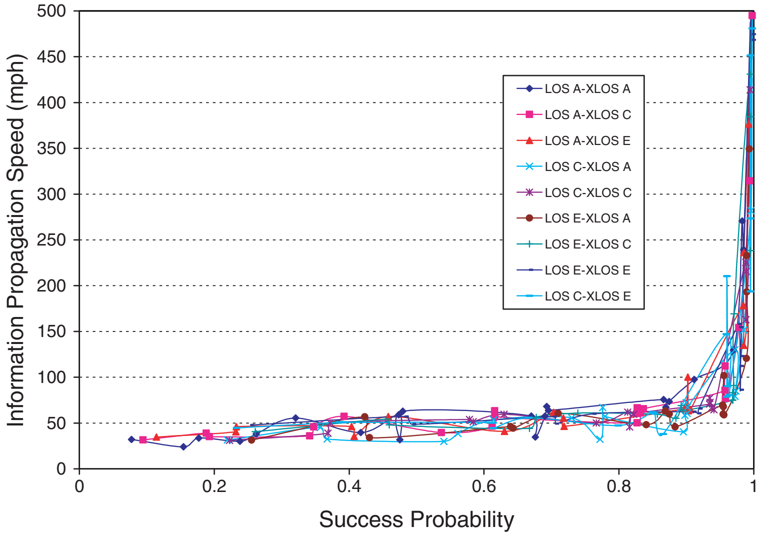


Fig. 12. Relationship between information propagation speed and probability of successful IVC between any two vehicles.

traffic), information propagation is mainly by multi-hop IVC which should be virtually instantaneous (limited only by IVC technology); otherwise vehicle movement in opposite direction should be the primary mechanism to pass along the incident information packet (limited by the speed of the opposing traffic, i.e., 50–70 mph). The combination of these effects is captured by the relationship between information propagation speed and probability of successful IVC, as shown in Fig. 12.

5. Information propagation in arterial networks

In this section, we turn our focus to two-dimensional arterial street networks. In our simulation of information dissemination in the arterial networks, the traffic information wave propagates in two-dimensional space. Three levels of O/D demand (assumed uniform) are used in our simulation studies to generate light, moderate and heavy traffic flow conditions in the arterial network. Table 2 shows average vehicle speeds and vehicle densities under these three O/D demands conditions in the simulation.

The arterial roadway network investigated in our studies consists of a 5000 m × 5000 m grid; the distance between any two neighboring signalized intersections is 1 km. The network is modeled with 144 two-direction links; each direction of an individual link is a 2-lane 500 m-long local street roadway with speed limit of 45 mph. Fig. 13 shows a sketch of the study network.

In order to avoid marginal effects from the networks when vehicles are either just released from their origins or will arrive at their destinations, statistical calculations are performed only when vehicles are in the 2.5 km × 2.5 km middle area of the network (see Fig. 13).

5.1. Information propagation in arterial networks under incident-free conditions

The mix of multiple traffic flows and information flows in the two-dimensional arterial study network causes the relationships between these flows and information dissemination by inter-vehicle communication

Table 2
O/D demands for two-dimensional arterial network

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

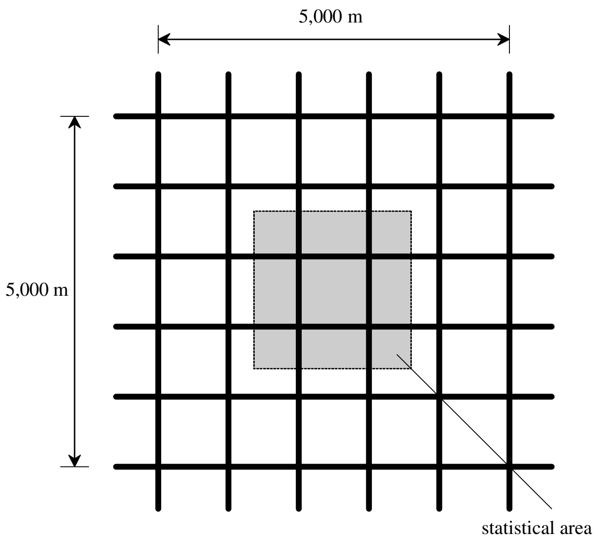


Fig. 13. Arterial grid network.

