Study of connectivity in vehicular ad hoc networks

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Abstract— **We investigate connectivity in ad hoc network formed between vehicles that move in the same direction on a typical highway. We use the common model in vehicular traffic theory in which a fixed point on the highway sees cars passing it separated by times with exponentially distributed duration. We obtain the distribution of the distances between cars, which allows us to use techniques from queuing theory for studying connectivity. We obtain explicit expressions for the expected connectivity distance as well as the probability distribution and expectation of the number of cars in a platoon. The analytical model we present is able to describe the effects of various system's parameters, including road traffic parameters (i.e. speed distribution and traffic flow) and transmission range of vehicles, on the connectivity. We further provide bounds obtained using stochastic ordering techniques. Our approach is based on the work of Miorandi and Altman [13] that transformed the problem of connectivity distance distribution into that of the distribution of the busy period of an equivalent infinite server queue. We use our analytical results along with publicly available road traffic statistical data to understand connectivity in VANETs.**

Keywords- Connectivity, VANETs, Infinite server Queues.

I. INTRODUCTION

Vehicular Ad-Hoc Networks (VANETs) are special type of Mobile ad Hoc Networks (MANETs), where wireless-equipped vehicles form a network spontaneously while traveling along the road. Direct wireless transmission from vehicle to vehicle make it possible to communicate even where there is no telecommunication infrastructure such as the base stations of cellular phone systems or the access points of wireless dedicated access networks, needed in the previous Intelligent Transportation Systems (ITS) [1,2].

This new technology has been attracting lots of interest in the recent years for ITS and also causes joint efforts of governments, standardization bodies, car manufacturers, universities and research centers in several projects world-wide. The US FCC has allocated 75 MHz of spectrum in the 5.9 GHz band for Dedicated Short Range Communication (DSRC) to enhance the safety and productivity of the nation's transportation system [3]. The FCC's DSRC ruling has permitted both safety and non-safety (commercial) applications, provided that safety is assigned priority. The USDOT and IEEE have taken up the standardization of the associated radio technology Wireless Access for Vehicular Environments (WAVE), now described as IEEE 802.11p [4]. In addition some other projects outside the US like: PReVENT project [5] in Europe, InternetITS [6] in Japan or Network on Wheels [7] in Germany are aimed to solve existing challenges. So in a near future, vehicles could benefit from spontaneous wireless communications.

There are many challenges in VANETs, as described in a survey [8]. According to FCC frequency allocation we can categorize two main classes of applications for vehicular ad hoc networks. The first category which was mentioned above is to improve the safety level in roads, and the second predicted to grow very fast in the near future, is commercial services i.e., comfort applications. In both beforehand mentioned categories, related (i.e. safety or comfort) messages should be exchanged between vehicles.

In this paper we consider traffic in a highway where vehicle travel without interrupt. From the theory of traffic [9] we know that there are three macroscopic parameters including speed (km/h), density (veh/km/lane) and flow (veh/h/lane) which describe the traffic state. The average values of these parameters are related as follows:

$$F = S \cdot K \qquad (1)$$

Where F is traffic flow, S is mean speed and K is density.

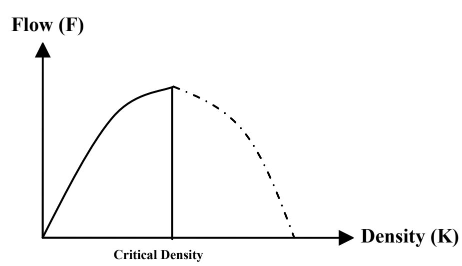

Figure1. The relationship between basic parameters in traffic theory

Road's traffic can be seen in two different phases as shown in Fig.1. First when the density is low, vehicles drive as fast as they want. This state holds until the density reaches a so called, critical value. This phase called free-flow traffic is shown by solid lines. Beyond this density, some vehicles have to control their speed in order to keep safe distance from others. This phase is called forced flow and is shown with dashed line. If the density increases more, the traffic reaches a jam state where vehicles have to completely stop. Connectivity obviously is the

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best in the jam state, and is worse at light load corresponding to the free-flow phase in which it might not be possible to transfer a message to another vehicle because of disconnections.

