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SHORT COMMUNICATION

Effect of minimum headway distance on connectivity of VANETs

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ABSTRACT

The knowledge of vehicle headway distribution is essential for estimating the probability of connectivity in vehicle ad hoc networks. We consider the distribution of vehicles in a single lane, taking into account that consecutive vehicles have to maintain a minimum safe distance between them. It is shown that the account of safe distance improves the agreement between vehicles theoretical spacing distribution and empirical data in single lane traffic. We study how this minimum distance affects the connectivity probability in light traffic conditions. We show that the headway distribution of single lane traffic in the free flow conditions is better modeled using a shifted exponential model which takes into account the safe distance between vehicles. We also show that neglecting this effect will result in overestimating the connectivity in vehicular ad hoc networks, therefore, underestimating the communication range needed to establish the network with a given connectivity probability. The effect is stronger for shorter transmission range.

1. Introduction

Vehicular ad hoc networks (VANETs) are special types of mobile ad hoc networks (MANETs). In a VANET, vehicles are equipped with radio devices to enable them to exchange traffic information without the need of an infrastructure [1–4]. The original focus of VANETs is to increase safety in the road. VANETs can support driver assistance systems [5]. They collect and distribute safety information to aid in car collisions prevention by warning drivers about potential danger before they actually face it [6]. VANET applications can be broadly divided into two categories: safety applications and user applications. Besides decreasing the number of road accidents, safety applications include warning messages about accidents, intersections, and road congestion. User applications include electronic toll collection, dissemination of travel and tourism information, advertisements, and entertainment. Two basic user-related applications are Internet Connectivity and Peer-to-Peer Applications [6,7]. They can also be used in efficient route planning [8]. IEEE has introduced the Wireless Access for Vehicular Environments (WAVE) standard, described as IEEE 802.11p [9], which covers several vehicle-to-vehicle communication issues.

It is necessary to estimate the connectivity probability of VANETs under various traffic conditions, to assess the reliability of the communication, hence determine the required transmission range. VANETs are featured by constantly changing topology [4] due to high mobility of network nodes. Other properties that distinguish VANETs from other MANETs include high probability of network partitions, and no guarantee of end-to-end connectivity [6,7]. Also, unlike other MANETs, the movement of nodes in a VANET is restricted to the roads on which the vehicles travel [7]. The knowledge of vehicle headway distribution is essential for estimating the probability of connectivity in VANETs. Several connectivity studies have relied on the assumption that inter-vehicle spacing distribution is exponential [1]. This assumption is valid for sparse free-flow traffic where inter-vehicle spacings are uncorrelated. However, it does not take into account the tendency of the drivers to keep safe distances to the leading cars. This has an appreciable influence on the connectivity within the VANET as we discuss in the next sections.

This paper considers the effect of minimum distance between any two consecutive vehicles on the spacing distribution. We propose a shifted exponential distribution as a more accurate model of inter-vehicle spacing distribution in single-lane situations under light traffic conditions. We use real-road data taken from the Berkeley Highway Laboratory (BHL) [10]. The data are obtained in an analysis of traffic in a single lane, under light traffic conditions (1:00 am–3:00 am). We estimate the probability of connectivity of a VANET using both the exponential and the shifted exponential

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models to show the effect of the minimum headway distance on the connectivity probability in light traffic conditions. We show that using the exponential model (i.e. neglecting the minimum headway distance) will result in overestimating the probability of connectivity in agreement with empirical data.

The rest of paper is organized as follows: Section 2 provides a discussion of the related work, this includes the different distribution models that are used to describe vehicle spacing distributions, and the studies of VANET connectivity based on such models. In Section 3, we discuss in more details the exponential model and point out its limitations, and then introduce the shifted exponential headway distribution model. Section 4 discusses the effect that the shifted exponential model has on estimating the probability of connectivity of VANETs. Conclusions and future work are provided in Section 5.