to be extremely complicated. Because vehicles are distributed in two-dimensional space, vehicle density in the traffic network is greater than in the one-dimensional space of the freeway cases; correspondingly, IVC-equipped vehicles generally have a greater chance to exchange information under the same IVC market penetration rate. On the other hand, information flow is not aided as much by traffic flow as in two-direction freeway cases because of slower-moving traffic in arterial street networks—a result of intersection signal control. From Fig. 14, we can see that even in heavy traffic conditions, individual IVC-equipped vehicles cannot consistently find other IVC vehicles among neighboring vehicles within IVC communication radius range for a market penetration of 0.20 and values of communication radius range less than or equal to 100 m.

For the arterial case, instead of maximum propagation distance (the uni-dimensional measure used in the freeway case), we focus on a measure of how broadly the traffic information is disseminated in the two-dimensional traffic network under some specific tolerances regarding the age of the information. Specifically, we define as *link travel time coverage percentage*, $\mathrm{TT}_{\mathrm{cov}}(r)$, the average among all IVC vehicles in the network

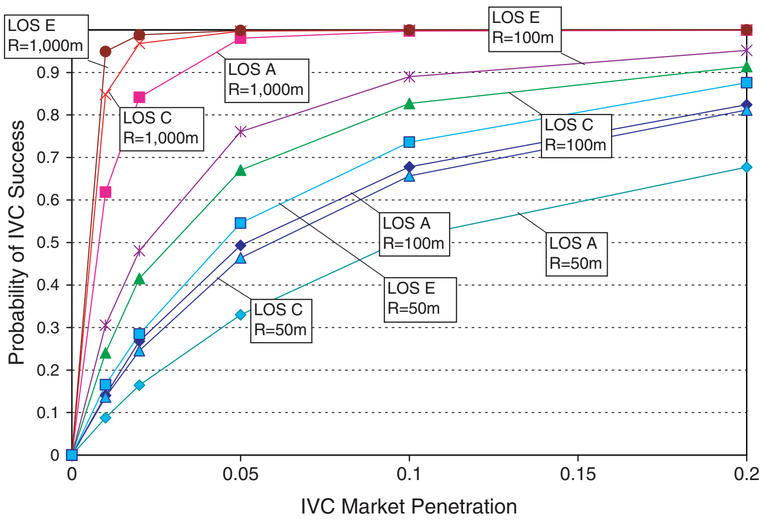


Fig. 14. Likelihood of successful information chain.

during the rth communication cycle of the ratio of the number of links for which travel information stored in each IVC vehicle is newer than the current time minus some time delay parameter, t_{tol}, to the number of total links in the study network. That is,

$$\mathrm{TT}_{\mathrm{cov}}(r) = \frac{1}{|\mathbf{V}_{\mathrm{IVC}}(t)|\cdot|\mathbf{N}|}\sum_{\forall v\in\mathbf{V}_{\mathrm{IVC}}}\sum_{\forall l\in\mathbf{N}}\delta_v^l(r);\quad r=1,\ldots,n_{\mathrm{c}}$$

where $\mathbf{N}$ is the set of network links included in the statistical calculations,

$$\delta_v^l(r) = \begin{cases} 1 \text{ if information regarding link } l \text{ in information buffer of vehicle } v \text{ is more recent than } t - t_{\mathrm{tol}} \\ 0 \text{ otherwise.} \end{cases}$$

The results for this measure averaged over all communication cycles and simulation runs, i.e.,

$$\overline{\mathrm{TT}}_{\mathrm{cov}} = \frac{1}{n_{\mathrm{c}}\cdot n_{\mathrm{seed}}}\sum_{r=1}^{n_{\mathrm{c}}}\sum_{s=1}^{n_{\mathrm{seed}}}\mathrm{TT}_{\mathrm{cov}}(r)$$

are shown in Fig. 15.