We study in the paper connectivity of vehicular ad-hoc networks operating in the free-flow regime. We use the common model in vehicular traffic theory in which any given point in space (i.e. on the highway) sees cars passing it separated by times with random duration distributed exponentially. We obtain the distribution of the distances between cars at steady-state which allows us to use techniques originating from queuing theory for studying connectivity. We obtain explicit expressions for the expected connectivity distance as well as the probability distribution and expectation of the number of cars in a platoon. The analytical model we present is able to describe the effects of various system's parameters, including road traffic parameters (i.e. speed distribution and traffic flow) and transmission range of vehicles, on the connectivity. We further provide bounds obtained using stochastic ordering techniques. The approach we use for our analysis is based on the work of Miorandi and Altman that transformed the problem of connectivity distance distribution into that of the distribution of the busy period of an equivalent infinite server queue. We use our analytical results along with publicly available road traffic statistical data to understand connectivity in VANETs.

II. Related Works

Connectivity in mobile ad hoc networks has a mature body of research and there are many works discussed it through simulation or analytical evaluation [10-13]. The great body of these works studies the problem in static networks and is more suitable for sensor networks. However, some of them also tried to tackle the problem of connectivity in presence of mobility but their attempts are for low-mobility networks and/or usually for well-known mobility models. So our work is different from this body of research in the way that we consider vehicular movements which a special type of mobility with many distinctive characteristics.

Recently some authors studied the connectivity in vehicular networks specifically. Since due to high relative speed between cars, network's topology changes very fast, some works tried to predict link's life times [14, 15]. In [16] the authors study the trajectory duration for a typical highway scenario through simulation. The authors of [17] used analytical and simulation studies for finding the link's life time. Another category of related research studies the minimum transmission range (MTR) providing connectivity. Works of authors in [18] which are simulation study try to find MTR for different type of scenarios and freeways and also [19] discuses the connectivity with static transmission range through simulation of different vehicle's scenarios.

The rest of this paper is organized as follows: in section 3 we first introduce our model and find the distribution of inter-vehicle distance. Then in section 4 we analyze the connectivity metrics. The effects of various parameters on the connectivity will be studied in section 5. In Section 6 we show some numerical results based on statistic from vehicle's traffic data.

III. The Analytical Model

Assume an observer stands at a point, say point 0, of an uninterrupted highway (i.e., without traffic lights, etc.). Also, assume vehicles pass the observer with i.i.d. exponentially distributed inter-arrival times with mean $1/\lambda$. To simplify presentation of the main ideas, we assume there are N discrete levels of constant speed v_i, $(i = 1..N)$ in the highway. The speeds are i.i.d., and independent of the inter-arrival times. Denote the rate of arrivals of cars at each level of speed by $\lambda_i, (i = 1..N)$, so we have $\sum_{i=1}^{N} \lambda_i = \lambda$. The arrival process of cars with speed v_i is a Poisson process with parameter $\lambda_i, (i = 1..N)$ and these N processes are independent. Given these assumptions, the inter-arrival time distribution of process i is

$$P(T_i > \tau) = 1 - F_{T_i}(\tau) = e^{-\lambda_i \tau} \quad (2)$$

and that of the global arrival process is:

$$P(T > \tau) = 1 - F_T(\tau) = e^{-\sum_i \lambda_i \tau} = e^{-\lambda \tau} \quad (3)$$

In order to investigate the connectivity, we invoke an equivalent infinite server queuing model. It was observed in [13] that its busy period has the same distribution as the connectivity distance in an ad hoc network. Moreover, the number of customer served during the busy period have the same distribution as the number of mobiles in a connected cluster (platoon) in the ad hoc network. The equivalence is obtained when the inter-arrival times in the infinite server queue have the same distribution as the distance between successive cars and when the service times have the same distribution as the transmission range of the mobiles. We thus have to determine the distribution of L, the random variable representing the distance between two consecutive cars, when the first one is at point 0 (the observer). It can be represented as $L = V\,T$, where V is a random variable representing the speed of the second car and with probability $P_i = \lambda_i / \lambda$ it takes the value equal to vi.

