Modeling of the dynamic flow propagation of multiple units of information under vehicle-to-vehicle communications based advanced traveler information systems

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ABSTRACT

In a vehicle-to-vehicle (V2V) communications based advanced traveler information system (ATIS), the dynamic flow propagation of multiple units of information depends on the interactions between the traffic and inter-vehicle communication characteristics and constraints, and the consequent dynamics. This study models the dynamic flow propagation of multiple units of information using a multi-layer framework that captures the dynamics of the three interacting layers: physical traffic flow, inter-vehicle communication and information flow. The traffic flow dynamics are captured using a cell transmission model in the physical traffic flow layer. The inter-vehicle communication layer uses the time-dependent locations of vehicles in the traffic flow layer and inter-vehicle communication related constraints to determine the occurrences of inter-vehicle communication. The information flow layer depicts the flow of multiple units of information as a network. Thereby, the proposed framework describes how the dynamic flow propagation of multiple units of information can be mapped from the traffic flow dynamics and the inter-vehicle communication constraints. Synthetic experiments analyze the interactions between the traffic flow dynamics and inter-vehicle communication constraints, and the flow propagation characteristics of multiple units of information. They illustrate that the proposed multi-layer framework enables the integration of the traffic flow dynamics and inter-vehicle communication constraints to generate insights on the flow propagation of multiple units of information. Also, they indicate that it can be extended to incorporate the dynamic flow propagation characteristics of multiple units of information into the design of robust V2V-based ATIS architectures.

Keywords: V2V communications based ATIS; multi-layer framework; dynamic flow propagation of multiple units of information; time-dependent vehicle knowledge; traffic flow dynamics; inter-vehicle communication constraints.
1. Introduction

Vehicle-to-vehicle (V2V) communications can facilitate a broad range of applications, including road safety (Naranjo et al., 2016), cooperative driving (Goodall et al., 2014), and advanced traveler information system (ATIS) (Wang et al., 2016) applications. In the ATIS context, V2V communications can provide a capability for vehicles to exchange time-dependent information on the network traffic conditions. Thereby, suitably-equipped vehicles can generate data on their time-dependent locations, and consequently their experienced travel times on the links traversed on their routes. We refer to the time-dependent link travel time experienced by a vehicle as “a unit of information”. As vehicles generate their own link travel experience data over time and space, a V2V-based ATIS entails the propagation of multiple units of information. The vehicles carry such information and exchange it with other vehicles through V2V communications without any central coordination. Consequently, the traffic dynamics and inter-vehicle communication constraints lead the dynamic flow propagation of multiple units of information.

The dynamic flow propagation of multiple units of information leads to each vehicle having time-dependent knowledge on the traffic network conditions, labeled the “vehicle knowledge,” based on its own experienced link travel time data and similar data received from the other equipped vehicles. The current traffic state estimation of each equipped vehicle based on its time-dependent knowledge represents an input for the associated driver to determine his/her route choice. As the route choice decisions of all drivers lead to the traffic flow network evolution, the information flow evolution and propagation influences the dynamics of the network traffic flow. More broadly, an understanding of how the information evolves and propagates is critical to develop system-level strategies for information flow routing and vehicular route guidance.

The dynamic flow propagation of multiple units of information generates two challenges for the modeling of the V2V-based ATIS. First, the propagation of each unit of information depends on the vehicular traffic flow dynamics and the inter-vehicle communication constraints introduced by the V2V communications technology and the ambient traffic flow characteristics. To address the complexity associated with modeling the propagation of multiple units of information under traffic flow dynamics and inter-vehicle communication constraints, simulation-based approaches (Schroth et al., 2005; Smith and Razo, 2014) have been proposed. Although these approaches can model the propagation of information flow, they lack insights to understand the characteristics of the information flow propagation and their interactions with the traffic flow and the inter-vehicle communication. To the best of our knowledge, there is no approach to address the propagation of multiple units of information flow.

Second, as multiple units of information in the network are dynamically exchanged across vehicles, it is necessary to track the propagation of multiple units of information flow in a computationally efficient manner. That is, we need to map what information is generated and when/where the information propagates. Kim and Peeta (2016) model a V2V-based ATIS as consisting of three interacting layers: physical traffic flow, inter-vehicle communication and information flow. They propose a graph-based multi-layer framework that enables the computationally efficient tracking of information propagation using a simple graph-based search algorithm and the computationally efficient storage of information through a single graph database. The focus of that framework is to develop a computationally efficient graph mechanism to track and store the dynamic vehicle knowledge, and provide an explicit retrospective modeling capability to track how information flow evolves and propagates.
However, it incorporates a simulation-based traffic flow model and a set of inter-vehicle communication constraints to determine the information flow propagation. That is, the simulation model is used to replicate the traffic flow dynamics as well as determine when and where inter-vehicle communication would occur subject to the inter-vehicle communication constraints. The use of such a simulation-based approach limits the understanding of the dynamics of the information flow characteristics, such as the information forward/backward propagation wave speeds, spatial information propagation front, spatio-temporal density of informed vehicles and the spatio-temporal characteristics of vehicle knowledge.