2. Related work

2.1. Headway distribution models

According to Kerner's three phase traffic theory [11], traffic can be either in free-flow phase (light traffic), synchronized flow (in-between), and wide moving jam (highly congested). Traditionally, exponential (Poisson) distribution is assumed to model traffic headway distribution under free-flow conditions [12,13]. Some authors even theorized that inter-vehicle distances follow an exponential (Poisson) distribution [14], regardless of the traffic conditions. Several studies used empirical data to confirm that the exponential model is a good fit for the distributions of inter-vehicle spacings and inter-contact times between vehicles [12–14]. Recent studies confirmed that this assumption is indeed valid in light traffic (free flow phase) [3,15–17]. As for other traffic regimes, different models were proposed that provide better fits for the empirical data. This includes generalized-extreme-value and log-normal distributions to model headway distribution in synchronized flow phase [1,18]. Theoretical models were presented from different physical perspectives (e.g. scatter theory and random matrix theory) [19,20]. Gaussian unitary ensemble (GUE) was used to model distribution in traffic jam [16], and a super-statistical approach for headway distribution in the synchronized-flow phase [16]. Also, a study suggests that inter-arrival times (alternative to distances) can be modeled using a Gaussian-exponential mixture model [8].

2.2. Connectivity probability of VANETs

With the rise of VANETs, connectivity became a fundamental requirement in planning such networks [12]. Connectivity analyses require having very accurate distribution models. Connectivity of VANETs has been addressed using different approaches. One approach is to consider connectivity in highways in totally ad hoc manner. Other papers have studied connectivity when relay nodes (road-side units) are utilized. Also, connectivity in two-dimensional networks (such as urban environments), and the effect of traffic lights on such networks is studied. The work presented here is limited to highway traffic, where the network is established in ad hoc manner (no aid from infrastructure units is provided).

A number of studies have used some of the previously discussed headway distribution models in analyzing VANET connectivity in freeways. In [1] the authors used the GEV distribution model to study connectivity in the transition phase between free-flow and congestion. In [17] GUE model was used in studying connectivity in congested traffic phase. In [21], an analytical expression is derived to estimate the connectivity, based on the assumption that headway distribution is an unstable distribution.

Table 1
Comparison between the two models.

	Exponential	Shifted exponential
Model	$F(x) = 1 - e^{-\rho x}$	$F(x) = 1 - e^{-\rho(x-b)}$
Parameters	$\rho = 2.07$ veh/km	$\rho = 2.35$ veh/km
		$b = 39.1$ m
RMSE	0.0381	0.0183

Most connectivity studies (e.g. [1,2,17]) rely on using exponential distribution to estimate connectivity in light traffic conditions, e.g. early morning hours [1]. The exponential distribution implies that the distances between successive vehicles are uncorrelated. It ignores the vehicle length. Moreover, it neglects the minimum safe distance required between any two successive vehicles traveling down the same lane [22]. These effects have a little influence on the evaluation of headway distributions under the free flow conditions, where the mean distance between vehicles is measured in hundreds of meters. However, the situation might be different when studying connectivity in such conditions.

3. Headway distance distribution in free-flow traffic

In free flow conditions, where the density of traffic is sufficiently low, drivers can choose their own speed. The distances between cars are uncorrelated. Traffic congestion is a characterized by slower speeds, longer trip times, and increased queuing. Transition between these two modes has been studied (see for example Refs. [3,16]). As discussed earlier, different models exist for headway distribution under congested traffic conditions, or in the transitional phase. We study the free flow in very light traffic conditions. Such conditions have minimum car density on roads, hence, minimum connectivity probability of VANETs.

Under light traffic conditions, distances between cars are traditionally modeled using exponential distribution. Eq. (1) shows the exponential distribution model:

$$F(x) = (1 - e^{-\rho x})u(x) \tag{1}$$

where ρ is the mean density of vehicles and $u(x)$ is the Heaviside unit step function.

This distribution model permits zero distance between successive vehicles, which is impossible. Vehicles have to keep a minimum – safe – distance from each other. We propose slightly modifying the exponential distribution model of Eq. (1) as follows:

$$F(x) = (1 - e^{-\rho(x-b)})u(x - b) \tag{2}$$

In order to avoid the zero headway distance problem, the shift parameter b in Eq. (2) is used to model the minimum inter-vehicle distance.

To justify this, we apply both models to empirical real traffic data. We fit the data to both models using non-linear least squares analysis. The values of the root mean square error (RMSE) for both models are shown in Table 1. The values of the parameters ρ and b given in the table are the result of the fitting.

3.1. Description of traffic data

The empirical vehicles data used in this study are obtained from Berkeley Highway Laboratory (more detailed reports are found in [23]). The data are collected using dual loop detectors installed on the five lane interstate I-80 road in California. There are 8 dual-loop stations distributed along a 2.7-mile road segment. Each station is a pair of inductive loop detectors, one upstream and one downstream in the same lane. Each detector is electively a square. They are 6 ft across, and their centers are 20 ft apart. Each vehicle stream