Link Delay Modeling for Two-Way Traffic Road Segment in Vehicular Networks

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Abstract. This paper proposes 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 are able to communicate with each other by dedicate 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 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.

Keywords: Vehicular networks · VANET · Link delay · Two-way · Expectation

1 Introduction

Vehicular Ad Hoc Networks (VANETs) have been researched widely recently. 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 the 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 driving safety, a lot of vehicles will be equipped with DSRC devices in the near future. These technologies will be more important as autonomous vehicles are under development by major automotive vendors, such

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as Audi [5], Ford [6], and Mercedes-Benz [7]. Furthermore, inter-vehicle communications can facilitate the Internet connectivity of vehicles. These communications can reduce the dependence on 4G-LTE networks for cost effectiveness.

In multihop infrastructure-to-vehicle data delivery, accurate link delay is required for reliable unicast [2] or multicast [8]. Many data forwarding schemes [2,8] 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. Precise two-way link delay is necessary to provide better services and connectivity to vehicles. This paper proposes a formulation of expected link delay for a two-way road segment, assuming that the length of road, 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 utilizing road statistics such as average arrival rate and vehicle speed.
- Validation of our model. We validate our model with extensive simulations.

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. Section 5 evaluates 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 Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) data forwarding for safety and driving efficiency [1,2]. VANETs have 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 a road segment. There are several research activities [1,9] to formulate expected link delay on a road segment with these characteristics of VANETs. TBD [1] proposes link delay for a road segment with one-way traffic and Liu et al. in [9] suggest average message delivery delay with a bidirectional traffic model.

Link delay for one-way traffic is modeled by TBD [1]. It models link delay for one-way traffic assuming that inter-arrival times between vehicles are distributed exponentially. First, a source vehicle can transmit its packets in a neglectably short time through vehicles constructing a network component, which is a connected VANET via communication range. Then, the next carrier carries the packet 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, [1] formulates the average distance between the source vehicle and the next carrier. It is modeled as the sum of inter-distances between adjacent vehicles. Since it is assumed that the inter-arrival time is distributed exponentially, the inter-distance is also exponentially distributed. If the inter-distance is shorter than the communication range of vehicles, we can say that they 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, [1] derives average carry distance and carry delay. However, in reality, two-way roads are dominant over one-way roads. Therefore, we need link delay information of two-way road traffic situation to make decisions about delay over real roads.

Expected link delay for two-way traffic [9] is formulated, 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 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 drive two times faster than the average speed of the road segment.

In this case, the only way to deliver a packet forward is constructing a network component containing stationary vehicles. 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 stationary vehicles through the assumption of a Poisson distribution. The number of vehicles is 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 network component long enough to connect stationary vehicles decreases more quickly as the average distance between stationary vehicles becomes larger. The expected delay for each hop becomes very long in the case of a sparse road situation.

3 Problem Formulation

In this section, we describe our goal, assumptions, and high-level design of our model. Given the road statistics, our goal is to model link delay for a two-way road segment. This link delay information is necessary to estimate the packet delay on VANETs with two-way traffic road situation. Our assumptions and high-level idea are as follows:

Assumptions

- Vehicles are equipped with DSRC [3] devices.
- RSUs collect road statistics, such as speeds and arrival rates from vehicles through DSRC devices.

– Relay nodes are deployed for each intersection. These relay nodes receive and deliver packets as temporary packet holders.

High-level Idea. 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 arrives at I_i, a relay node holds the packet until a proper packet carrier arrives. The packet carrier carries the packet and forwards it as soon as it encounters a network component. Then, the next carrier carries the packet until it encounters another network component. This carry and forwarding is repeated while the packet is being delivered. We model two-way link delay as we derive the average forwarding distance and average carry time of the packet carriers.