This study proposes a multi-layer framework to address the propagation of multiple units of information flow by capturing the dynamics of the three interacting layers so as to generate the aforementioned insights. The physical traffic flow layer is represented using an analytical model (the Cell Transmission Model (CTM)) and the inter-vehicle communication layer is represented using the communication range and an aggregate function that links the inter-vehicle communication success rate and the density of the V2V-equipped vehicles. As graph structure is shown to be able to track the spatiotemporal characteristics of information flow explicitly and in a computationally efficient manner (Kim and Peeta, 2016), we adapt the graph-based representation of information flow propagation in the proposed multi-layer framework. The term “information flow” denotes the flow of raw traffic data (such as the time-dependent experienced link travel time) between vehicles, and not processed data through mechanisms such as data fusion. Hence, this study does not intend to determine how the information flow layer, through the information content, would affect the traffic flow layer. Rather, as stated earlier, it seeks to determine how the dynamics of multiple units of information flow (in terms of the information forward/backward propagation waves, spatial propagation fronts, spatiotemporal vehicular knowledge characteristics, etc.) can be mapped from the traffic flow dynamics (in terms of the traffic forward/backward propagating waves, etc.) and the inter-vehicle communication constraints. Therefore, adding CTM-based traffic dynamics in the physical traffic flow layer, and integrating it with the graph-based multi-layer framework (Kim and Peeta, 2016), does not add much computational burden in this study context.

While widely-used analytical models exist to characterize traffic flow dynamics in a network context, and inter-vehicle communications constraints associated with range, interference and bandwidth have been well-studied in the communications domain, existing analytical models to characterize the evolution and propagation of information under V2V communications have key limitations, especially for the V2V-based ATIS, and even more so when multiple units of information are considered.

First, analytical approaches (Wu et al., 2004; Wang, 2007) to integrate the traffic flow and the inter-vehicle communication have limitations to characterize the underlying dynamics within a layer or the interactions among layers. From the traffic flow layer perspective, they do not describe several key phenomena of real-world traffic flow such as kinematic waves, and queue formation and dissipation. Instead, they focus on the instantaneous spatial propagation of information and do not consider the time dimension. To do so, they rely on the independent vehicle mobility assumption whereby the locations of vehicles are pre-determined based on statistical distributions of the spatial headway. Thereby, they lack realism in terms of modeling traffic flow dynamics. From the perspective of the interactions among layers, the V2V communication constraints are not well-captured in the inter-vehicle communication layer. The information propagation mechanism in these studies often assumes that the V2V communications can occur successfully up to a predefined distance representing the
communication range, and none beyond it. Thereby, the interference and bandwidth are ignored in the modeling.

Second, most existing analytical approaches (Wang, 2007; Ukkusuri and Du, 2008) assume that information propagates instantaneously across multiple vehicles through a multi-hop process based on the perspective that the speeds at which vehicles move are negligible compared to the speed at which information propagates via inter-vehicle communication. A multiple hop implies a unit of information can propagate through an instantaneous relay process to all vehicles which are serially connected to the vehicle disseminating the information by being within communication range of any vehicle within this series. However, the instantaneous multi-hop assumption does not factor interference effects and the size of information, which are significant characteristics of the V2V-based ATIS where multiple vehicles frequently exchange or disseminate information. Further, due to the assumption of instantaneous information propagation, the traffic flow dynamics and its interactions with the inter-vehicle communication constraints are ignored. That is, the transfer of a unit of information from one vehicle to another that is not in its vicinity can entail some time, which requires the consideration of the traffic flow dynamics as vehicles move continuously. This aspect is significantly exacerbated when multiple units of information flow are exchanged. A consequence of this aspect is that information needs to be tracked in terms of when and where a vehicle receives the information to determine the spatiotemporal propagation of information. So, while the assumption of instantaneous information propagation can be analytically convenient, it has limitations to model the V2V-based ATIS.

Third, most of the aforementioned analytical approaches analyze the propagation of a single unit of information. An example is the propagation of upstream collision warning information to allow other drivers approaching the affected location to be aware of the impending situation. By contrast, a V2V-based ATIS entails the propagation of multiple units of information. Extending a single unit of information propagation model to capture the propagation of multiple units of information in space and time is neither simple nor straightforward, in terms of determining how the information flow dynamics can be mapped from the traffic flow dynamics and the inter-vehicle communication constraints.

