Computer Networks 110 (2016) 253–265

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Two-way traffic link delay modeling in vehicular networks

Jinho Lee [a], Jaehoon (Paul) Jeong [b,*], David H.C. Du [c]

[a] Department of Computer Science and Engineering, Sungkyunkwan University, Republic of Korea
[b] Department of Interaction Science, Sungkyunkwan University, Republic of Korea
[c] Department of Computer Science and Engineering, University of Minnesota, USA

ARTICLE INFO

Article history:
Received 16 April 2016
Revised 3 October 2016
Accepted 4 October 2016
Available online 5 October 2016

Keywords:
Vehicular networks
VANET
Two-way
Link delay
Data forwarding

ABSTRACT

This paper proposes a modeling of expected link delay (i.e., data delivery delay) on a two-way road segment for carry-and-forward data delivery schemes in vehicular networks. Recently, a lot of vehicles can communicate with each other by dedicated short-range communications (DSRC) for vehicular networking. In the near future, more vehicles will be equipped with DSRC devices because of governmental policies for driving safety. In this paper, we derive a link delay model on a two-way road segment. This link delay model is essential to support multihop infrastructure-to-vehicle or vehicle-to-vehicle data delivery in vehicular networks as disruption tolerant networks. Through simulation, it is shown that our two-way link delay model is more accurate than the legacy two-way link delay model. Furthermore, by applying our model to data unicasting, we show that our model is precise enough to support the efficient data unicasting on vehicular networks.

1. Introduction

Nowadays, Vehicular Ad Hoc Networks (VANETs) have been researched widely and intensively. The importance of VANET is getting higher as the demand on vehicular networks increases for communications among vehicles for the driving safety and Internet connectivity [1,2]. For example, a vehicle in a blind spot can be detected by inter-vehicle communications and a smartphone can give a pedestrian an alarm message when a vehicle is approaching from behind. This communications is achieved by Dedicated Short-Range Communications (DSRC) devices [3]. As U.S. Department of Transportation tries to mandate to equip DSRC devices to all light vehicles [4] for the driving safety, a lot of vehicles will be equipped with DSRC devices in the near future. This technology will be more important as autonomous vehicles are under development by major automotive vendors, such as Audi [5], Ford [6], and Mercedes–Benz [7]. Furthermore, inter-vehicle communications can facilitate the Internet connectivity of vehicles through Road-Side Units (RSUs) [8], which are connected to the Internet. This communications can reduce the dependency on 4G–LTE networks with cost effectiveness.

In multihop infrastructure-to-vehicle data delivery, accurate link delay is required for reliable unicast [2] or multicast [9] data delivery. With such reliable data delivery, customized notification delivery services can be offered [10]. For example, when an accident happens either at an intersection or in a road segment, with multihop Infrastructure-to-Vehicle (I2V) data delivery, Traffic Control Center (TCC) promptly disseminates the accident notification to each relevant vehicle that will pass through the accident road spot according to its navigation path. By this customized notification, the relevant vehicles will be able to detour more proactively and efficiently for better navigation. Many data forwarding schemes [2,9] are based on one-way link delay model (i.e., the expected data delivery on a road segment with one-way road traffic). However, two-way roads are dominant over one-way roads in real road traffic environments. In the two-way roads, vehicles moving on both directions (i.e., forward and backward traffic for a directed road segment) can be used for rapider data forwarding than vehicles moving on only one direction because more vehicles on both directions participate in data forwarding than those on one direction. We define two-way road link delay (called two-way link delay) as the delay that a packet takes to move from the entrance to the exit in a *two-way traffic road segment* by the packet forward-and-carry process of vehicles [1,2]. On the other hand, we define one-way road link delay (called one-way link delay) as the delay that a packet takes to move from the entrance to the exit in a *one-way traffic road segment* by the packet forward-and-carry process of vehicles [1,2]. It is clear that a link delay modeling in a two-way traffic road segment can provide rapider and more reliable packet delivery service for vehicles than a link delay model in a one-way

* Corresponding author.
E-mail addresses: jinholee@skku.edu (J. Lee), pauljeong@skku.edu (J. Jeong), du@cs.umn.edu (D.H.C. Du).

http://dx.doi.org/10.1016/j.comnet.2016.10.003
1389-1286/

traffic road segment. Thus, this paper proposes a formulation of expected link delay for a two-way road segment as a two-way link delay model, assuming that the road length, average arrival rate, and vehicle speed are available. Our intellectual contributions are as follows:

- Two-way link delay model. We propose a two-way link delay model on a road segment by utilizing road statistics such as average arrival rate and vehicle speed. Based on this model, we can accurately estimate the packet delivery delay over a two-traffic road segment through a forward-and-carry approach.
- Validation of our link delay model. Through simulations, we validate our link delay model by showing the effectiveness of unicast data forwarding in a road network with two-way road segments.

The remainder of this paper is structured as follows. Section 2 is the literature review of link delay modeling. Section 3 formulates our two-way link delay model. Section 4 describes the modeling of link delay in a two-way road segment and road networks. Section 5 evaluates our two-way link delay model with simulation results. Section 6 concludes the paper along with future work.

2. Related work

Much research has been done on multihop I2V, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) data forwarding for the driving safety and driving efficiency [1,2,11]. VANET has distinctive characteristics from conventional Mobile Ad Hoc Networks (MANETs) such as vehicles' restricted moving area and predictable mobility in a short period. Due to these characteristics, we can expect vehicles' partitioning and merging on road segments or intersections. There are several research activities [1,12] to formulate expected link delay on a road segment with these characteristics of VANETs. TBD [1] proposes a link delay model for a road segment with one-way traffic and Liu et al. in [12] suggest a link delay model for bidirectional road traffic model in a road segment.

TBD [1] models link delay for one-way traffic, assuming that inter-arrival times between vehicles are exponentially distributed. First, a source vehicle can transmit its packets in a negligibly short forwarding delay through vehicles constructing a network component, which is a connected VANET via communication range. Then, the next carrier carries the packets through the rest of the road segment. We refer to the length of the rest of the road as *carry distance* (l_c). In this scenario, the main portion of link delay is the carry delay which is $\frac{l_c}{v}$ where the average vehicle speed is v. Since this model assumes that the link delay is approximately the same as the carry delay, the link delay is $\frac{l_c}{v}$. In order to derive average carry distance, TBD computes the average forwarding distance between the source vehicle and the next carrier. This average forwarding distance is modeled as the sum of inter-distances between adjacent vehicles. Since it is assumed that the inter-arrival time is exponentially distributed, the inter-distance is also exponentially distributed. If the inter-distance is shorter than the communication range of vehicles, we can say that the vehicles are connected. This model suggests the average number of hops between the source vehicle and the next carrier and the average distance of two connected vehicles. With this information, TBD derives average carry distance and carry delay. However, in reality, two-way roads are dominant over one-way roads. Therefore, we need link delay estimate of two-way road traffic situation to make a decision on the expected delivery delay over real roads.

Liu et al. analyzes Message Delivery Delay (MDD) in VANET with a Bidirectional Traffic Model [12], assuming that the two-way traffic is a combination of two Poisson point processes. If two vehicles are moving toward each other with constant speed v, one vehicle can see that the other is approaching it with the speed $2v$. In the sense of relative speed, one vehicle is identical to one stationary vehicle and the other vehicle is a vehicle moving toward the stationary vehicle with the speed $2v$. This model assumes that vehicles on one side of road is stationary. On the other hand, vehicles on the other side are moving two times faster than the average speed of the road segment.

In the previous two models of link delay on a one-way or two-way road segment, the way to deliver a packet through packet forwarding is to use a network component (i.e., VANET), consisting of vehicles interconnected through a communication range. The source vehicle transmits its packets immediately if it belongs to a network component. Otherwise, the source vehicle waits until a new network component arrives. If the length of the network component is long enough, the source vehicle forwards its packets toward the next carrier. This forward-and-wait process is repeated until the packets are delivered to the end of the road segment. In this model, we can get the average number of intermediate vehicles through the assumption of a Poisson distribution. The number of vehicles is regarded as the same with the number of hops to forward packets to the end of the road segment. This model suggests that the link delay is the sum of per-hop delays. The probability to construct a long network component for a fast forwarding over the road segment decreases more quickly as the average distance between intermediate vehicles becomes larger. Especially, the expected delay for each hop becomes very long in the case of a light road traffic situation.

3. Problem formulation

In this section, we describe the assumptions, goal, and high-level idea of our link delay model. Given the road statistics, this paper aims at modeling the link delay for a two-way road segment or a road network. This link delay information is useful to estimate the packet delivery delay on VANETs with two-way traffic road situation.