Since vehicles can move in multiple directions in urban arterial street networks, there is no requirement for each individual IVC-capable vehicle to find other IVC vehicles in its neighboring vehicles within IVC communication radius range during every communication cycle for the information chain not to be broken. Consequently, it would be expected that information should be more easily disseminated in urban traffic networks than in one-direction freeway networks. However, because of the significantly lower speed of vehicles moving in urban streets due to stop-and-go traffic patterns arising from intersection traffic signal controls (as compared to relatively fast-moving vehicles in freeway networks), information propagation in urban networks is much slower than in two-direction freeway networks. We find from these very limited studies that an information chain can be built in this particular idealized urban arterial network for relatively low IVC market penetration rates only for communication radius range on the order of 500 m, or about half the distance between intersections. However, it must be emphasized that the simulation presumes that communication can be established without line-of-sight requirements, or without interference. In real-world cases, the results could be significantly worse than in the simulation, since IVC communication conditions could be compromised by the high density of high-rise buildings in urban areas, which would tend to produce an IVC communication success rate much lower than the conditions assumed in the simulation.

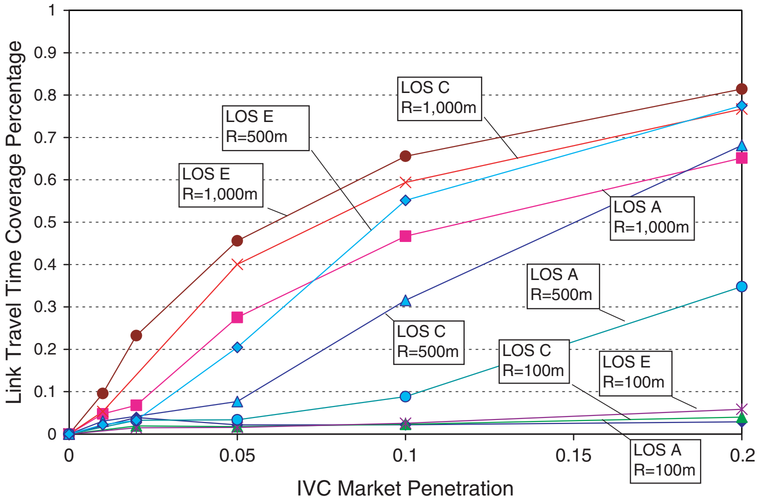


Fig. 15. Percentage of links with "real-time" travel time information (information delay tolerance = 60 s).

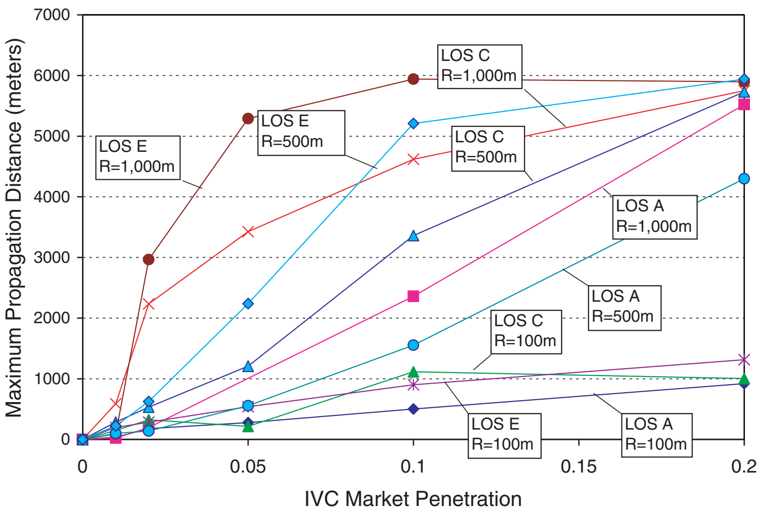


Fig. 16. Maximum information propagation distance (information delay tolerance = 60 s).

5.2. *Information propagation in arterial networks under incident conditions*

In the simulation of the incident scenario, an incident that causes total blockage in one direction of the roadway and renders roadway capacity in that direction close to zero, is assumed to occur on a link that is close to the center of the study grid network. Although using the same concept as used in the freeway cases, here we calculate maximum incident information packet propagation distance, the maximum difference between the incident location and locations of the IVC vehicles which have received incident information packet at any time t after the incident occurs, using Manhattan rather than Euclidean distance. (Manhattan distance is the distance between two points measured along axes at right angles.) The Manhattan propagation distance of the incident information at $t = 60$ s following the accident for various parameters is shown in Fig. 16.