This paper seeks to bridge the aforementioned gaps in the literature in the V2V-based ATIS context by proposing a multi-layer framework to model the flow of multiple units of information as a complex system comprised of three interacting layers. Shown in Fig. 1, these layers include the traffic flow, the inter-vehicle communication, and the information flow layers. The traffic flow dynamics are captured by a cell-transmission model (CTM) in the physical traffic flow layer. The inter-vehicle communication layer uses the time-dependent locations of vehicles and a traffic flow variable (the density of the V2V-equipped vehicles) in the traffic flow layer and inter-vehicle communication related constraints/function to determine the occurrence of inter-vehicle communications. The information flow layer depicts the flow of multiple units of information as a network whose nodes correspond to events of travel experience data generation and inter-vehicle communication, and links indicate the direction of information flow.

The contributions of this study are: (i) developing a model for the propagation of multiple units of information in space and time, (ii) mapping the information flow dynamics from the traffic flow dynamics and the inter-vehicle communication constraints, (iii) illustrating the information forward/backward propagation waves, the spatial information propagation front, and spatio-temporal density of informed vehicles, and (iv) modeling the spatio-temporal
characteristics of vehicle knowledge as a building block for providing a descriptive capability and developing system-level strategies under V2V-based ATIS.

The remainder of the paper is organized as follows. Section 2 discusses proposed models to integrate the traffic flow and inter-vehicle communication layers. Section 3 describes the information flow layer using a graph-based information flow network to map the information flow dynamics based on the interactions involving the other two layers. Section 4 discusses the characteristics of the information flow dynamics. Section 5 discusses synthetic experiments and analyzes the capabilities of the proposed approach. Section 6 provides some concluding comments.

Fig. 1. Conceptual overview of the multi-layer framework.

2. The physical traffic flow and inter-vehicle communication layers

2.1. Physical traffic flow layer

The physical traffic flow layer captures the spatiotemporal interactions between vehicles through a cell-transmission model (Daganzo, 1994). It is a discrete approximation to the LWR model (Lighthill and Whitham, 1955; Richards, 1956) through the use of a trapezoidal flow-density relationship. The CTM captures several key congestion phenomena in an explicit manner, making it a suitable platform for modeling the traffic flow dynamics. In the proposed framework, the following traffic flow characteristics are identified from this layer: (i) dynamic traffic vehicular movement, and the impacts of congested traffic such as the backward propagating traffic wave, and (ii) “travel experience data,” which represents the actual travel experiences of vehicles along their route trajectories.
Under V2V-based ATIS, a traffic flow layer consists of a physical traffic network \( G^T = (N,A) \) and vehicles \((x, y \in X)\) have an ability to communicate with each other. A set \( N \) of nodes corresponds to physical intersections or designated points, and a set \( A \) of directed links corresponds to road links. The link is further divided using the set of cells \( H \) with the cell length equal to the distance traveled at free flow speed in one time interval \( \Delta t \), and the set of cell connectors \( E \). The maximum number of vehicles that can be present in a cell \( a \) at time \( t \in T \) is \( N_a(t) \), and the maximum flow from cell \( a-1 \) to cell \( a \) is \( Q_a(t) \) for time interval \((t, t+1)\). The free-flow speed and traffic backward wave propagation speed are denoted as \( v \) and \( r \), respectively. Further, denote \( n_a(t) \) as the number of vehicles in cell \( a \in H \) at time \( t \in T \), and \( y_a(t) \) as the number of vehicles that are routed by cell connector \((a-1, a) \in E \) for time interval \((t, t+1)\). The CTM is based on two main constraints on flow conservation and flow restriction:

\[
\begin{align*}
n_a(t) &= n_a(t-1) + y_{a-1}(t-1) - y_a(t-1), \quad \forall a-1, a \in H, t \in T, \quad (1) \\
y_a(t) &= \min \{ N_a(t), Q_a(t), \delta(N_a(t) - n_a(t)) \}, \quad \forall a \in H, t \in T, \quad (2)
\end{align*}
\]

where the ratio \( \delta \) is determined by \( r/v \). Equation (1) represents the flow conservation that indicates the cell occupancy at time \( t \) is equal to its occupancy at time \( t-1 \) plus inflow and minus the outflow. Equation (2) represents the flow propagation that is restricted by the three traffic conditions of the underlying trapezoidal flow density relationship: (i) free flow, (ii) saturated flow, and (iii) congested flow.

![Fig. 2. The travel experience data generation, and interactions among the vehicles.](image)

While the conventional CTM can track the traffic flow variables (density, flow, and speed), it cannot track the individual vehicles’ locations. The proposed CTM is extended to track the individual vehicle’s trajectory and the associated multiple units of travel experience data generation. The following steps are implemented similar to Cheu et al. (2008). First, the vehicle identification number is generated as a sequential number based on the order a vehicle enters the...
network. The vehicle arrival headways are assumed to be uniform within the time interval. For each time step, the CTM moves some vehicles from cell $a$ to the downstream cell $a+1$, and the first and last entering vehicle IDs to cell $a+1$ are updated and stored. In this manner, we assume that no overtaking is allowed within a cell and the First-In-First-Out (FIFO) property is preserved.