Form (3) we know that

$$P(v_i T > x) = e^{-\frac{\lambda}{v_i} x} \quad \text{which implies} \quad (4)$$

$$P(L > x) = 1 - F_L(x) = \sum_i P_i \times P(v_i T > x) = \sum_i P_i e^{-\frac{\lambda}{v_i} x} \quad (5)$$

This is the hyper-exponential distribution. In some previous works, the distribution of the distance between vehicles has been assumed exponential [17,20,21]. This implies implicitly that the speeds of all cars are replaced by some constant speed. Since one of our main concerns is to investigate the effect of speed on the connectivity, we continue our discussion with the more general and accurate distribution given in (5).

We next show how to import the parameters P_i and v_i to our model. It has been widely accepted in vehicle traffic theory that the distribution of speeds is normal, and there are some values for average and variance for some experimented observations [9, 17]. So the speeds are distributed according to the following probability density function:

$$f_V(v) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(v-\mu)^2}{2\sigma^2}} \qquad (6)$$

We shall use a truncated version of this distribution to avoid dealing with negative speed or even to avoid getting close to zero speed (the latter would otherwise cause problems in (4) and (5) and elsewhere; in fact it can be seen that a speed of zero does not make sense since a car cannot cross the observer if it has speed zero). We thus define two limits for the speed (i.e. v_{min} and v_{max} for minimum and maximum levels of vehicle's speed in a highway, respectively) we can re-write the inter-vehicle distance in (5) by replacing P_i and v_i as follows:

$$P(L > x) = \int_{v_{\min}}^{v_{\max}} \hat{f}(v) e^{-\frac{\lambda x}{v}} dv \qquad (7)$$ where,

$$\hat{f}_V(v) = \frac{f_V(v)}{\int_{v_{\min}}^{v_{\max}} f_V(s)ds} = \frac{2 f_V(v)}{erf(\frac{V_{\max} - \mu}{\sigma\sqrt{2}}) - erf(\frac{V_{\min} - \mu}{\sigma\sqrt{2}})}, v_{\min} \le v \le v_{\max} \qquad (8)$$

So the equation (7) can be written generally as follows:

$$P(L > x) = \frac{2\int_{v_{\min}}^{v_{\max}} e^{(-\frac{(v-\mu)^2}{2\sigma^2} - \frac{\lambda x}{v})}}{\sigma\sqrt{2\pi}\left(erf(\frac{v_{\max} - \mu}{\sigma\sqrt{2}}) - erf(\frac{v_{\min} - \mu}{\sigma\sqrt{2}}) \right)} dv \qquad (9)$$

where by definition $erf(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-t^2} dt$, is the error function. Table I shows some values calculated by the mentioned way [17].

The other important parameters needed to import by our model are the maximum and minimum speed of vehicles. Noting that the area under the normal curve for speeds in $(\mu - 3\sigma, \mu + 3\sigma)$ is about 99.7% of the whole area, we take $v_{\min} = \mu - 3\sigma$ and $v_{\max} = \mu + 3\sigma$. Clearly we do not lose the generality by beforehand mentioned parameter selection and one can import the parameters differently for specific highway based on fully experimental data.

TABLE I. NOMINAL VALUES FOR SPEED DISTRIBUTION

$\mu[km/h]$	$v_{85}[km/h]$	$\sigma[km/h]$
70	≈ 90	21
90	≈ 120	27
110	≈ 145	33
130	≈ 170	39
150	195	45

IV. CONNECTIVITY ANALYSIS

As mentioned in the previous section, we use the results connectivity expressions from [13] based on an equivalent infinite server queue. We shall use VANET's terms instead of queuing terms. The authors in [22] found general presentation for busy period in $GI/G/\infty$ queuing system and also some closed-form equations for some special cases. In this section, since inter-vehicle distances are hyper-exponentially distributed and by assumption, there is one fixed transmission range we use $GI/D/\infty$ model. In the following we find the distribution of connectivity distance (the total distance that a packet can reach from a given car at point 0), and the distribution of the number of vehicles in each platoon.