4 Delay Model

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

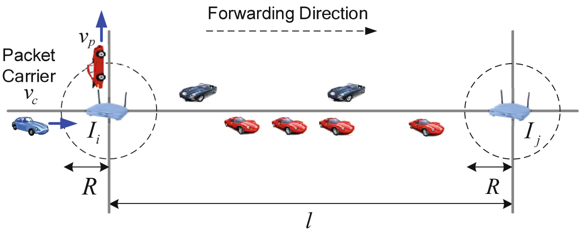


Fig. 1. Network environment

In Fig. 1, the previous packet carrier (v_p) passed by intersection I_i and forwarded its packets to the relay node installed at I_i. Then, the relay node holds them until a vehicle moving in the Forwarding Direction arrives. Once the new packet carrier (v_c) toward the intended direction arrives, the relay node transmits packets to v_c. The packets are delivered to I_j by repetitive carry and forwarding process. We define the *link delay* as the time 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. λ_f is the arrival rate of vehicles moving forward (from I_i to I_j). λ_b is that of vehicles moving backward (from I_j to I_i).

Note that the forwarding delay is ignorable compared to the carry delay. It takes only a few microseconds to forward packets under VANETs conditions. Thus, for simplicity, we consider that the link delay is the same as the carry delay.

Our goal in this paper is: *Given the road statistics such as vehicle arrival rates and average vehicle speed, how can we formulate the expected link delay on a two-way road segment?* For the *link delay*, 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*.

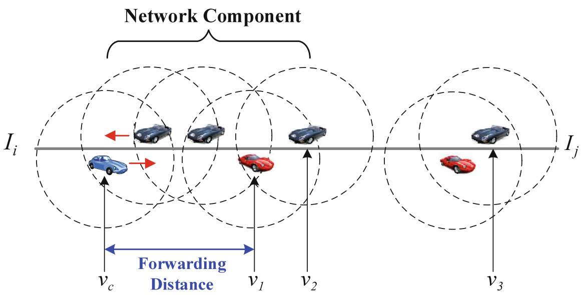


Fig. 2. A road segment with relay nodes at the both ends

Definition 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. Figure 1 shows a network component consisting of vehicles* $v_c, \ldots, v_2$.

Definition 2 (Component Length). *Let Component Length (denoted as l_n) be the length of a Network Component.*

Definition 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 (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.*

Definition 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 two-way traffic road snapshot and the snapshot of one-way, two-lane traffic road. Thus, we can derive $E[l_n]$ considering a one-way, two-lane traffic road. We assume that the vehicle speed is a constant v. Let λ_f be the vehicle arrival rate for forward direction and λ_b be the vehicle arrival rate for backward direction. Let $\lambda = \lambda_f + \lambda_b$. Note that if two vehicles arrive at a certain intersection within $a = \frac{R}{v}$, they are inter-connected by the wireless communication range R. Since a carry vehicle always moves forward, we can compute the probability that the backmost vehicle is moving forward as $\frac{\lambda_f}{\lambda}$.

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:

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

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

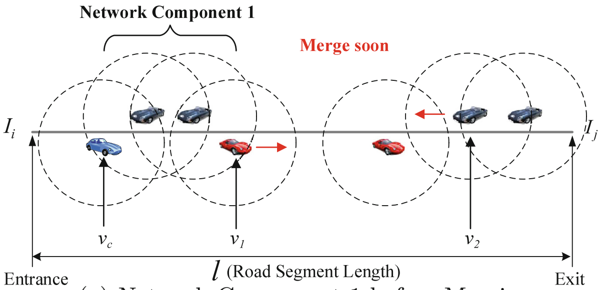
Now, we derive the *expected forwarding distance* ($E[l_f]$) considering the directions of vehicles on a finite road. In Fig. 2, the forwarding distance is the distance between v_c and v_1. According to (1) and (2), we can formulate $E[l_f]$ as we derive $E[l_n - l_f]$.

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

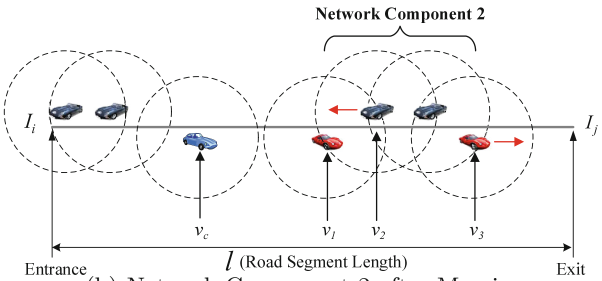
Since l_n is formulated as the expected sum of the inter-distances of adjacent vehicles (D_h), a network component consists of $\lfloor \frac{E[l_n]}{E[D_h|D_h \le R]} \rfloor$ vehicles in average where $E[D_h \mid D_h \le R]$ is the average vehicle inter-distance within a network component. Let $m = \lfloor \frac{E[l_n]}{E[D_h|D_h \le R]} \rfloor$ where $\lfloor x \rfloor$ is the largest integer less than or equal to x. If we choose a vehicle on the road snapshot, it is either moving forward or moving backward. Considering the ratio of forward-moving vehicles to 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,

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

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 [1].