Similar to past analytical studies that only consider a single straight road topology for a V2V-based system, our approach also focuses on single road topologies. However, in our case, this is because we newly seek to incorporate traffic flow dynamics analytically to obtain a basic understanding of its impact on the propagation of multiple information units. We do so using an ordinary cell in CTM. Hence, the study experiments in Section 5 are conducted for a bidirectional single highway. In future work, we aim to extend this to include different types of road geometry (e.g. merging and diverging nodes, and intersections).

As presented in Fig. 2, the generated travel experience data contains its vehicle identification (VID) number, the identification number of the link traversed, the link entrance time, and the link travel time.

2.2. Inter-vehicle communication layer

The occurrence of the inter-vehicle communication is subject to inter-vehicle communication related technical constraints such as communication range, interference and bandwidth. In this study, the time-dependent locations of vehicles and the density of the V2V-equipped vehicles in the traffic flow layer are used as key determinants of the inter-vehicle communication characteristics.

An issue that may arise in the integration of the physical traffic flow and the inter-vehicle communication layers is the different time scales to reflect the events in the two layers. Typically, inter-vehicle communication events can occur much more frequently compared to traffic-related events (such as travel experience data generation). In the study experiments, the traffic flow is updated in the CTM every 6 seconds for computational efficiency. Also, the frequency of inter-vehicle communication is assumed to be 2 Hz (Karagiannis et al., 2011) for data transfer due to the limited bandwidth. Then, the impacts of the dynamic changes in the vehicle positions cannot be captured within the traffic flow update interval. To reconcile this issue, we use the cumulative success rate of inter-vehicle communication $Z$ which is defined as the probability that a vehicle communicates with another vehicle within communication range during the traffic flow update interval (6 seconds). The cumulative success rate of inter-vehicle communication is estimated through the simulation of scenarios (Kim et al., 2014). The aim of the simulation is to derive an aggregate function for the cumulative success rate of inter-vehicle communication for different densities of V2V-equipped vehicles within communication range. To do so, a traffic flow simulator, DYNASMART (Mahmassani et al., 1998), is used to generate the movements of all vehicles under various scenarios with different demand levels and market penetration rates (of vehicles equipped for V2V communications), and track the trajectories of all equipped vehicles.

A pair of equipped vehicles within communication range (200 meters) can potentially communicate with each other at any time through V2V communications. However, multiple communications from vehicles within the communication range can cause interference and result in the failure of this inter-vehicle communication. The interference level can be measured by comparing the signal power of the specific inter-vehicle communication of interest with the signal powers of the other inter-vehicle communications within this communication range, as follows (Gupta and Kumar, 2000):
Let $\theta_k$ denote the GPS location coordinate of an equipped vehicle $k$ within communication range, $k \in X$, as illustrated in Fig. 3. Suppose a subset of vehicles within the communication range simultaneously transmit information at some time instant, leading to possible interference. The signal power decays with distance from a broadcasting vehicle $k$ as $1/|\theta_k - \theta_j|^2$. The transmitted information through the inter-vehicle communication of interest from a vehicle $x$ is successfully received by a vehicle $y$ if it satisfies the minimum signal-to-interference ratio of $\beta$ (the study experiments use $\beta = 2$ based on Gupta and Kumar, 2000). It is assumed that the power levels of vehicles ($T_s$ and $T_k$) are identical and the ambient noise power level ($N$) is zero. Based on the interference level implied by equation (3), a simulation is conducted to check whether information is successfully transmitted between vehicles $x$ and $y$ every 0.5 seconds during a 6-second time interval. From the perspective of the cumulative success rate of inter-vehicle communication, information is successfully transmitted between vehicles $x$ and $y$ if it satisfies the minimum signal-to-interference ratio at least once during this 6-second time interval.

\[
\frac{T_s}{N + \sum_{k \in X} T_k} \geq \beta
\]

(3)

Given a specific density, $q$, of equipped vehicles within the V2V communication range, 1,000 simulation runs are performed using different demand levels and market penetration rates that are randomly chosen from specific ranges. In the study experiments, we use demand levels between 1 veh./lane/mile to 160 veh./lane/mile in discrete units of 1 veh./lane/mile, and market penetration rates between 0.05 to 0.5 in discrete units of 0.05. Then, $Z(q)$ is obtained based on the simulation results as:

\[
Z(q) = \frac{s_q}{1000}
\]

(4)

where $s_q$ is the number of simulation runs in which information is successfully received under the scenario ($q$). The estimation results provide an aggregate function, which is the cumulative
success rate of inter-vehicle communication \((Z)\) for different densities is a negative exponential function of the density of equipped vehicles within V2V communication range, as follows:

\[
Z(q) = 0.9411 \cdot e^{-0.066q}
\]  

(5)

Fig. 4 shows that the cumulative success rate of inter-vehicle communication \(Z(q)\) decreases with the density of V2V-equipped vehicles. As the density of equipped vehicles varies across cells with time, \(Z\) also varies. Therefore, the function \(Z\) represents how the dynamics of traffic flow (the density of the V2V-equipped vehicles) affect the success rate of inter-vehicle communication.