Our assumptions are as follows:

- Vehicles are equipped with DSRC [3] devices.
- Relay Node (RN) is a stand-alone DSRC infrastructure node that is deployed at each intersection and is not connected to the Internet. This RN receives packets from vehicles and delivers packets to other vehicles as a temporary packet holder.
- RSUs collect road statistics, such as speeds, arrival rates, and branching probabilities from vehicles through DSRC devices where the branching probability is the probability that a vehicle at the end (i.e., intersection) of the current road segment moves to the start of another adjacent road segment. Note that an RSU can also play a role of an RN as a temporary packet holder.

Our goal in this paper is as follows: *Given the road statistics, such as (i) vehicle arrival rates and average vehicle speeds in a two-way road segment and (ii) branching probabilities at an intersection, how can we formulate the expected link delay on the two-way road segment?*

The high-level idea for link delay modeling is as follows. We define link delay as the elapsed time to deliver a packet from an intersection (I_i) to another intersection (I_j). When a packet is generated by an RSU at I_i or a packet arrives at an RN at I_i, either the RSU or RN at I_i holds the packet until a proper packet carrier arrives at the intersection I_i. The packet carrier carries the packet and forwards it to a next packet carrier as soon as it encounters a network component having the next packet carrier. Then, the next carrier carries the packet until it encounters another network component. This carry and forwarding is repeated until the packet is

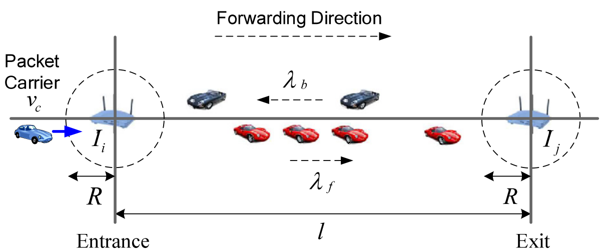

Fig. 1. Road segment with relay nodes at both ends.

delivered to an RN at the end of the road segment. We model two-way link delay on a road segment by deriving the average forwarding distances and average carry delays of packet carriers. We will explain the detailed modeling for link delay in Section 4.

4. Delay model

In this section, we model the link delay, considering road statistics such as average speed, vehicle arrival rate, and branching probabilities. We assume that RNs are installed at both ends of a road segment. When packets arrive at an RN, it holds packets until a vehicle passes by the RN.

In Fig. 1, when a vehicle at an entrance intersection I_i generates packets or packets arrive at the RN (I_i), the RN holds them until a vehicle moving in the Forwarding Direction arrives. As shown in Fig. 1, once the new packet carrier (v_c) toward the intended forwarding direction arrives, the RN transmits packets to v_c. The packets are delivered to an exit intersection I_j by repetitive carry and forwarding process. We define *link delay* as the time difference between the packet arrival time instants at I_i and I_j.

Let us consider a road segment with length l, vehicle arrival rates λ_f and λ_b, average vehicle speed v, and communication range R where λ_f is the arrival rate of vehicles moving forward (from I_i to I_j), which is called forward vehicle arrival rate, and λ_b is that of vehicles moving backward (from I_j to I_i), which is called backward vehicle arrival rate.

Note that the forwarding delay is ignorable compared to the carry delay. This is because it takes only a few microseconds to forward packets under VANET conditions. Therefore, for simplicity, we consider that the link delay is the same as the carry delay, which is the dominant factor of the link delay.

To derive *link delay* in a two-way road segment, we assume that packets are delivered by the cycles of carry and forwarding. In order to derive the expected link delay, we need to derive the average lengths of the *carry distance* and the *forwarding distance*. We define the following terms to derive the *link delay*.

Definition 4.1 (Network Component)**.** Let *Network Component* be a group of vehicles that can communicate with each other via either one-hop or multi-hop communication. Fig. 2 shows a network component consisting of vehicles v_c, ... , v_2.

Definition 4.2 (Component Length)**.** Let *Component Length* (denoted as l_n) be the length of a Network Component.

Definition 4.3 (Forwarding Distance)**.** Let *Forwarding Distance* (denoted as l_f) be the physical distance which a packet travels through forwarding within a Network Component from the packet carrier (v_c). When the packet carrier (v_c) encounters a Network Component, it immediately forwards its packets to the farthest vehicle moving to the same direction with v_c in the Network Component. In Fig. 2, v_c forwards packets to v_1. In this case, the Forwarding Distance is the distance between v_c and v_1.

Definition 4.4 (Carry Distance)**.** Let *Carry Distance* (denoted as l_c) be the physical distance where a packet is carried by a packet carrier (v_1) until it encounters another vehicle (v_3) moving backward, belonging to another network component.

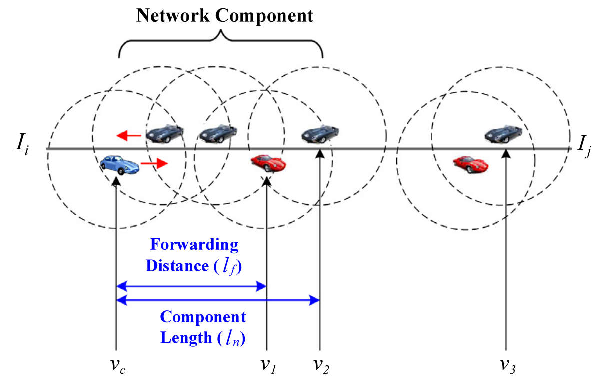

Fig. 2. Network Component.

Definition 4.5 (Carry Delay)**.** Let *Carry Delay* (denoted as d_c) be the delay that a packet is carried by a packet carrier (v_1) for carry distance l_c such that $d_c = l_c/v$ for vehicle speed v.

4.1. Average component length for finite road length

In this subsection, we formulate *average component length* ($E[l_n]$) for a finite road. $E[l_n]$ can be computed as the expected sum of the inter-distances of adjacent vehicles (D_h) within a network component. For simplicity, we consider a road snapshot to calculate $E[l_n]$. Let us suppose that the vehicles on the road have the identical shapes of front side and rear side. Then, one cannot tell the difference between the snapshot of two-way traffic one-lane road and the snapshot of one-way traffic, two-lane road. Thus, we can derive $E[l_n]$ considering a one-way traffic, two-lane road. We assume that the vehicle speed is a constant v. Let λ_f be the forward vehicle arrival rate and λ_b be the backward vehicle arrival rate. Let $\lambda = \lambda_f + \lambda_b$. Note that if two vehicles arrive at a certain intersection within a duration $a = \frac{R}{v}$, they are inter-connected by the wireless communication range R. Since a carry vehicle always moves forward, we can compute the probability that the head vehicle in the network component toward the exit intersection is moving forward as $\frac{\lambda_f}{\lambda}$. Note that the head vehicle among the vehicles within the network component is closest to the exit intersection.

According to the detailed derivation in [1] and the probability of the carry vehicle's forward moving direction ($\frac{\lambda_f}{\lambda}$), we obtain $E[l_n]$ for finite road length in two-way road segment as follows:

$$E[l_n] = \frac{\lambda_f}{\lambda}\left(\frac{\alpha\left((N-1)\beta^N - N\beta^{N-1} + 1\right)}{(1-\beta)^2} + l\beta^N\right), \tag{1}$$

where $\alpha = ve^{-\lambda a}(\frac{1}{\lambda} - (a + \frac{1}{\lambda})e^{-\lambda a})$, $\beta = 1 - e^{-\lambda a}$, and $N = \lceil \frac{\beta(1-\beta)}{\alpha} l \rceil$.

4.2. Average forwarding distance for finite road

Now, we derive the *expected forwarding distance* ($E[l_f]$) by considering the directions of vehicles on a finite road. In Fig. 2, the forwarding distance is the distance between v_c and v_1. According to (1), we can formulate $E[l_f]$ as follows.

$$\begin{aligned} E[l_f] &= E[l_n - (l_n - l_f)] \\ &= E[l_n] - E[l_n - l_f]. \end{aligned} \tag{2}$$

Since l_n is formulated as the expected sum of the inter-distances of adjacent vehicles (D_h), a network component consists of $\lfloor \frac{E[l_n]}{E[D_h|D_h \le R]} \rfloor$ vehicles in average where $E[D_h|D_h \le R]$ is the

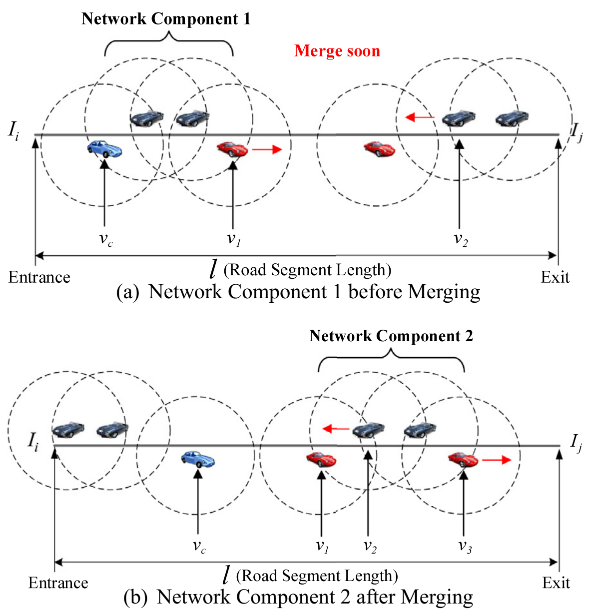

Fig. 3. Renewal process scenario.