The probability generating function of the number of vehicles in each platoon is given by [22]:

$$\widetilde{N}(z) = z.\frac{1 - F_L(R)}{1 - zF_L(R)} \qquad (10)$$

where $F_L(R)$ is the distribution function of inter-vehicle distance and R is the fixed transmission range of each vehicle. So the random variable N, defined as the number of nodes in each platoon, has following probability mass function:

$$P[N = k] = (1 - F_L(R)) \cdot F_L(R)^{(k-1)} \quad k = 1, 2, \ldots \qquad (11)$$

Hence the probability that at least k vehicles are connected is:

$$P_N(k) = P[N \ge k] = \sum_{t=k}^{\infty} P[N = t] = F_L(R)^{(k-1)} = \left(1 - \sum_i P_i e^{-\frac{\lambda}{v_i}R}\right)^{(k-1)} = \left(1 - E(e^{-\frac{\lambda}{V}R})\right)^{(k-1)} \qquad (12)$$

Furthermore the expected value of the number of vehicles in each platoon is given by:

$$E(N) = \lim_{z \to 1} \frac{\partial \widetilde{N}(z)}{\partial z}\bigg| = \frac{1}{1 - F_L(R)} = \frac{1}{\sum_i P_i e^{-\frac{\lambda}{v_i}R}} = \frac{1}{E(e^{-\frac{\lambda}{V}R})} \qquad (13)$$

Moreover, form (11) we can easily find the probability of isolation for a given node (i.e. there is just one vehicle in a cluster) is obtained as:

$$P_I = 1 - F_L(R) = \sum_i P_i e^{-\frac{\lambda}{v_i}R} = E(e^{-\frac{\lambda}{V}R}) \qquad (14)$$

In order to find the distribution of the connectivity distance d, we use results from [22] (i.e. equation 3.4) for its Laplace Transform (LST) which is denoted by $P_d^*(s)$. It may be obtained as follows:

$$P_d^*(s)=\frac{e^{-sR}(1-F_L(R))}{1-\int_0^R e^{-sx}dF_L(x)}$$

$$=\frac{e^{-sR}(\sum_i P_i e^{-\frac{\lambda}{v_i}R})}{1-\lambda\sum_i \frac{P_i}{v_i}(\frac{1}{\lambda/v_i+s})\left[1-e^{-(\lambda/v_i+s)R}\right]} \quad (15)$$

which is difficult to invert. We are able however to compute the expected connectivity distance as follows:

$$E(d)=-\frac{\partial P_d^*(s)}{\partial s}\bigg|_{s=0}=\frac{\sum_i P_i v_i-\sum_i P_i v_i e^{-\frac{\lambda}{v_i}R}}{\lambda\sum_i P_i e^{-\frac{\lambda}{v_i}R}} \quad (16)$$

$$=\frac{E(V)-E(Ve^{-\frac{\lambda}{V}R})}{\lambda E(e^{-\frac{\lambda}{V}R})}=\frac{E(V-Ve^{-\frac{\lambda}{V}R})}{\lambda E(e^{-\frac{\lambda}{V}R})}$$

V. EFFECT OF TRAFFIC PARAMETERS ON THE PERFORMANCE

A. Platoon size.

The ISC Ordering. Increasing Stochastic (ISC) ordering between two random variables is defined as follows [23]:

$$V\underset{inc}{\le}V' \Leftrightarrow E[f(V)]\le E[f(V')] \quad \text{for all } f \,\big|\, f(x) \text{ is increasing in } x \quad (17)$$

Now, let $f(x)=e^{-\frac{\lambda}{x}R}$, clearly this function is increasing in x; hence we can have the following results:

$$V\underset{inc}{\le}V'\Rightarrow E(e^{-\frac{\lambda}{V}R})\le E(e^{-\frac{\lambda}{V'}R})\Rightarrow \left(E(e^{-\frac{\lambda}{V}R})\right)^{-1}\ge\left(E(e^{-\frac{\lambda}{V'}R})\right)^{-1}\Rightarrow E(N)\ge E(N') \quad (18)$$

We conclude that for a fixed distribution of T, the expected number of vehicle in a platoon decreases if the velocity increases in the stochastic order.