![Estimation of cumulative success rate of V2V communication](image)

**Fig. 4.** Estimation of cumulative success rate of V2V communication \((Z(q))\).

3. **Information flow layer**

3.1. **Information flow network construction**

Table 1 shows the notation of variables for the graph-based representation of the information flow network. Driven by the events in the other two layers, the information flow network evolves over time in that new nodes are generated, some nodes gain new links, and some nodes and links are deleted. The information flow network \(G = (N, C, A, M)\) consists of two types of nodes: (i) a “travel experience data (TED)” node \(\in N\), and (ii) a pair of “virtual inter-vehicle communication (VIC)” nodes \(\in C\) (one for broadcast and the other for receiving).

The dynamics of information flow evolution and propagation are represented through two type of links: (i) the directed information flow propagation trajectory links (T-link) \(\in A\) representing the TED-TED, TED-VIC, VIC-TED or VIC-VIC node connections based on the trajectories of the vehicles, and (ii) the inter-vehicle communication based information flow propagation links (I-link) \(\in M\) connecting each pair of nodes (VIC-VIC) corresponding to inter-vehicle communication events.
Table 1
Notation to represent variables in the information flow layer.

<table>
<thead>
<tr>
<th>Information flow layer</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G^i = (N^i, C^i, A^i, M^i))</td>
<td>the set of travel experience data (TED) nodes</td>
</tr>
<tr>
<td>(N^i)</td>
<td>the set of virtual inter-vehicle communication (VIC) nodes</td>
</tr>
<tr>
<td>(C^i)</td>
<td>the set of nodes in the information flow network, (P^i = (N^i, C^i), N^i \cap C^i = \emptyset)</td>
</tr>
<tr>
<td>(P^i)</td>
<td>the set of information flow propagation trajectory links (T-link) indicating the vehicle trajectory direction based on the traffic flow</td>
</tr>
<tr>
<td>(A^i)</td>
<td>the set of inter-vehicle communication based information flow propagation links (I-link) denoting the direction of information flow based on the inter-vehicle communication</td>
</tr>
<tr>
<td>(M^i)</td>
<td>travel experience data (TED) node indicating a travel experience data generated by vehicle (x) at node (i) at time (t), (\forall x \in X, \forall i \in N, i_x^t \in N^i)</td>
</tr>
<tr>
<td>(\lambda_x^t)</td>
<td>virtual inter-vehicle communication (VIC) node denoting that vehicle (x) broadcasts travel experience data at time (t), (\lambda_x^t \in C^i)</td>
</tr>
<tr>
<td>(\bar{\lambda}_x^t)</td>
<td>virtual inter-vehicle communication (VIC) node denoting that vehicle (y) receives travel experience data at time (t), (\bar{\lambda}_x^t \in C^i)</td>
</tr>
<tr>
<td>(p_x^t, q_x^t)</td>
<td>nodes in the information flow network associated with vehicle (x) at time (t), (p_x^t, q_x^t \in P^i)</td>
</tr>
<tr>
<td>((p_x^t, q_x^t))</td>
<td>information flow propagation trajectory link associated with the trajectory direction of vehicle (x) from time (t_1) to time (t_2), (p_x^t, q_x^t \in P^i), (\forall x \in X, t_1 &lt; t_2)</td>
</tr>
<tr>
<td>((\lambda_x^t, \bar{\lambda}_x^t))</td>
<td>inter-vehicle communication based information flow propagation link representing the direction of information flow (from vehicle (x) to vehicle (y)), ((\lambda_x^t, \bar{\lambda}_x^t) \in C^i, x \neq y, t_1 = t_2)</td>
</tr>
</tbody>
</table>

3.2. Information flow generation/deletion

The event that a V2V communications equipped vehicle reaches a physical intersection in the traffic layer entails the generation of travel experience data for the link traversed. A TED node, denoted as \(i_x^t \in N^i\), represents the travel experience data generated by vehicle \(x \in X\) at node \(i\) at time \(t\).