average vehicle inter-distance within a network component. Let $m = \lfloor \frac{E[l_n]}{E[D_h | D_h \leq R]} \rfloor$ where $\lfloor x \rfloor$ is the largest integer less than or equal to x. If a vehicle is chosen on the road snapshot, it is moving either forward or backward. Considering the ratio of the forward-moving vehicles to the total vehicles, it is moving forward with probability λ_f/λ or moving backward with probability λ_b/λ. The direction of the vehicle is determined by Bernoulli trials. $l_n - l_f$ is determined by the number of successive vehicles moving backward from the head vehicle in a network component. For example, in Fig. 2, the head vehicle (v_2) is moving backward and the next one (v_1) is moving forward. Considering the probability mass function of Geometric distribution, the probability of this case is $\frac{\lambda_f}{\lambda_f+\lambda_b} \frac{\lambda_b}{\lambda_f+\lambda_b}$. In the same way, $l_n - l_f = k \times E[D_h \mid D_h \leq R]$ with probability $\frac{\lambda_f}{\lambda_f+\lambda_b} (\frac{\lambda_b}{\lambda_f+\lambda_b})^k$ where k is the successive number of backward-moving vehicles from the head vehicle in the network component. Thus,

$$E[l_n - l_f] = \sum_{k=0}^{m} kE[D_h \mid D_h \leq R] \frac{\lambda_f}{\lambda_f + \lambda_b} \left(\frac{\lambda_b}{\lambda_f + \lambda_b} \right)^k, \tag{3}$$

where $E[D_h \mid D_h \leq R] = v\frac{1/\lambda - (a+1/\lambda)e^{-\lambda a}}{1-e^{-\lambda a}}$ according to the derivation of vehicle inter-distance within communication range in [1].

4.3. Link delay on a road segment

Here, we derive the delivery delay on a road segment. Let us assume that RNs are installed at both ends of the road segment. We model the time difference between the packet generation at one end and the packet arrival at the other end. A packet carrier forwards its packets whenever it encounters a new network component. As shown in Fig. 3(a), the current packet carrier (v_c) forwards its packets to the next carrier (v_1) immediately. Then, v_1 carries the packets until it comes to the communication range of v_2. As shown in Fig. 3(b), when v_1 encounters v_2 within the communication range, v_1 forwards its packets to v_3. Then, v_3 carries the packets until it encounters another vehicle moving backward, which belongs to another network component. In this way, the packets are delivered to the exit intersection of the road segment. From this example, we can generalize the packet delivery process as a *renewal process* where each transaction consists of forwarding and carry process.

Since the inter-arrival time of backward-moving vehicles ($\tilde{T_h}$) is assumed to be exponentially distributed with the arrival rate λ_b, the inter-distance between backward-moving vehicles ($\tilde{D_h}$) is also exponentially distributed. As shown in Fig. 2, the expected distance between v_1 and v_2 is $E[l_n - l_f] + E[\tilde{D_h} \mid \tilde{D_h} > R]$ where $E[l_n - l_f]$ is the expected carry distance within the current network component and $E[\tilde{D_h} \mid \tilde{D_h} > R]$ is the average inter-distance of the vehicles moving backward. We derive $E[\tilde{D_h} \mid \tilde{D_h} > R]$ as follows:

$$\begin{aligned}
E[\tilde{D_h} \mid \tilde{D_h} > R] &= \int_{x=R}^{\infty} xP(\tilde{D_h} = x \mid \tilde{D_h} > R)dx \\
&= \int_{s=0}^{\infty} (R+s)P(\tilde{D_h} = R+s \mid \tilde{D_h} > R)ds \\
&= \int_{s=0}^{\infty} (R+s)P(\tilde{D_h} = s)ds \\
&\quad (\because \text{ Memorylessness of exponential random variable}) \\
&= \int_{s=0}^{\infty} R \times P(\tilde{D_h} = s)ds + \int_{s=0}^{\infty} s \times P(\tilde{D_h} = s)ds \\
&= R + \int_{s=0}^{\infty} s \times P(\tilde{D_h} = s)ds \\
&= R + v\int_{t=0}^{\infty} t \times P(\tilde{T_h} = t)dt \\
&\quad (\because \text{ Change of variable}) \\
&= R + vE[\tilde{T_h}] \\
&= R + \frac{v}{\lambda_b}.
\end{aligned} \tag{4}$$

Note that v_1 transmits packets to v_2 if their inter-distance is less than or equal to R and their relative speed is $2v$. Then, according to (4), the carry delay d_c has the following expectation:

$$\begin{aligned}
E[d_c] &= (E[l_n - l_f] + E[\tilde{D_h} \mid \tilde{D_h} > R] - R)/2v \\
&= \left(E[l_n - l_f] + \frac{v}{\lambda_b}\right)/2v.
\end{aligned} \tag{5}$$

Then, according to 5, the *carry distance* l_c has the following expectation:

$$\begin{aligned}
E[l_c] &= vE[d_c] \\
&= \left(E[l_n - l_f] + \frac{v}{\lambda_b}\right)/2.
\end{aligned} \tag{6}$$

The packets will be carried by $E[l_c]$ during a carry phase, hence the expected length of a cycle is $E[l_f] + E[l_c]$. Based on renewal process, this process is repeated for $\frac{l-R}{E[l_f]+E[l_c]}$ times, since an RN is installed at I_j along with the communication range R. When packets are generated at I_i, there are two cases to deliver the packets to I_j Let X be link delay for a road segment of length l with forward vehicle arrival rate λ_f and backward vehicle arrival rate λ_b.

- **Case 1: Immediate forward:** Assume that T_h^* is the inter-arrival time between the vehicles moving forward. If there is a next packet carrier in the communication range of the RN at I_i, the packets can be forwarded over the road segment with the cycles of forwarding and carry. Based on the number of cycles from (2), (5), and (6), such a probability and the conditional expectation of link delay are as follows where $a = \frac{R}{v}$ [2]:

$$\begin{aligned}
P(\text{Case1}) &= P(T_h^* < a) \\
&= 1 - e^{-\lambda_f a}, \\
E[X|\text{Case1}] &= \frac{l-R}{E[l_f] + E[l_c]} \times E[d_c].
\end{aligned} \tag{7}$$

- **Case 2: Wait and carry:** If there is no vehicle moving forward in the communication range of the RN at I_i, the packets need

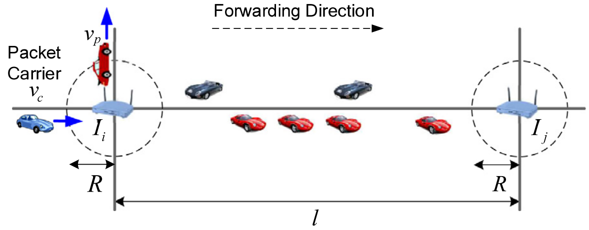

Fig. 4. Road network with relay nodes.

to wait the inter-arrival time for the forward vehicle arrival rate λ_f, that is, $1/\lambda_f$. Then, they can be forwarded in the same way with Case 1. Such a probability and the conditional expectation of link delay are as follows [2]:

$$P(\text{Case2}) = P(T_h^* \geq a) = e^{-\lambda_f a},$$
$$E[X|\text{Case2}] = \frac{1}{\lambda_f} + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]. \quad (8)$$

Considering both cases, the average link delay with RNs at both intersections is:

$$E[X] = P(\text{Case1})E[X|\text{Case1}] + P(\text{Case2})E[X|\text{Case2}] = \frac{1}{\lambda_f}e^{-\lambda_f a} + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]. \quad (9)$$

Note that our link delay model in (9) can adapt itself to different road conditions, such as road accident and road maintenance. This is because the average vehicle speed (v) and the vehicle arrival rates (λ_f and λ_b) become changed according to such conditions, which are used as input in the link delay model in (9). Also, it is remarkable that our link delay model in (9) is suitable for both a highway and local roadway as long as a road segment of length l from an entrance point to an exit point is defined in either a highway or local roadway with the average vehicle speed (v) and the vehicle arrival rates (λ_f and λ_b). In addition, the temporal variation in road conditions in the time per day or the day per week can be accommodated into our link delay model in (9) since our link delay estimates are computed with the average vehicle speed (v) and the vehicle arrival rates (λ_f and λ_b) according to the road conditions in different time ranges (e.g., rush hours, day-time hours, and night hours) or different days (e.g., weekdays and weekend).

