Local Density Estimation Based on Velocity and Acceleration Aware in Vehicular Ad-Hoc Networks

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Abstract. In vehicular ad-hoc networks (VANET), node density is constantly changing in both time and space. Well communication quality depends on the nodes density. Knowing the density of the vehicle communication system is very important for achieving better wireless communication performance. In recent years, many researchers have proposed a resource allocation scheme based on vehicle density. Therefore, in this paper, we introduced an acceleration aware density estimation (VAADE) algorithm to map the relationship between vehicle density and resource requirements. In VAADE, a car estimates the density of the driving road according to its own velocity and acceleration in real time. VAADE is accurate because it employs both velocity and acceleration, which are sufficient for density estimation. The simulation results indicate that the proposed algorithm can map the relationship between the communication resource demands and the acceleration.

Keywords: Density estimation · Velocity and Acceleration Aware
Resource demands

1 Introduction

VANET as a promising Intelligent Transportation System (ITS) technology aims to realize a highly reliable and low latency communication. An effective resource allocation scheme can effectively improve resource utilization while reducing the likelihood of transmission collisions. To this end, the researchers proposed a dynamic allocation of resources scheme, such as based on vehicle density of one lane. Other applications, such as traffic status monitoring, routing and distribution of data, also use the information which is provided by density estimation to make the decision.

As an essential metric, traffic density is used in many traffic information systems and also affects the performance of vehicular networks such as capacity, routing

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efficiency, delay, and robustness. The commonly used vehicle density estimation scheme is designed for Infrastructure-Based Traffic Information Systems [1] (IBTIS). However, these mechanisms are of low reliability, limited coverage, and require high deployment and maintenance costs. The most important is that it can't calculate density estimate in real time. As for Infrastructure-Based density estimation algorithms are not enough for the highly dynamic and scalable environment of VANET system. The infrastructure-Free Traffic Information System [2] (IFTIS) was designed to provide vehicles with an estimate of traffic density on urban roads. Thanks to most vehicles now are equipped with built-in wireless communication capabilities, vehicle density can be measured more accurate in real-time [3].

In this paper, the classical density estimation is introduced and simulated. As an improvement, we proposed a local and real-time density estimation algorithm that requires the vehicle to track its own speed and acceleration pattern, because of the strong correlation between these two metrics and road state.

The rest of the paper is organized as follows. In Sect. 2, the relevant topics in traffic theory are introduced. The traffic simulation environment is given in Sect. 3. Explain and simulate the classical Artimy's method for local density estimation in Sect. 4. Then we proposed Velocity and Acceleration Aware Density Estimation (VAADE) in Sect. 5. Finally, Sect. 6 gives some conclusions.

2 Introduction to Traffic-Flow Theory

There are three main quantities in traffic-flow theories: density, flow, and speed [7]. The density k is the amount of vehicles per unit distance that pass a detector, expressed in vehicles per kilometer per lane (veh/km/lane). The flow f means the number of vehicles that pass an observer per unit time, presented in vehicles per hour per lane (veh/h/lane). The speed u equals to the distance that a vehicle travel per unit time, expressed in kilometers per hour (km/h). The relationship among the three quantities is like

$$f = u \times k. \tag{1}$$

Several theories attempt to define the relationships among these three variables in (1), but no one completely done. The following is a brief introduction to the principles most relevant to the scope of this paper.

Car-following models describe the speed-density relationship that is suitable for a dense single lane traffic where overtaking is not permitted and assume that each driver responds in a particular way to the stimulation of the front or rear vehicle. On the other hand, this model do not apply in free-flow case where no communication like broadcast occurs.

In Pipes proposed car-following model, it assumes that drivers maintain a certain distance with neighboring vehicles. Given the relation of the following

$$u = \lambda\left(\frac{1}{k} - \frac{1}{k_{jam}}\right), \tag{2}$$

where λ represents the vehicle interaction sensitivity, and k_{jam} is the maximum traffic density of vehicle when the road congest.