Fig. 5 shows that a vehicle \(x \in X\) reaches nodes \(i\) and \(j\) at times \(t_1\) and \(t_2\), respectively. TED nodes \(i_x^t\) and \(j_x^t\) in \(G^i\) are generated at the corresponding intersections sharing the same topology as the physical nodes \(i, j \in N\), but at times \(t_1\) and \(t_2\), respectively. The definition of the TED node illustrates that it can also aid in characterizing the spatiotemporal location of vehicles. This is because the travel experience data generation for a vehicle follows its trajectory in the traffic flow layer. Thus, \(i_x^t\) represents the spatiotemporal vehicle trajectory for vehicle \(x \in X\); that it is located at node \(i\) at time \(t\).
3.3. Information flow evolution and propagation

Characteristics of the information flow evolution and propagation are captured through the VIC nodes and the directed link representations (T-links and I-links) in the $G^I$. First, the inter-vehicle communication by a vehicle with vehicles in its vicinity (communication range) leads to information being broadcast from that vehicle. When vehicle $x$ communicates with vehicle $y$ and shares its travel experience data, a pair of VIC nodes $\lambda^i_x$ and $\bar{\lambda}^i_y \in C^i$ is generated in $G^I$ corresponding to the inter-vehicle communication event. The VIC node pairs are partitioned into two subsets: broadcasting VIC node $C^i_b$ and receiving VIC node $C^i_r$ ($C^i_b, C^i_r \subseteq C^i$).

A set of inter-vehicle communication based information flow propagation links (I-links), $(\lambda^i_x, \bar{\lambda}^i_y) \in M^I$ in $G^I$, is defined as follows:

$$M^I = \{ (\lambda^i_x, \bar{\lambda}^i_y) \in C^i_b \times C^i_r | x \neq y, t_1 = t_2 \} \quad (6)$$

A pair of VIC nodes is connected by a directed I-link, from the broadcasting VIC node $\lambda^i_x \in C^i_b$ to the receiving VIC node $\bar{\lambda}^i_y \in C^i_r$, to represent the corresponding information flow evolution and propagation through the inter-vehicle communication. Given the instantaneous nature of a single inter-vehicle communication event, the broadcasting and receiving of information occur at the same time.

Fig. 6 illustrates a traffic flow layer and an inter-vehicle communication layer with four vehicles ($x$, $y$, $w$, and $z$), and the generation of the corresponding VIC nodes and I-links in the $G^I$. For example, a broadcasting VIC node $\lambda^i_y$ and a receiving VIC node $\bar{\lambda}^i_x$ represent the occurrence of the inter-vehicle communication from vehicle $y$ to vehicle $x$ at time $t_7$, and the directed I-link $(\lambda^i_y, \bar{\lambda}^i_x)$ connects them. These VIC nodes play the role of information flow propagation
junctions, at which the information flow merges from another vehicle for the receiving node or diverges to another vehicle from the broadcasting node.

![Diagram of information flow evolution and propagation](image)

**Fig. 6.** Information flow evolution and propagation.

The travel experience data generation for a vehicle follows its trajectory in the traffic flow layer. The associated spatiotemporal dynamics are represented by a set of information flow propagation trajectory links (T-link). A set of T-links $A^I$ is defined as follows:

$$A^I = \{(p^i_x, q^i_x) \in (P^I \times P^I) \mid \forall x \in X, t_1 < t_2\}$$  \hspace{1cm} (7)

A directed T-link connects TED-TED, TED-VIC, VIC-TED or VIC-VIC nodes based on the trajectory of vehicle $x$ from time $t_1$ to time $t_2$ ($t_1 < t_2$). Fig. 6 illustrates that the directed T-links in $G^I$ connect the nodes based on the each vehicle’s trajectory direction. For example, T-links $(i^i_x, j^i_x)$, $(j^i_x, \lambda^i_x)$ and $(\lambda^i_x, \lambda^i_x)$ connect the TED-TED, TED-VIC, and VIC-VIC nodes based on the trajectory of vehicle $x$ consistent with the evolution of time. These T-links explain how information flow propagates along with each vehicle’s trajectory.

4. **Characterizing the information flow dynamics**

4.1. **Graph structure of information flow network and the forward search algorithm to track the information flow propagation**

The graph structure of $G^I$, through the node and link representations, can map of what/when/where information is generated and how it propagates. In this context, the spatiotemporal propagation of a particular unit of information is represented by a connected group of TED nodes (interpreted as a vehicle's time-dependent locations) and the associated directed links from the specific TED node at which the travel experience data of interest is
generated. Thereby, determining the TED nodes that are connected from a specific node in $G^i$ provides an understanding of the characteristics of the information flow evolution and propagation.

This is done using a graph-based forward search algorithm, by traversing the direction of the flow of information from the specific TED node where the unit of information (travel experience data of interest) is generated and identifying other vehicles’ time-dependent locations at which this information is obtained. Fig. 7 conceptually shows the propagation of information flow generated by vehicles $w$ and $z$ obtained from $G^i$ using the forward search algorithm. Each unit of information propagation constitutes a different subgraph of $G^i$ (blue and light red colored subgraphs in the figure). The encircled TED nodes in Fig. 7 correspond to the generated travel experience data of interest, and TED nodes in each subgraph indicate the locations of vehicles. The VIC nodes enable the information flow propagation to other vehicles through the inter-vehicle communication. This graph structure illustrates the information flow evolution and propagation explicitly.