4.4. Link delay on a road network

In Section 4.3, we derived the link delay on a road segment. For a road network, we define the link delay as the time difference between the arrival times at both ends of a road segment. With this link delay, we estimate a link delay on a road network. Let us assume that RNs are installed at all intersections. As shown in Fig. 4, the previous packet carrier (v_p) forwards packets to the RN, which holds the packets until the next carrier (v_c) arrives at the intersection with the RN. In order to derive the delivery delay from I_i to I_j, we need a branching probability (p_b), which is the probability that a vehicle entering an intersection moves to a certain adjacent road segment. We can compute p_b with road statistics, that is, the ratio of the branching number for an adjacent road segment to the total arrival number for an intersection. Considering the branching probability p_b, we can derive the link delay on a road network with the following three cases:

- **Case 1: Immediate forward:** Assume that T_h^* is the inter-arrival time between the vehicles moving forward according to the intended packet forwarding direction. If there is a next packet carrier in the communication range of the RN at I_i, such a probability and the conditional expectation of link delay are:

$$P(\text{Case1}) = P(T_h^* < a) = 1 - e^{-\lambda_f a},$$
$$E[X|\text{Case1}] = \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]. \quad (10)$$

- **Case 2: $v_p$carries for itself:** If v_p moves to the intended packet forwarding direction and there is no vehicle moving forward in the communication range of the RN at I_i, we need to consider the moving time of v_p. v_p forwards packets immediately to the RN as it reaches the communication range of the RN. After $a(=R/v)$ seconds, v_p reaches the intersection and carry the packets again. Such a probability and the conditional expectation of link delay are:

$$P(\text{Case2}) = P(T_h^* \geq a) \times p_b = e^{-\lambda_f a} \times p_b,$$
$$E[X|\text{Case2}] = \frac{R}{v} + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]. \quad (11)$$

- **Case 3: Wait and carry:** If v_p does not move to the intended packet forwarding direction and there is no vehicle moving forward in the communication range of the RN at I_i, the RN holds packets until a vehicle arrives to the forwarding direction. Such a probability and the conditional expectation of link delay are:

$$P(\text{Case3}) = P(T_h^* \geq a) \times (1-p_b) = e^{-\lambda_f a} \times (1-p_b),$$
$$E[X|\text{Case3}] = \frac{1}{\lambda_f} + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]. \quad (12)$$

Considering **Cases 1, 2 and 3**, the expected link delay on a road network is:

$$E[X] = P(\text{Case1})E[X|\text{Case1}] + P(\text{Case2})E[X|\text{Case2}] + P(\text{Case3})E[X|\text{Case3}] = e^{-\lambda_f a}\left(p_b\frac{R}{v} + \frac{1-p_b}{\lambda_f}\right) + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]. \quad (13)$$

5. Performance evaluation

We validate our model on a road segment and a road network, respectively, by comparing with simulation results. We built our own simulator on the scheduler provided by SMPL [13] in C. The mobility patterns of vehicles follow a Hybrid mobility model of City Section Mobility model [14] and Manhattan Mobility model [15]. In Section 5.1, we validate our link delay model for a road segment, which is derived in Section 4.3. Our model is compared with the mean link delay for a road segment under various conditions. In Section 5.2, our link delay model for a road network is validated. For the validation, we run simulations under the same condition with TSF [2]. TSF is a multihop I2V unicast data forwarding scheme on VANET. For the multihop I2V unicast, the infrastructure should precisely expect the position of a target vehicle and an End-to-End (E2E) packet delivery delay (called E2E delay). We consider such an E2E delay as the sum of link delays for a road network, as derived in Section 5.2. Our model is validated such that we can expect an E2E delay precise enough to deliver packets for the multihop I2V unicast. We compare our TSF using our two-way link delay model (called TSF+) with the legacy TSF using one-way link delay model in [2] (called TSF). We show that our TSF+ using two-way traffic can deliver packets faster than the legacy TSF using one-way traffic on two-way road conditions through extensive simulations.

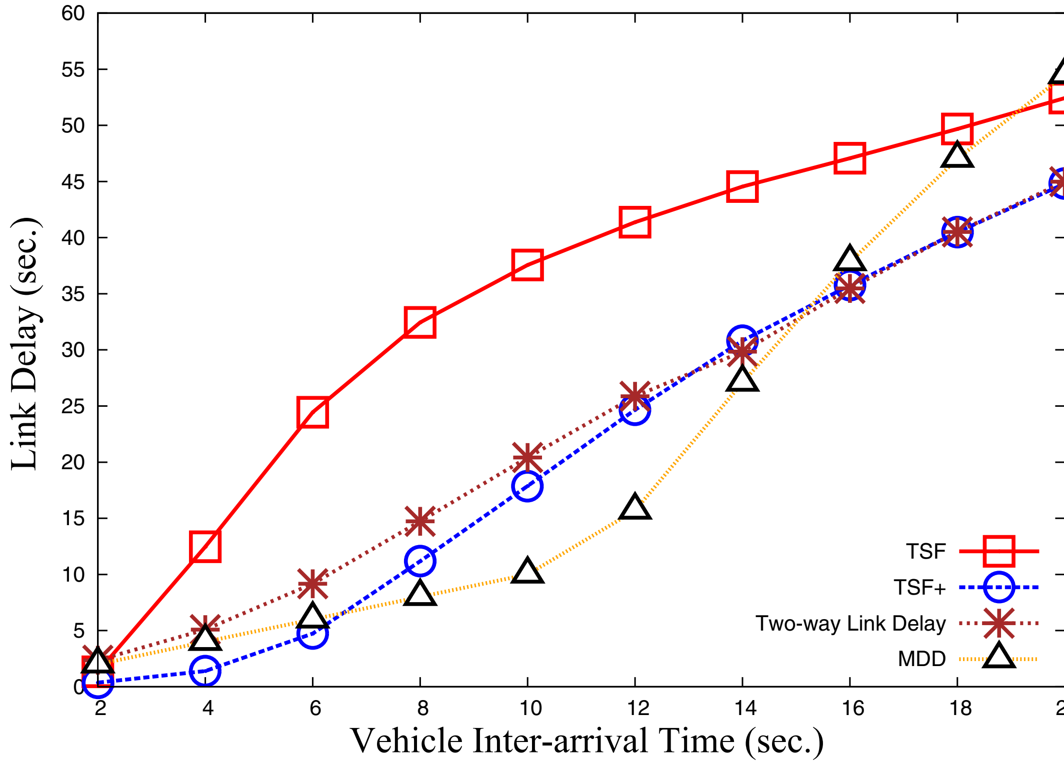

Fig. 5. Link delay versus vehicle inter-arrival time.

Table 1
Simulation configuration.

Parameter	Description
Road condition	The road is straight and 1 km long.
Communication range	$R = 200$ m (i.e., 656 feet)
Inter-arrival time	$\lambda_f = \lambda_b = 10$ s
Vehicle speed	$v \sim N(40, 5)$ MPH

5.1. Link delay model on a road segment

We validate our model on a road segment by comparing its expectations with simulation results. As shown in Table 1, vehicles travel along a path of length 1000 m that is a straight road. They move with speed $v \sim N(40, 5)$ MPH. The communication range of DSRC devices is 200 m. At both ends (i.e., intersections) of the road, RNs are installed.

- **Performance metric**: We use *average link delay* as a performance metric.
- **Parameters**: We investigate the impacts of *average arrival rate* $\lambda (= \lambda_f + \lambda_b)$, *average vehicle speed* μ_v, and *vehicle speed standard deviation* σ_v.

The analytical results of our two-way link delay model (denoted as Two-way link delay) are compared with the simulation results that are the ground truth of a data forwarding scheme (denoted as TSF+) using two-way traffic for data forwarding. Furthermore, they are compared with the analytical results of another link delay model using two-way traffic for data forwarding (denoted as MDD) [12] and the simulation results of a data forwarding scheme using one-way traffic for data forwarding (denoted as TSF) [2], respectively.

5.1.1. Impact of vehicle arrival rate λ

At first, we show how link delay changes as vehicle inter-arrival time varies. Note that the vehicle inter-arrival time is the reciprocal of vehicle arrival rate λ. As shown in Fig. 5, one-way traffic simulation result (denoted as TSF) has longer delay than two-way traffic simulation result (denoted as TSF+). Vehicles deliver packets faster by using two-way traffic. Thus, we can deliver packets with shorter delay if we utilize the direction and location information from GPS-based navigation system. As shown in Fig. 5, our model accurately expects the link delay. Since Message Delivery Delay (called MDD) in [12] does not consider the mobility of vehicles toward the forwarding direction, the expectation diverges exponentially. In comparison with MDD [12], our model provides a reasonably accurate result close to the simulation result.

5.1.2. Impact of vehicle speed μ_v

Here, we investigate the impact of vehicle speed on link delay. As shown in Fig. 6, in our two-way model (denoted as Two-way Link Delay) and two-way simulation result (denoted as TSF+), the higher vehicular speed results in the longer delivery delay for a heavy traffic case. This is because the higher speed causes the longer inter-distance between vehicles. Moreover, the probability to construct a network component becomes low. Thus, the higher speed results in the longer delay for even the heavy traffic case.