3 Traffic Simulation Environment

'Simulation of Urban Mobility' (SUMO) is designed to produce realistic traffic patterns and handle large road networks as a highly portable, microscopic and continuous road traffic simulation package. The car movement pattern in SUMO is developed by Kraußβ, which is a space-continuous and time-discrete car-following model [5]. Traffic assignment in SUMO employs the DUA-approach [6].

The traffic simulation environment we used is shown in Fig. 1. According to SUMO's configuration, vehicles travel in a two-lane road where overtaking is allowed.

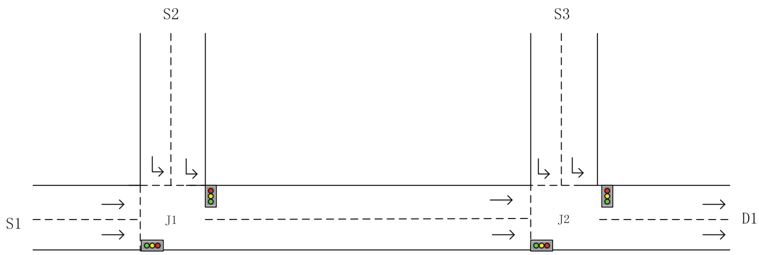


Fig. 1. The simulation environment

There are three sources S1, S2 and S3, one destination D1, obviously two T-Junctions J1 and J2. Define the maximum speed of each lane as 15 m/s (equal to 54 km/h). The junction J1 and J2 are both set with traffic light, while traffic light in J2 always be in red state, which causes an increase in vehicle density until the traffic jam happened.

4 Local Density Estimation

In this section, we deduce a relationship for local density estimate according to the car-following model, the NaSch-S2S model and the two-fluid model. It will be proven that cars' own movement pattern can be used to estimate the local vehicle density.

4.1 Density Estimation

As mentioned earlier, car-following models suggests some relationship between the average velocity and density like Eq. (2). According to that, the average velocity can be expressed as a function of density

$$u = u(k). \tag{3}$$

Two-fluid theory relates the fraction of vehicles that are stopped in traffic f_s to the average speed of all vehicles [7]

$$u = u_{\max}(1 - f_s)^{\eta+1}, \tag{4}$$

where η indicates the service quality of vehicular network, u_{max} equals to the allowed maximum velocity on the road.

According to the definition of $f_{s,}$ it can be obtain by the total vehicle numbers N and the stopped vehicles numbers $N_{s,}$ which can be obtained by an external observer

$$f_s = N_s/N \tag{5}$$

From (2), we get the normalized vehicle density k' is

$$k' = \left(\frac{u'}{\lambda'} + 1\right)^{-1}, \tag{6}$$

where $k' = k/k_{jam}$, $u' = u/u_{max}$ and $\lambda' = \lambda/(u_{max}\, k_{jam})$, respectively.

According to (4) and (5), the normalized average vehicles' speed is

$$u' = \left(1 - \frac{N_s}{N}\right)^{\eta+1} \tag{7}$$

Substituting (7) into (6), finally estimated density K is shown as following

$$K = \left[\frac{(1 - N_s/N)^{\eta+1}}{\lambda'} + 1\right]^{-1} \tag{8}$$

4.2 Evaluation of Local Density Estimation

Simulation using the vehicle network mentioned earlier to determine whether (8) can provide a reasonable density estimate of various traffic conditions. In the simulation, we calculate f_s and K in each time step. Due to vehicle density variable in spaces and time, the density measurement over the whole road segment does not reflect the local traffic conditions experienced by vehicles. Therefore, we only estimate density of vehicles between J1 and J2 with length of 1000 m. All the parameters in the simulation scenario are summarized in Table 1.

In order to show the accuracy of the density estimation, comparison chart between estimate density K and actual density k is shown below.