![Diagram of information flow network](image)

**Fig. 7.** Subgraph of information flow network $G^i$ indicating information flow propagation.

### 4.2. Identification of information forward/backward propagation wave

This section illustrates the information forward/backward propagation waves, spatial propagation fronts, and the spatio-temporal density of informed vehicles to characterize the information flow dynamics. When a unit of information is spreading, an information propagation wave separates the traffic flow into the informed and uninformed regions and moves towards the uninformed region (Kim et al., 2014). Of particular interest is the rate of spread of the information propagation wave front; the wave front refers to the boundary between the informed and uninformed regions. Viewed over the entire network in Fig. 8(a), the propagation of the information occurs as a spatial wave, with most cases of information propagation occurring near the information propagation wave front. It characterizes the spatiotemporal information flow propagation, describing how the traffic density changes lead to the dynamics of information flow.
Fig. 8(b) illustrates how the propagation of a single unit of information is represented by a subgraph of \(G\). The subgraph structure can explicitly address when and to which vehicle a specific unit of information propagates. For example, the flow of travel experience data generated by vehicle \(z\) to vehicles \(y\) and \(x\), and the information propagation front locations, can be tracked using the TED nodes. Fig. 8(a) illustrates an information forward propagation wave that is moving in the direction of vehicular traversal. Since vehicles carry the information and the information can leap forward through V2V communications, the information propagation wave speed is always greater than or equal to a vehicle’s speed.

**Fig. 8.** Illustration of the information forward propagation wave.

### 5. Numerical experiments

#### 5.1. Experiment setup

As shown in Fig. 9(a), a bi-directional three-lane highway is considered for the experiments where all cells have homogeneous characteristics. The traffic network consists of 100 cells and 99 cell connectors, which is equivalent to 11 miles of highway length. Each link consists of 10 cells. The cell length is 0.11 miles with a time step of 6 seconds. The cell parameters include backward propagating traffic wave speed of 22 mph, capacity of 2,350 vehicles per hour and free flow speed of 65 mph. A pre-defined market penetration rate of 50% is assumed. Initially, the east bound (EB) traffic density is 40 veh./mile/lane and the west bound (WB) density is 13.3 veh./mile/lane.

To consider the impact of traffic shock waves, we assume that an incident occurs on the EB highway on link 8 at time 10 minutes, and that is initial capacity is recovered at 15 minutes, as illustrated in Fig. 9(a). The incident reduces the highway capacity by 1/3 of its initial value. A shock wave forms and travels backward at 22 mph. The resulting spatiotemporal contour plot of...
the average traffic density is shown in Fig. 9(b). Area A denotes a uniform traffic stream on the uncongested highway section. Area B is where the underlying traffic shock wave propagates backward due to the incident. Areas C and D denote the moving and discharging queue regions, respectively. The WB highway has a uniform traffic stream for all sections.

**Fig. 9.** Study traffic network and traffic density contours.

5.2. *Interaction between the traffic flow and inter-vehicle communication layers*

Fig. 10 shows a heat map of the frequency of the inter-vehicle communication events under the different traffic conditions. The red color indicates higher frequency and blue color indicates lower frequency of inter-vehicle communication events. It illustrates how different density levels of equipped vehicles affect the inter-vehicle communication frequency.

A higher density level in the traffic network leads to a greater likelihood of communication with other vehicles under the same market penetration rate. As the interference level increases, it leads to lower success rate of communication. Specifically, for the EB highway, under the uncongested traffic condition in area A, successful inter-vehicle communications take place 15-25 times in a cell. As the density level increases in area C, vehicles are more likely to exchange information. However, as the density level increases further in the traffic shock wave region (area B), the success rate of V2V communications is reduced due to the much higher impact of interference, resulting in reduced inter-vehicle communication frequency. Also, since the traffic density is low in area D, the opportunity for V2V communications is limited.

For the WB case, though the traffic stream is uniform, the occurrence of inter-vehicle communications can be affected by interference arising from the opposite direction (EB). A high density level in the EB reduces the success rates of inter-vehicle communication in the WB context, as illustrated by areas F and G area.
Fig. 10. Heatmap showing inter-vehicle communication frequency.

5.3. Information forward propagation wave

The trajectories of the information forward propagation wave front with the underlying traffic conditions are shown in Fig. 11. Information generated at every minute from vehicles at point A propagates in the downstream direction.

The information forward propagation wave speed varies as the downstream traffic density changes. As the information is transported by moving vehicles and broadcasted, the speed of information flow propagation depends on the underlying traffic speed and information propagation characteristics. The information forward propagation wave speed reduces after encountering the traffic shock wave (B and C areas) because of the reduced traffic flow speed and the limited inter-vehicle communication occurrences due to the higher interference. These observations are consistent with Fig. 10, which illustrates the likelihood of inter-vehicle communication at different density levels. In the queue dissipation area (area D), the information forward propagation wave speed is faster than that of the B and C areas, since traffic is at free flow speed and inter-vehicle communication takes place more frequently.