5.1.3. Impact of vehicle speed standard deviation σ_v

We observe the impact of vehicle speed standard deviation on link delay. We increase vehicle speed standard deviation from 1 to 10 *MPH*. As shown in Fig. 7, link delay becomes shorter as the speed standard deviation becomes larger. If two vehicles move to the same direction with the same speed to the same direction, and they are out of communication range, there is no chance to make a network component. However, in case of a different speed case, a faster vehicle can catch up with a slower vehicle and they can construct a network component. This phenomenon happens more

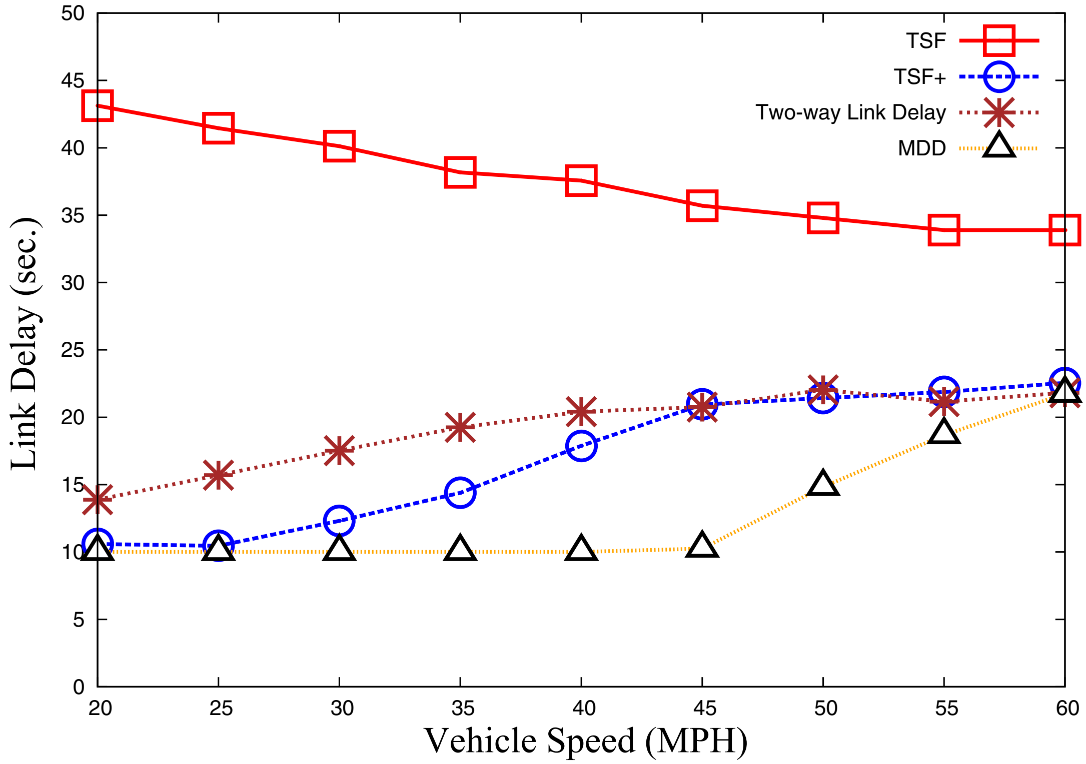

Fig. 6. Link delay versus average vehicle speed.

often in case of a large standard deviation than a small standard deviation. The link delay using two-way traffic is almost a half of that using one-way traffic in most cases, as shown in Fig. 7.

5.2. Link delay model on a road network

Here, we validate our model as we apply our model on a unicast forwarding scheme called TSF [2] on a road network. For the unicast forwarding, TSF selects a rendezvous point of a packet and a destination vehicle along with an accurate delivery delay estimation as a target point. In order to select a rendezvous point among the intersections that the destination vehicle will pass through, TSF calculates *delivery probabilities* at those intersections, which are the probabilities that the packet arrives earlier than the destination vehicle. TSF calculates this *delivery probability*, assuming that the packet delivery delay and the vehicle travel delay follow the Gamma distributions $d \sim \Gamma(\kappa, \theta)$. The means of both the packet delivery delay and the vehicle travel delay are estimated as the sum of the mean delays for road segments along with the trajectories, respectively. The variances of the delays are estimated in the same way. From these mean delivery delay and the variance information, the parameters κ and θ of the Gamma Distribution for the delay (i.e., packet delivery delay or vehicle travel delay) can be computed as in TSF [2]:

$$\theta = \frac{Var[d]}{E[d]} = \frac{\sigma^2}{\mu},$$
$$\kappa = \frac{E[d]}{\theta} = \frac{\mu}{\theta} = \frac{\mu^2}{\sigma^2}. \quad (14)$$

In Fig. 8, P_i is the packet delivery delay from an RSU to the target point n_i. V_i is the vehicle travel delay, which is the moving time of the destination vehicle to the target point n_i. Thus, TSF calculates the delivery probability as $P[P_i \le V_i]$. $P[P_i \le V_i]$ is derived as (2) in TSF [2] as follows:

$$P[P_i \le V_i] = \int_0^{TTL} \int_0^{v} f(p)g(v)\,dp\,dv, \quad (15)$$

where $f(p)$ is the probability density function (PDF) of packet delay p, $g(v)$ is the PDF of vehicle delay v, and TTL is the packet's Time-To-Live. This probability is calculated for each intersection on the target vehicle's path. Parameters for V_i is estimated from the road statistics such as the average travel time and the average speed per road segment. In order to get such parameters for P_i, we utilize our link delay model and its standard deviation derived in Appendix A. The simulation environment is the same as TSF [2]. The evaluation setting is as follows:

- **Performance metrics**: We use (i) *average E2E delivery delay*, (ii) *packet delivery ratio*, and (iii) *the standard deviation of E2E delivery delay* as performance metrics.
- **Baselines**: We compare our two-way link delay model (TSF+) with our previous one-way link delay model (TSF) [2] and another two-way link delay model called Message Delivery Delay (MDD) [12]. For the legacy TSF protocol [2], it is important to select transmission directions at intersections. By choosing road segments which have short expected link delays, the legacy TSF protocol reduces the E2E delay on a road network. On the same road network, we can reduce E2E delay by forwarding data through vehicles moving both directions on a road segment, that is, by using two-way traffic on a road segment. Then, we show that our model TSF+ is more precise than MDD [12] by comparing their E2E delays. The simulation results of TSF+, TSF, and MDD are ground truth. First, TSF+ is the enhanced data forwarding scheme of the legacy TSF protocol [2] using our two-way link delay model and two-way traffic for data forwarding. Second, TSF is the legacy TSF protocol using the one-way link delay model in [2] and one-way traffic for data forwarding. Third, MDD is the data forwarding scheme of the legacy TSF

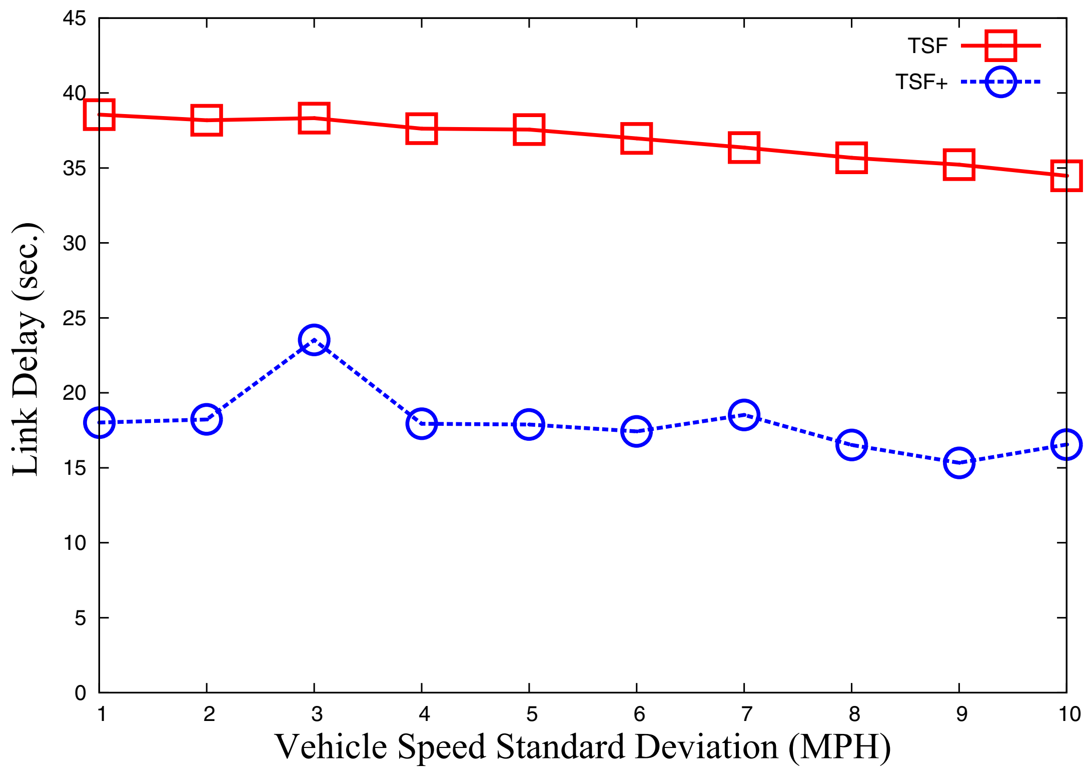

Fig. 7. Link delay versus vehicle speed standard deviation.