(a) Network Component 1 before Merging



(b) Network Component 2 after Merging

Fig. 3. Renewal process scenario

4.3 Link Delay Derivation with Renewal Process

A packet carrier forwards its packets when it encounters a new network component. As shown in Fig. 3, the current packet carrier (v_c) forwards its packets to the next carrier (v_1) immediately. Then, v_1 carries packets until it comes to the communication range of v_2. When v_1 encounters v_2, v_1 forwards its packets to v_3 as shown in Fig. 3(b). Then, v_3 carries the packets until it encounters another vehicle moving backward belonging to another network component. In this way, the packets are delivered over a 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.

It can be seen that the renewal process consists of repetitive *cycles* of forwarding and carry. Since the forwarding delay is neglectably short compared to the carry delay, the link delay for a cycle is approximately the same with carry delay. In order to derive the expected carry delay ($E[d_c]$) for a cycle, we need to formulate the expected distance between the packet carrier (v_1) and the approaching vehicle from the opposite side (v_2) in Fig. 3(a).

Since we assume that the inter-arrival time of backward-moving vehicles ($\tilde{T_h}$) is 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:

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

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),

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

Then, the *carry distance* is:

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

The packets move by $E[l_c]$ after 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 a relay node is installed on I_j along with the communication range R. When packets arrive at I_i, there are two cases to deliver packets to I_i.

– **Case 1: Immediate Forward:** Assume that T^* is the inter-arrival time between the vehicles moving forward. If there is a next packet carrier in the communication range of the relay node at I_i, such a probability and the conditional expectation of link delay are:

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

– **Case 2: Wait and Carry:** If there is no vehicle moving forward in the communication range of the relay node at I_i, such a probability and the conditional expectation of link delay are:

$$\begin{aligned} P(\text{Case 2}) &= P(T_h^* \geq a) \\ &= e^{-\lambda_f a}, \\ E[\text{Link Delay}|\text{Case 2}] &= \frac{1}{\lambda_f} + \frac{l - R}{E[l_f] + E[l_c]} \times E[d_c]. \end{aligned} \tag{8}$$

Considering both cases, the average link delay with relay nodes on each intersection is:

$$\begin{aligned} E[\text{Link Delay}] &= P(\text{Case 1})E[\text{Link Delay}|\text{Case 1}] + P(\text{Case 2})E[\text{Link Delay}|\text{Case 2}] \\ &= \frac{1}{\lambda_f} e^{-\lambda_f a} + \frac{l - R}{E[l_f] + E[l_c]} \times E[d_c]. \end{aligned} \tag{9}$$

5 Performance Evaluation

We validate of our model by comparing its expectation with simulation result. As shown in Table 1, vehicles travel over path length $1000m$ from both ends of the straight road. They move with speed $v \sim N(40, 5)$ MPH. The communication range of DRRC deivces is $200m$. At both ends (i.e., intersections), relay nodes are installed.

– **Performance Metric**: We compare *average link delay* with the expected link delay.
– **Parameters**: We investgate the impacts of *average arrival rate* $\lambda(= \lambda_f + \lambda_b)$, *average vehicle speed* μ_v, and *vehicle speed deviation* σ_v.

Our model is compared with simulation result which approximates the ground truth. Furthermore, we also compare the simulation result of two-way traffic with that of one-way traffic.

5.1 Impact of Vehicle Arrival Rate λ

At first, we show how the link delay changes as the vehicle inter-arrival time varies. Note that the vehicle inter-arrival time is the reciprocal of vehicle arrival rate λ. As shown in Fig. 4, one-way simulation result has longer delay than two-way simulation result. Vehicles deliver packets faster by using two-way traffic.