To be useful for V2V-based ATIS, the generated information has to propagate faster than the traffic backward propagating wave. Fig. 12 illustrates how fast the information generated downstream can reach the upstream traffic through the bi-directional traffic flow. The downstream traffic conditions on the EB facility are sensed by vehicles at point B and these travel experience data are received by the equipped vehicles in the opposite traffic direction (WB), and finally the EB vehicles at point A.

Each solid line in Fig. 12 connects the spatiotemporal locations where travel experience data is generated and where vehicles receive that information. As vehicles in the opposite direction carry and transmit the information, the traffic flow and the interference in the opposite direction affect the information flow propagation speeds. This indicates that the vehicles located at point A can receive the most recent information faster than the speed of the backward traffic shock wave (22mph).
Fig. 11. Trajectories of information forward propagation wave front.

Fig. 12. Information flow propagation speed.

5.4. Spatiotemporal characteristics of vehicle knowledge

As discussed heretofore, a V2V-based ATIS is inherently a decentralized system where the dynamic flow propagation of multiple units of information depends on the interactions between the traffic and inter-vehicle communication constraints. This implies that, at any given time, the information available to each vehicle may differ, and hence the specific interpretation of the network state of each vehicle may also vary. In the multi-layer framework, the time-dependent vehicle knowledge of interest consists of a set of subgraphs in $G^1$. The evolution of the vehicle
knowledge can be tracked from any point using the graph-based reverse search algorithm (Kim and Peeta, 2016).

![Graph showing knowledge tracking](image)

**Fig. 13.** Illustration of the time-dependent knowledge of vehicles located on link 4.

![Graph showing knowledge at a given time](image)

**Fig. 14.** Illustration of the knowledge of vehicles located at link 4 at a given time point.

Fig. 13 shows the spatiotemporal knowledge of vehicles located on link 4 at different time points. The set of travel experience data on the downstream link 8 is received by vehicles on the upstream link 4, and each distribution graph shows a range of travel times at different times (17,
22, 27, and 32 minutes). Duplicate data (spatiotemporal data of the same vehicle) and older data (older than 15 minutes) are discarded. The figure indicates that each vehicle has different time-dependent knowledge of the traffic conditions due to the dynamics of multiple units of information flow propagation. This is because of the different information flow propagation speeds, which depend on the dynamics of traffic flow and inter-vehicle communication. Fig. 14 illustrates that the spatiotemporal knowledge of vehicles can be different for vehicles at the same location (link 4) at a given time (22 minutes).

6. Concluding comments

Due to the multi-dimensional impacts of traffic flow dynamics and inter-vehicle communication constraints on information flow evolution and propagation, the need to understand their interdependencies is a fundamental problem for a V2V-based ATIS. The existing literature in this domain typically focuses on the propagation of a single unit of information. There is a key need for modeling frameworks to explain how multiple units of information flow evolve and propagate, particularly in terms of the linkage to the interactions with traffic flow and inter-vehicle communication dynamics.

This study proposes a multi-layer framework to model multiple units of information flow evolution and propagation by integrating a traffic flow model and an inter-vehicle communication model. Traffic flow dynamics are captured by the CTM in the physical traffic flow layer. The inter-vehicle communication layer uses the time-dependent locations of vehicles and the density of the V2V-equipped vehicles as inputs for an aggregate function (equation 5) of the inter-vehicle communication success rate. Then, the information flow evolution and propagation is modeled using a graph-based representation. The proposed modeling framework enables capturing the information flow dynamics (in terms of the information forward/backward propagation waves, spatial propagation fronts, spatiotemporal vehicular knowledge characteristics, etc.) using the traffic flow dynamics (in terms of traffic forward/backward propagating waves and traffic flow variables) and the inter-vehicle communication events.

Synthetic experiments seek to map how the information flow dynamics are determined by the traffic flow dynamics and the inter-vehicle communication constraints. The occurrence of the inter-vehicle communication varies as the underlying traffic density changes. This leads to varying information forward/backward propagation wave speeds under different traffic conditions. The experiments also seek to understand the interactions involving information flow in terms of the spatiotemporal characteristics of the time-dependent vehicle knowledge. They illustrate that the proposed multi-layer framework can integrate the dynamics of traffic flow and inter-vehicle communication constraints to generate insights for the propagation of the multiple units of information flow.

This study offers the potential to develop a new generation of V2V communications based route guidance strategies with individual routing decisions. These include fully decentralized V2V communications based routing that relies solely on the vehicle-level knowledge, and more advanced hybrid systems that combine both centralized and decentralized information strategies under V2V-based ATIS.

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