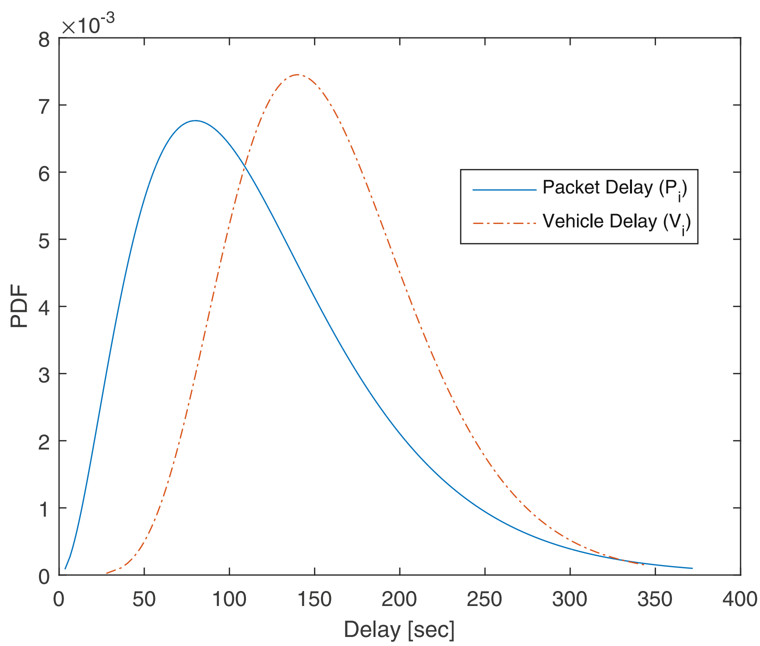

Fig. 8. Packet delay distribution and vehicle delay distribution.

protocol with another two-way link delay model in [12] and two-way traffic for data forwarding.

- **Parameters**: We investigate the impacts of *the number of vehicles on the road network n, average vehicle speed v, vehicle speed standard deviation* σ, and *the number of RSUs on the road network N*.

We validate our link delay model on the simulation setting shown in Table 2. The road network has 49 intersections. The communication range of DSRC devices is 200m. For performance evaluation, we applied three link delay models, such as two two-way link delays (TSF+ and MDD) and one one-way link delay (TSF) to the legacy TSF protocol for data forwarding, which is a multihop I2V data delivery scheme.

5.2.1. *Impact of vehicle number* n

We investigate the impact of the number of vehicles on E2E delay. As shown in Fig. 9, E2E delay tends to decrease as the number of vehicles increases. Error bars indicate the range of $(mean - standard\_deviation, mean + standard\_deviation)$. TSF+ with

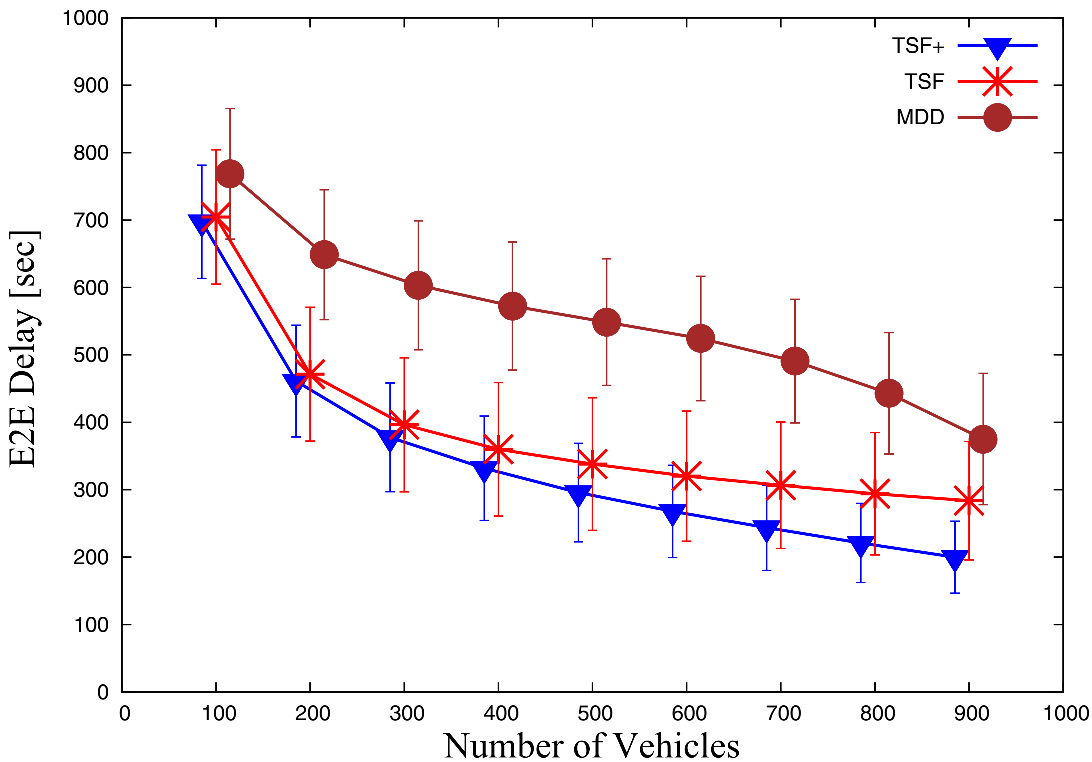

Fig. 9. E2E delay versus vehicle number.

Table 2
Simulation configuration.

Parameter	Description
Road condition	The number of intersection is 49. The area of the road map is 8.25 km × 9 km, i.e., 5.1263 miles × 5.5923 miles.
Communication range	$R = 200$ m, i.e., 656 feet.
Number of vehicles (n)	The number n of vehicles moving within the road network. The default of n is 300.
Time-To-Live (TTL)	The expiration time of a packet. The default TTL is the vehicle trajectory's lifetime, i.e., the vehicle's travel time for the trajectory, i.e., 2086 s.
Vehicle speed (v)	$v \sim N(\mu_v, \sigma_v)$ where $\mu_v = \{20, 25, \ldots, 60\}$ MPH and $\sigma_v = \{1, 2, \ldots, 10\}$ MPH. The maximum and minimum speeds are $\mu_v + 3\sigma_v$ and $\mu_v - 3\sigma_v$, respectively. The default of (μ_v, σ_v) is (40, 5) MPH.
Number of RSUs (N)	The number of RSUs deployed on the road networks. The default number of RSUs is 5.

our two-way link delay model shows shorter delay than TSF with one-way link delay model in [2]. It is consistent with our intuition that link delay with two-way traffic is shorter than link delay with one-way traffic. MDD with the two-way message delivery delay model in [12] shows longer delay than TSF. This is because the imprecise link delay for a road segment results in conservative rendezvous point selection. Thus, RSUs using MDD forward packets to farther RNs as target points.

5.2.2. Impact of vehicle speed μ_v

We investigate the impact of average vehicle speed on E2E delay. As shown in Fig. 10, E2E delay tends to decrease as the vehicle speed increases. In a light traffic situation, waiting time and carry delay take the large portion of E2E delay. The higher vehicle speed results in the shorter carry delay on road segments, leading to the overall shorter E2E delay.

5.2.3. Impact of vehicle speed standard deviation σ_v

We investigate the impact of vehicle speed standard deviation on E2E delay. As shown in Fig. 11, E2E delay slightly increases as the standard deviation increases. When an RSU selects the rendezvous point for data unicasting, the large standard deviation results in a more conservative selection, leading to the longer E2E delay.

5.2.4. Impact of RSU number N

Finally, we investigate the impact of the number of RSUs on E2E delay. As shown in Fig. 12, E2E delay decreases as the number of RSUs increases. This is because the average distance from an RSU to a target point for the destination vehicle decreases as more RSUs are deployed.

Therefore, from the previous simulation results, it can be concluded that our forwarding scheme with two-way link delay model is a promising unicast forwarding scheme in road networks with two-way traffic road segments.