Convex ordering is defined as below [23]:

$$V\underset{cnx}{\le}V' \Leftrightarrow E[f(V)]\le E[f(V')] \quad \text{for all } f \,\big|\, f(x) \text{ is convex in } x \quad (19)$$

Note that for concave function the direction of inequality is reversed in the right-hand of (19).

$f(x)=e^{-\frac{\lambda}{x}R}$ is convex in x when $0<x\le\lambda R/2$ and otherwise it is concave. Hence we obtain:

$$V\underset{cnx}{\le}V'\Rightarrow E(e^{-\frac{\lambda}{V}R})\le E(e^{-\frac{\lambda}{V'}R})$$
$$\Rightarrow\left(E(e^{-\frac{\lambda}{V}R})\right)^{-1}\ge\left(E(e^{-\frac{\lambda}{V'}R})\right)^{-1}\Rightarrow E(N)\ge E(N') \quad (20)$$
$$\text{if}\quad P(V<\lambda R/2)=1$$

This result means that if the supports of speed distributions are lower than $\lambda R/2$, the expected number of vehicles in a platoon increases if the velocity decreases in the convex order. Similarly,

$$V\underset{cnx}{\le}V'\Rightarrow E(e^{-\frac{\lambda}{V}R})\ge E(e^{-\frac{\lambda}{V'}R})$$
$$\Rightarrow\left(E(e^{-\frac{\lambda}{V}R})\right)^{-1}\le\left(E(e^{-\frac{\lambda}{V'}R})\right)^{-1}\Rightarrow E(N)\le E(N') \quad (21)$$
$$\text{if}\quad P(V>\lambda R/2)=1$$

Thus, if the supports of speed distributions are larger than $\lambda R/2$, the expected number of vehicles in a platoon increases (resp. decreases) if the velocity increases in the convex (resp. concave) order. Since the function $f(x)=e^{-\frac{\lambda}{x}R}$ is increasing, for this case we can extend the ordering to increasing concave which is also called second-order stochastic ordering [24].

B. Connectivity distance.

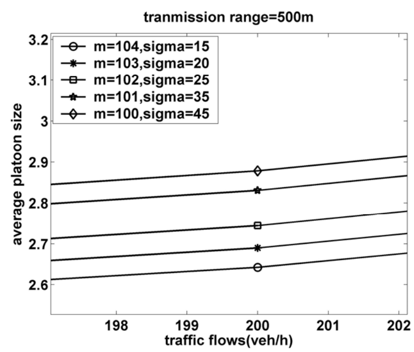
In this part of the paper we want to investigate similar discussion about distance of connectivity. First we know that $f(x)=x(1-e^{-\frac{\lambda}{x}R})$ is a concave function in all positive values of x. So considering (19) we can write

$$V\underset{cnx}{\le}V'\Rightarrow\begin{cases}E(e^{-\frac{\lambda}{V}R})\le E(e^{-\frac{\lambda}{V'}R})\\ E(V(1-e^{-\frac{\lambda}{V}R}))\ge E(V'(1-e^{-\frac{\lambda}{V'}R}))\end{cases}$$
$$\Rightarrow\frac{E(V(1-e^{-\frac{\lambda}{V}R}))}{\lambda E(e^{-\frac{\lambda}{V}R})}\ge\frac{E(V'(1-e^{-\frac{\lambda}{V'}R}))}{\lambda E(e^{-\frac{\lambda}{V'}R})}\Rightarrow E(d)\ge E(d') \quad (22)$$
$$\text{if}\quad P(V<\lambda R/2)=1$$