The results indicate that, even for relatively low market penetration rates, incident information can be expected to propagate effectively under all traffic conditions for communications ranges greater than about 500 m. (Note that, in Fig. 16, the asymptotic behavior toward 6000 m is due to the information wave having met the boundary of the simulated network.)

6. Summary and conclusions

In summary, in this paper we focus on the evaluation of a self-organizing, distributed traffic information system from the viewpoint of transportation engineering, studying traffic information propagation in the traffic networks using a simulation framework. The feasibility analysis of the proposed system, assumed to be market-driven, self-maintained and totally independent of any public infrastructure, is designed to shed some light on certain wireless communication requirements under various traffic conditions and network formats.

Following the analyses of the results of the simulation studies, some conclusions are finalized as follows:

1. It may be extremely difficult to evolve the proposed self-organizing vehicle-to-vehicle based system to support information propagation for location sensitive, real-time traffic information in freeway networks in which communication is only among vehicles moving in the same direction, especially if the IVC equipment market penetration rate is low and communication radius range is short—two conditions that are likely to characterize the proposed system in its start-up period. Under incident conditions, for such market conditions and available IVC technologies, the incident information wave generally travels slower than does the traffic shock wave due to the incident.

2. For market conditions and available IVC technologies that are likely to prevail during the system's start-up period, the incident information wave generally travels faster than the traffic shock wave due to the incident freeway networks in which vehicles that are moving in opposite directions in close proximity to each other can exchange information.
3. Traffic information dissemination in two-dimensional urban arterial networks via information exchange among IVC-equipped vehicles is also easier to achieve than in one-direction freeway network cases; however, propagation speed is generally slower than in two-direction freeway network cases. Bandwidth/data rate requirements for IVC in urban arterial streets are expected to be relatively high because of the representation of the complex network configurations and high density of vehicles in the traffic network due to the distribution of vehicles in two-dimensional space.

There are many potential directions in which the research in this paper can be extended and improved. In this initial stage of the analysis of the proposed system, vehicle-to-roadside station communication is not included in the simulation evaluation framework developed for this research. In order to study the full version of the system proposed, the communication between vehicle and roadside infrastructure should be integrated into our simulation evaluation framework. The characteristics of roadside vehicle communication (RVC) need to be identified and modeled in the simulation framework. A system integrating IVC and RVC could potentially have an explicit transportation systems management focus.

This paper investigates the propagation traffic-related information based upon "raw" data without being systematically processed for a specific purpose. Research aimed at better understanding of the traffic status of the traffic network based on the distributed traffic information may prove to be critical for each driver with IVC equipment to process information efficiently. Data mining or statistical methods may be utilized for distributed data processing to estimate the traffic condition in the network more accurately. Distributed traffic information processing will be an interesting topic, since the processing field traffic data for further usage traditionally has been centralized.

Issues related to bandwidth are generally too complicated to be addressed in this paper. Questions of what frequency is required to pass real useful data while not sending too much duplicate/similar data, what kind of data is useful or not useful, how quickly (timeliness) the data is needed, all need to be addressed. The answers to these questions relate to how to best organize the data, both for the individual vehicles own use as well as passing to others. Bandwidth is of course related to communication cycle—the less frequently data is broadcast to neighboring vehicles the less data (duplicate/similar or not duplicate/similar) transmitted between vehicles, leading to less bandwidth needed. Alternatively, infrequent broadcasting may lead vehicles within communication range to miss opportunity to exchange necessary or useful information, leading to the information chain to be easily broken. A proper treatment of these issues is well beyond the scope of the paper, which is intended to demonstrate the feasibility of such an IVC system.

Finally, we have focused on a simulation approach as the evaluation framework; an analytical approach toward analyzing information propagation in simple networks may be easy to formulate and serve as a better starting point for more complex systems via simulation.

Acknowledgments

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