6. Conclusion

In this paper, we propose a link delay model for a road segment with two-way road traffic and validate our model by applying our model to a data unicasting scheme. In order to derive the expectation of the link delay, we introduce the concept of *renewal process*. This assumes that the forwarding and carry phases alternate repeatedly. We formulate link delay with the sum of carry delays on

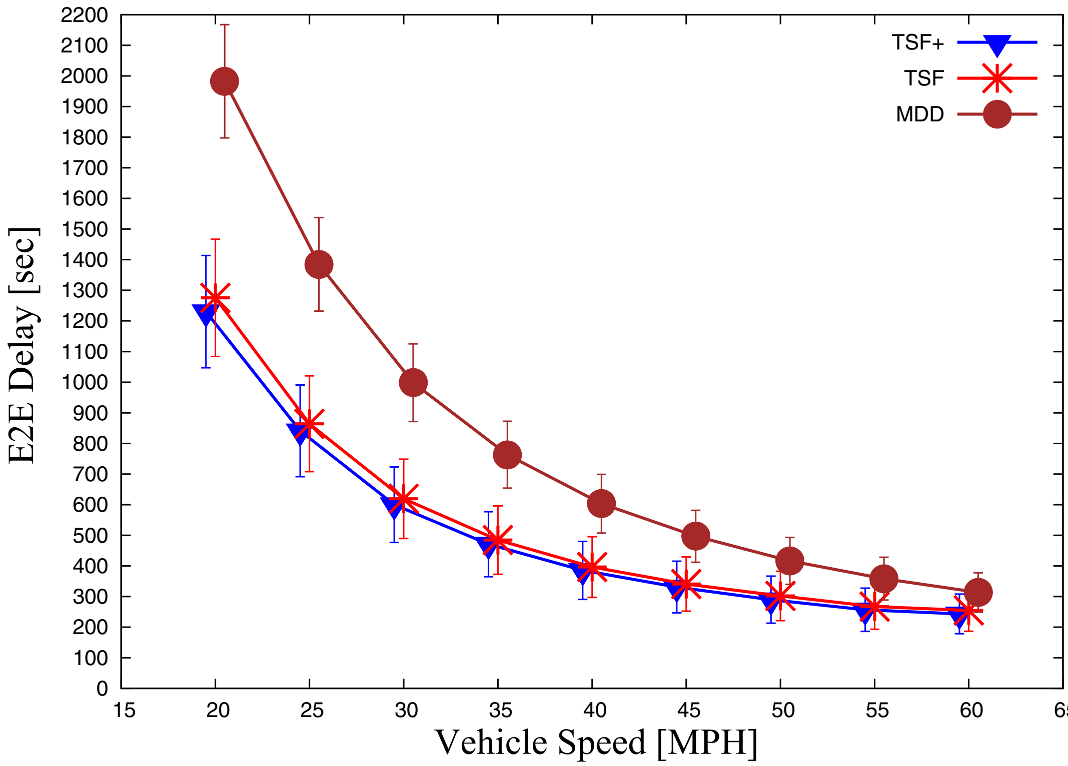

Fig. 10. E2E delay versus vehicle speed.

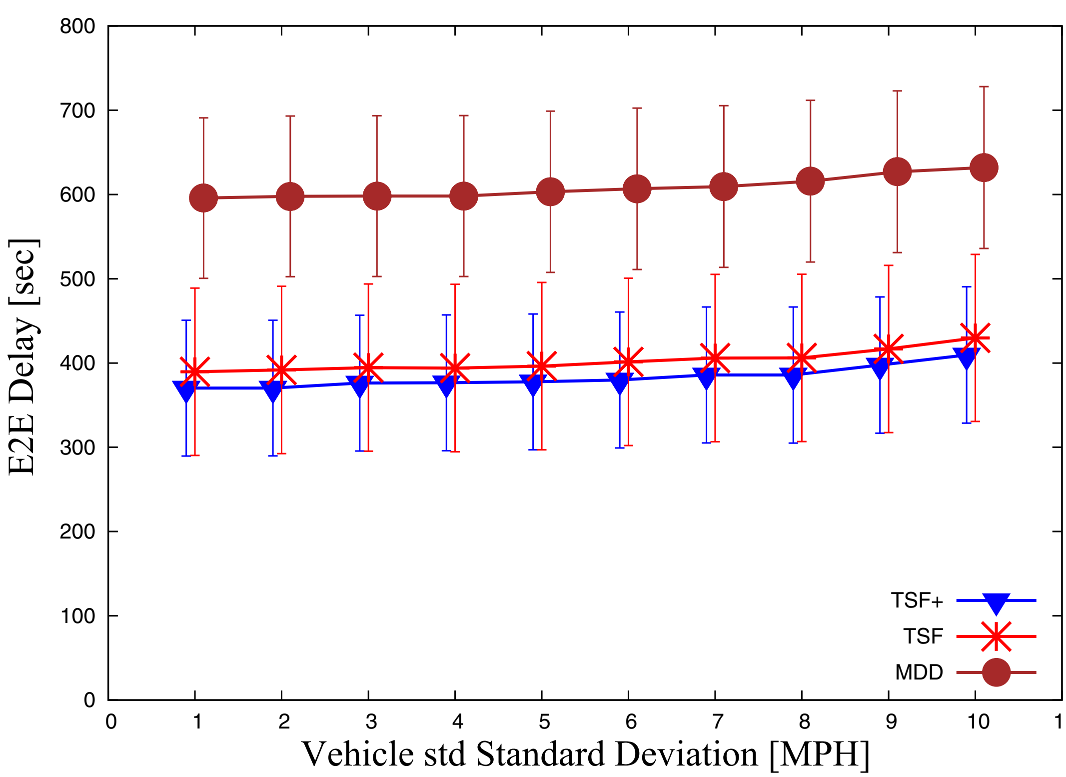

Fig. 11. E2E delay versus vehicle speed standard deviation.

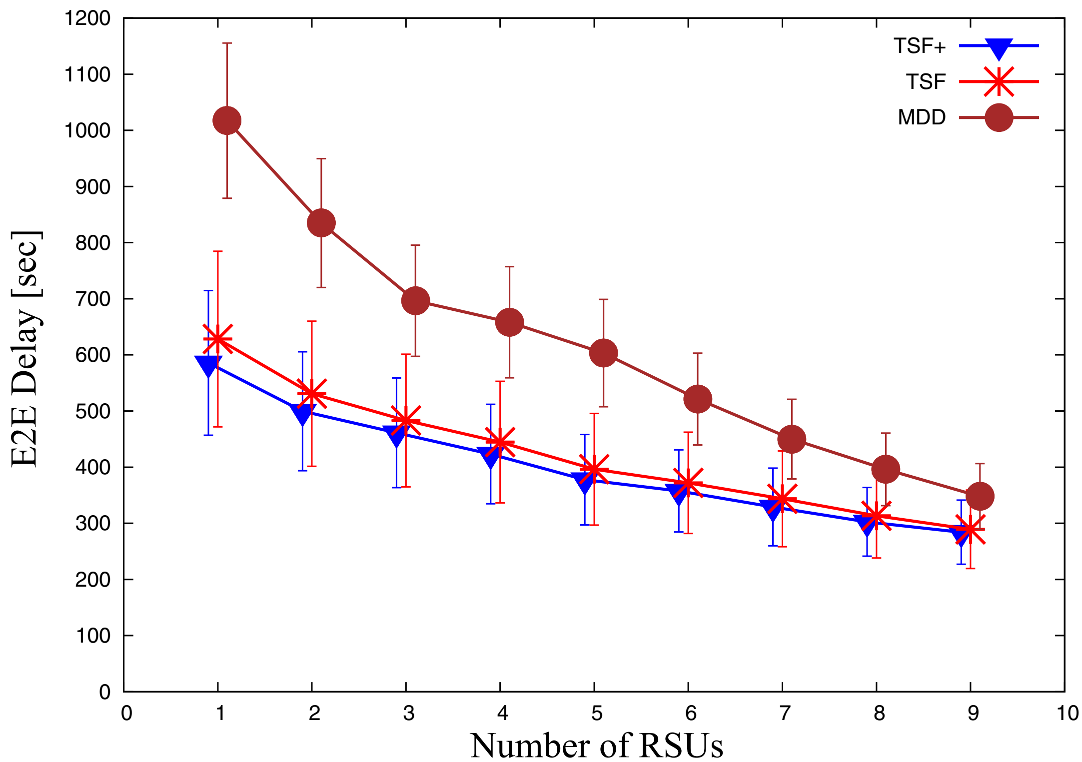

Fig. 12. E2E delay versus RSU number.

a road segment because the carry delay is dominant in the total forward-and-carry delay. Also, we validate our model by comparing expected link delays with simulation results on a road segment and show the performance of E2E delay on a road network. As future work, we will enhance our link delay model in a road segment with a traffic light in a more realistic road traffic simulator.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2014006438). This research was supported in part by Global Research Laboratory Program (2013K1A1A2A02078326) through NRF, the ICT R&D program of MSIP/IITP (14-824-09-013, Resilient Cyber-Physical Systems Research), and the DGIST Research and Development Program (CPS Global Center) funded by the Ministry of Science, ICT & Future Planning.