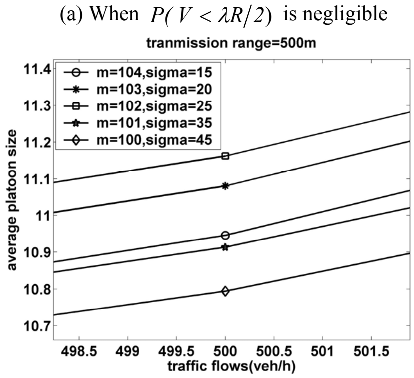
This result means that if the value of speeds is below $\lambda R/2$, the average distance which a message can be transmitted from a node in the origin (the observer) is decreasing as the velocity increases in the convex order.

VI. NUMERICAL RESULTS

In this section we investigate the connectivity by evaluating the model numerically. The proposed model covers general highway traffic as long as the inter-arrival times are independent. However as we mentioned in the section 1, the connectivity problem is worth analyzing in low density traffic situation when vehicles travel with high speed and this situation holds more in free-flow phase of traffic shown in Fig.1. In typical free-flow traffic the traffic flow is usually considered below 1000 [veh/h] for freeways and below 500 [veh/h] for other roads [9]. Moreover, since the proposed transmission range for DSRC standard is 1000m [3, 4], we study our results for flows below 700 [veh/h] and ranges below 1000m. In order to be able to present more tangible results we assume normal distribution for speeds which holds mostly for free-flow traffic and use the obtained values in table I. In the following figures speed distribution is denoted by *N (m, sigma)*, where *m* and *sigma* are average and standard deviation values respectively.



(a) When $P(V < \lambda R/2)$ is negligible



(b) When $P(V > \lambda R/2)$ is negligible

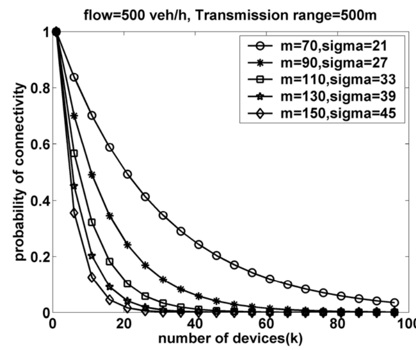
Figure2. Comparison of average platoon size

The second-order stochastic ordering for average platoon size has been shown in the Fig.2. The speed with higher average and lower variance is larger in sense of increasing concave order [24]. Fig 2.a treats the case where supports of V are larger than $\lambda R/2$, so increasing concave ordering result in (21) holds. The figure confirms the stochastic bound. However, when supports of V are lower than $\lambda R/2$, there is no special ordering between values of average platoon size. This issue is showed numerically in Fig 2.b.

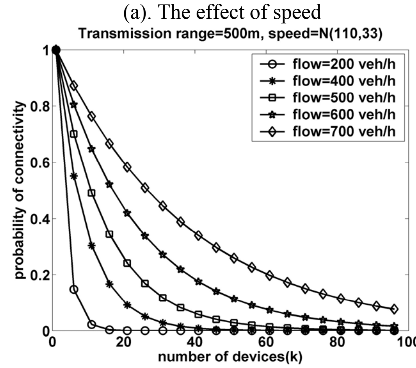
Fig. 3 shows the effects of vehicle's transmission range and road's traffics characteristics on the probability that at least k devices (vehicles) are connected. As shown, as mean speed increases, the probability of connectivity decreases convex. Furthermore, as the number of vehicles in the platoon increases, the probability of connectivity decreases in all cases. The mentioned phenomenon is also seen in case of increasing traffic flow and vehicle's transmission range. These quantitative values may be used by network designers to tune parameters like transmission range and other related parameters (in higher layers of protocol stack), in order to achieve intended connectivity.