Table 1. Simulation Configuration

Parameter	Description
Road condition	The road is straight and $1km$ long.
Communication range	$R = 200$ meters (i.e., 656 feet).
Arrival rates	$\lambda_f = \lambda_b = 1/10$ where λ_f is the arrival rate for forward vehicular traffic and λ_b is the arrival rate for backward vehicular traffic.
Vehicle speed	$v \sim N(40, 5)$ MPH.

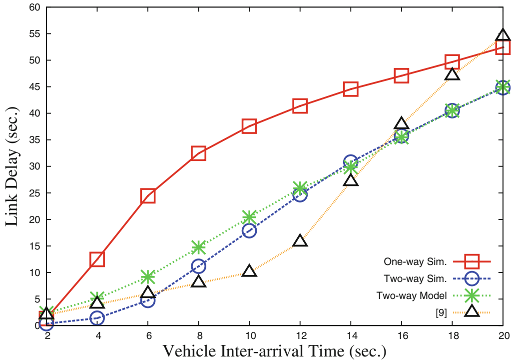


Fig. 4. Link delay versus vehicle inter-arrival time

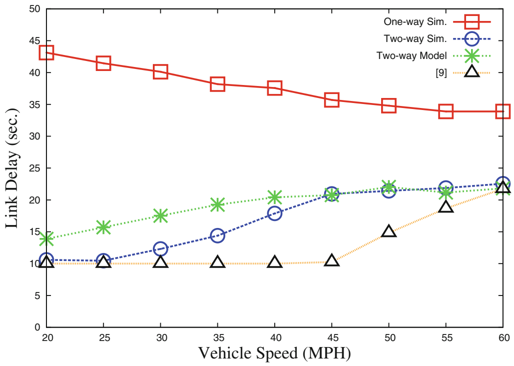


Fig. 5. Link delay versus average vehicle speed

Thus, we can deliver packets with shorter delay if we utilize the direction and location information from the GPS based navigation system. As shown in Fig. 4, our model accurately expects the link delay. Since [9] does not consider the mobility of vehicles toward forwarding direction, the expectation diverges exponentially. In comparison with [9], our model provides relatively closer result to the simulation result.

5.2 The Impact of Vehicle Speed μ_v

Here, we investigate the impact of vehicle speed to the link delay. As shown in Fig. 5, in our two-way model and two-way simulation, the higher vehicular speed results in the longer delivery delay for the dense 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 heavy traffic case.

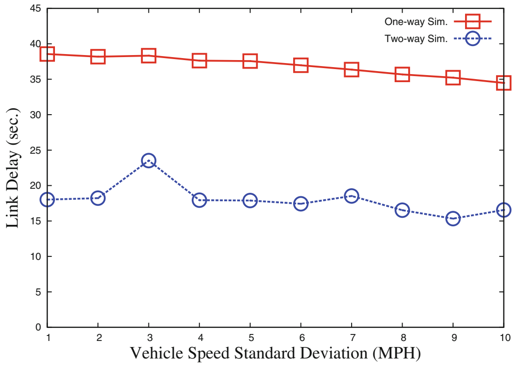


Fig. 6. Link delay versus vehicle speed standard deviation

5.3 The Impact of Vehicle Speed Deviation σ_v

We observe the impact of vehicle speed deviation to the link delay. We increase vehicle speed standard deviation from 1 to 10 MPH. As shown in Fig. 6, link delay becomes shorter as the speed standard deviation becomes larger. If two vehicles move to the same direction with the same speed, and they are out of communication range, there is no chance to make a network component. However, in case of different speed case, a faster vehicle can catch up with a slower vehicle and they can construct a network component. This phenomenon happens more often in case of a large standard deviation than a low standard deviation.

6 Conclusion

In this paper, we propose average link delay for a road segment with two-way road traffic. In order to derive the expectation, we introduce the concept of *renewal process*. This assumes that the forwarding and carry phases alternate repeatedly. We formulate link delay for a cycle because the carry delay is dominant, assuming that the inter-arrival time is distributed exponentially. This link delay modeling can be used for multihop infrastructure-to-vehicle data delivery in road networks. Two-way roads are dominant over one-way roads in real road networks. As future work, we will investigate link delay model, considering more realistic environments such as road networks with traffic signals. Also, we will evaluate data forwarding schemes for the multihop infrastructure-to-vehicle data delivery with our link delay model.

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