Appendix A. Variance of two-way Link delay model

In Section 4.4, we formulate the expectation of two-way link delay on a road network. Here, based on the expectation, we derive the variance of our model. For simplicity, we assume that $E[l_n - l_f]$ and the vehicle inter-arrival time are independent from (3). Here, we only consider **Case 1** that a relay node or an RSU directly forward packets to a vehicle moving toward the intended forwarding direction. In **Case 2** (i.e., a packet carrier entering a road segment carries packets by itself), the delay expectation ($E[X|\text{Case2}] = \frac{R}{v} + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]$) has one more constant term ($\frac{R}{v}$) compared to **Case 1**. In a light-traffic road, this constant term is relatively small where the road length l is much longer than the communication range R, that is, $l >> R$. On the other hand, in a heavy-traffic road, the probability of **Case 2** is low. Note that if we take account of **Case 3** that a relay node or an RSU hold packets until a next carry vehicle arrives, especially in a light-traffic road network, the link delay is approximately proportional to the waiting time on the intersection (i.e., $E[X|\text{Case 3}] \propto E[T_h^*]$ where T_h^* is the inter-arrival time between vehicles toward the forwarding direction). In (12), $E[X|\text{Case3}] = \frac{1}{\lambda_f} + \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]$. Here, $\frac{l-R}{E[l_f]+E[l_c]}$ is the average number of cycles of carry and forwarding phases along with a road segment, and $E[d_c]$ is the carry delay for each cycle. Since $\frac{l-R}{E[l_f]+E[l_c]} \times E[d_c]$ is bounded by the moving time ($\frac{l-R}{v}$) for a carry vehicle to pass through a road segment, $E[X|\text{Case 3}] \propto \frac{1}{\lambda_f} = E[T_h^*]$. Then, $Var[X|\text{Case 3}] \propto \frac{1}{\lambda_f^2}$ that diverges very quickly as λ_f becomes very small (i.e., close to 0). Thus, we consider only **Case 1** in order to obtain an approximate bounded variance. From (5) and (13), we derive two-way link delay as follows:

$$E[X] = \frac{l-R}{E[l_f]+E[l_c]} \times E[d_c] = \frac{l-R}{E[l_f]+E[l_c]} \times (E[l_n - l_f] + \frac{v}{\lambda_b})/2v. \quad \text{(A.1)}$$

Then, assuming that $\frac{l-R}{E[l_f]+E[l_c]}$ is constant, the variance of our model is as follows:

$$\begin{aligned} Var[X] &= Var\left[\frac{l-R}{E[l_f]+E[l_c]} \times d_c\right] \\ &= \left(\frac{l-R}{E[l_f]+E[l_c]}\right)^2 \times Var[d_c] \\ &= \left(\frac{l-R}{E[l_f]+E[l_c]}\right)^2 \times Var[\{(l_n - l_f) + v\tilde{T}_h\}/2v] \\ &= \left(\frac{l-R}{2v(E[l_f]+E[l_c])}\right)^2 \times Var[(l_n - l_f) + v\tilde{T}_h] \end{aligned}$$

$$
\begin{aligned}
&= \left(\frac{l-R}{2v(E[l_f]+E[l_c])}\right)^2 \times (Var[l_n - l_f] + v^2 Var[\tilde{T}_h]) \\
&\quad (\because \text{Bienayme formula}) \\
&= \left(\frac{l-R}{2v(E[l_f]+E[l_c])}\right)^2 \times \left(Var[l_n - l_f] + \frac{v^2}{\lambda_b^2}\right) \\
&= \left(\frac{l-R}{2v(E[l_f]+E[l_c])}\right)^2 \times \left(E[(l_n - l_f)^2] - E[l_n - l_f]^2 + \frac{v^2}{\lambda_b^2}\right) \\
&= \left(\frac{l-R}{2v(E[l_f]+E[l_c])}\right)^2 \\
&\quad \times \left[\left\{\sum_{k=0}^{m} k^2 E[D_h | D_h \le R]^2 \frac{\lambda_f}{\lambda_f + \lambda_b}\left(\frac{\lambda_b}{\lambda_f + \lambda_b}\right)^k \right.\right. \\
&\quad \left.\left. - E[l_n - l_f]^2\right\} + \frac{v^2}{\lambda_b^2}\right]. \qquad \text{(A.2)}
\end{aligned}
$$

References

[1] J. Jeong, S. Guo, Y. Gu, T. He, D.H.C. Du, Trajectory-based data forwarding for light-traffic vehicular ad hoc networks, IEEE Trans. Parallel Distrib. Syst. 22 (5) (2011) 743–757.

[2] J. Jeong, S. Guo, Y. Gu, T. He, D. Du, Trajectory-based statistical forwarding for multihop infrastructure-to-vehicle data delivery, IEEE Trans. Mob. Comput. 11 (10) (2012) 1523–1537.

[3] Y.L. Morgan, Notes on DSRC & WAVE standards suite: its architecture, design, and characteristics, IEEE Commun. Surv. Tut. 12 (4) (2012).

[4] U.S. Department of Transportation, Federal Motor Vehicle Safety Standards: Vehicle-to-Vehicle (V2V) Communications. http://www.gpo.gov/fdsys/pkg/FR-2014-08-20/pdf/2014-19746.pdf.

[5] C. Rauwald, H. Nichols, Audi tests driverless-car technology at 190MPH, 2014.

[6] M. Ramsey, G. Fowler, Ford chief says mass-market autonomous vehicle is priority, 2015.

[7] P. LeBeau, Mercedes' futuristic view: autonomy meets connectivity, 2015.

[8] A. Abdrabou, W. Zhuang, Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity, IEEE J. Sel. Areas Commun. 29 (1) (2011).

[9] J. Jeong, T. He, D.H.C. Du, TMA: trajectory-based multi-anycast forwarding for efficient multicast data delivery in vehicular networks, Elsevier Comput. Netw. (COMNET) 57 (13) (2013).

[10] J. Jeong, J. Kim, T. Hwang, F. Xu, S. Guo, Y.J. Gu, Q. Cao, M. Liu, T. He, TPD: travel prediction-based data forwarding for light-traffic vehicular networks, Elsevier Comput. Netwo. (COMNET) 93 (2015).

[11] J. Zhao, G. Cao, VADD: Vehicle-assisted data delivery in vehicular ad hoc networks, IEEE Trans, Veh. Technol. 57 (3) (2008) 1910–1922.

[12] Y. Liu, J. Niu, G. Qu, Q. Cai, J. Ma, Message delivery delay analysis in VANETs with a bidirectional traffic model, in: 7th International IEEE Conference on Wireless Communications and Mobile Computing (IWCMC 2011). IEEE, 2011.

[13] M.H. MacDougall, Simulating Computer Systems: Techniques and Tools, MIT Press, 1987.

[14] T. Camp, J. Boleng, V. Davies, A survey of mobility models for ad hoc network research, Wireless Commun. and Mobility Comput. (WCMC)Mobile Ad Hoc Networking: Research, Trends and Applications 2 (2002) 483–502.

[15] F. Bai, N. Sadagopan, A. Helmy, IMPORTANT:a framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks, INFOCOM. IEEE, 2003.

Jinho Lee has been an M.S. student in the Department of Computer Science Engineering at Sungkyunkwan University since 2015. His M.S. advisor is Professor Jaehoon (Paul) Jeong. He got his B.S. degree from the Department of Mathematics at Sungkyunkwan University in 2014. His research interests are vehicular networks and intelligent transportation systems. He is a member of IEEE and the IEEE Computer Society.

Jaehoon (Paul) Jeong is an assistant professor in the Department of Software at Sungkyunkwan University in Korea. He received his Ph.D. degree in the Department of Computer Science and Engineering at the University of Minnesota in 2009. He received his B.S. degree in the Department of Information Engineering at Sungkyunkwan University and M.S. degree from the School of Computer Science and Engineering at Seoul National University in Korea, in 1999 and 2001, respectively. His research areas are vehicular networks, Internet of things, wireless sensor networks, software-defined networking, network functions virtualization, and network security. Dr. Jeong is a member of ACM, IEEE and the IEEE Computer Society.

David H.C. Du received his B.S. degree in mathematics from National Tsing-Hua University, Taiwan, R.O.C. in 1974, and his M.S. and Ph.D. degrees in computer science from the University of Washington, Seattle, in 1980 and 1981, respectively. He is currently the Qwest Chair Professor at the Computer Science and Engineering Department, University of Minnesota, Minneapolis. His research interests include cyber security, sensor networks, multimedia computing, storage systems, and high-speed networking. Dr. Du is a fellow member of IEEE and the IEEE Computer Society.