Fig.4 shows effects of vehicle's transmission range and also road's traffics characteristics on the average connectivity distance. As one can conclude, the size of platoon changes very fast by small changes in speed distribution, traffic flow and transmission range.

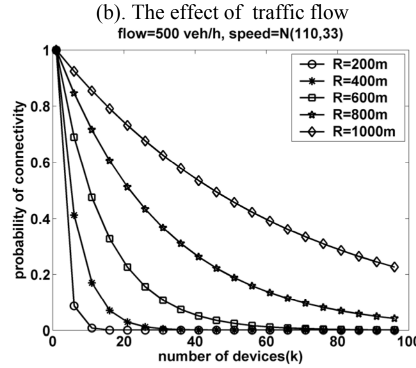
The connectivity distance is studied numerically based on mentioned nominal values, see Fig.5**.** As seen in the figure when the traffic flow increase, the average connectivity distance becomes better noticeably. This phenomenon takes place also for when the mean speed decreases. Moreover, it seems the effect of transmission range also shows similar trend.



(a). The effect of speed

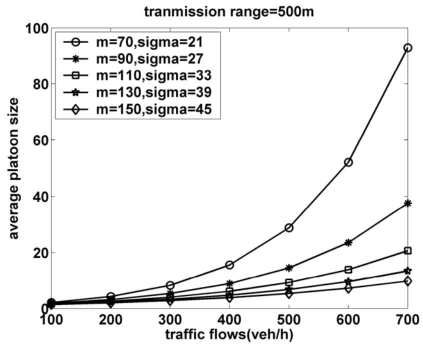


(b). The effect of traffic flow

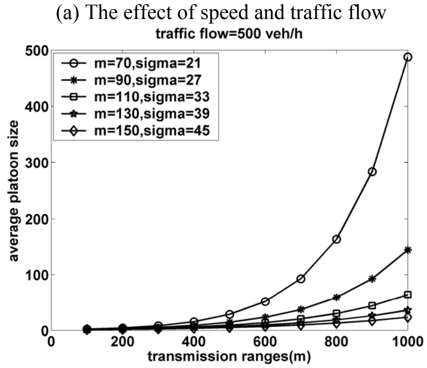


(c). The effect of vehicles' transmission range

Figure3. The effects of various parameter on $P_R(k)$

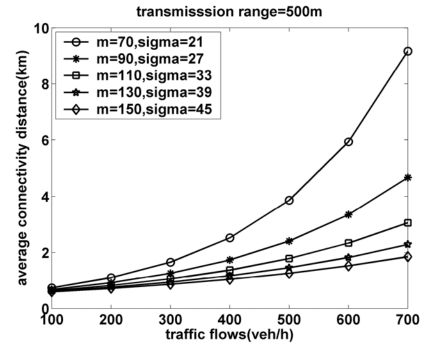


(a) The effect of speed and traffic flow

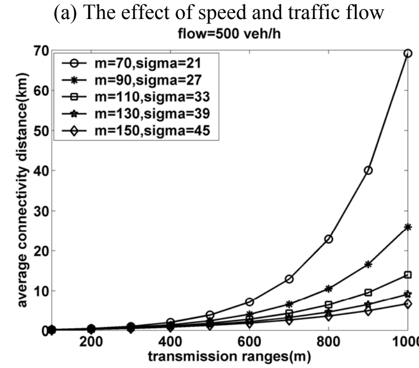


(b). The effect of speed and transmission range

Figure 4. The effect of various parameter on average platoon size



(a) The effect of speed and traffic flow



(b). The effect of speed and transmission range

Figure5. The effect of various parameter on average connectivity distance

VII. CONCLUSIONS

We have presented an analytical model for connectivity in vehicular ad hoc networks. We assumed exponential inter-arrival time between vehicles passing an observer and obtained the distribution of inter-vehicle distance. We used an equivalent infinite sever queue to obtain the expected distance of connectivity as well as the distribution and expected number of vehicles in a platoon. Finally we use our analytical results along with publicly available road traffic statistical data to understand connectivity in VANETs.

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