Figure 2 shows that (8) performs well in density estimation, but the K-k relation deviates from a straight line at the free-flow range (k < 1/5). Within that range, (8) has a constant value about 0.18, because of $N_s = 0$. In other word, (8) do better in congested traffic condition while not applicable in free-flow condition.

Table 1. Simulation parameters

Parameter	Font size and style
Simulation time	520 s
u_{max}	15 m/s
λ	0.5557
η	0

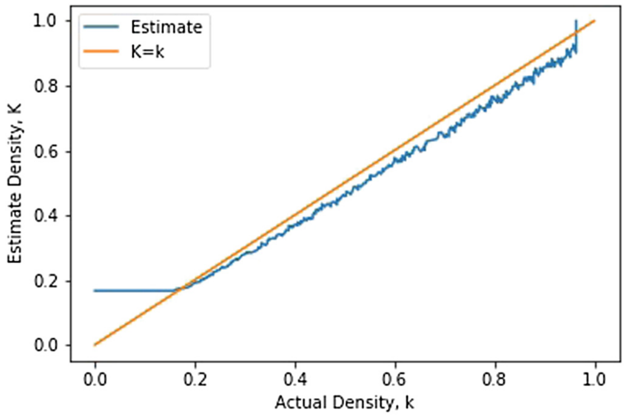


Fig. 2. Density estimate K versus actual density k

5 Velocity and Accelerate Aware Density Estimation

In the previous section we learned that (8) was not suitable for free-flow traffic condition, only in relation to the number of vehicles and cannot reflect the vehicle's communication needs. Therefore, an algorithm for estimating vehicle density using speed and acceleration is proposed.

In this paper, we defined D_s as density indicator of one road used for dynamic resource allocation. It is clear that resource required of vehicle communication are not only decided by the number of cars, but also with regard to the interaction frequency between cars.

5.1 Density Estimate

Mobility model of each individual vehicle are affected by the change of traffic flow. That means the mobility model is an excellent flow indicator used to estimate the density of neighboring vehicles. Two examples are given to illustrate this issue.

a. In free-flow network, vehicles tend to travel at reference velocity with little deviation of velocity and acceleration. In this case, drivers are more likely to keep a constant speed unless some emergencies are recognized.

b. For dense network, travel pattern of some vehicle has to change frequently. A driver tries to increase speed, while others restrict it. That means velocity and acceleration are easily change in a short time.

In this section, Velocity and Accelerate Aware Density Estimation (VAADE) is introduced. The estimate is done separately in each node and no more information from other vehicles are required.

Obtain vehicle's movement pattern information is the key of VAADE algorithm. For example, when a vehicle is at high speed, conclusion can be drawn that the density is low and only Basic Safe Message (BSM) are needed to be send. In other words, frequently changes in acceleration demonstrate a denser network, maybe a traffic accident is happened with too many event-triggered messages to broadcast. In view of the velocity and acceleration information of a car, four cases can be defined as follow:

(A) Higher velocity, lower acceleration
(B) Higher velocity, higher acceleration
(C) Lower velocity, lower acceleration
(D) Lower velocity, higher acceleration

Case A often occurs in free-flow situation where vehicles move at high constant speed and the variations in acceleration is approximately zero. Case B generally happens when emergency situations is detected by a driver. Case C means driver is moving freely. Due to the driver's personal behavior, the network may be sparse, and may be dense but not congested. Case D more likely to show a dense network, where vehicle is restricted by other's movement.

According to the discussion above, the high acceleration derivative usually indicates of many vehicles nearby or some emergency occurs. In the other word, the derivative of acceleration has a direct relationship with the density of the lane.

$$D_{\mathrm{s}} \propto \left| \frac{da}{dt} \right| \tag{9}$$

where a represents acceleration.

A high speed indicates a free-flow network. Thus D_s should be inversely proportional to velocity, so (9) can be modified to

$$D_{\mathrm{s}} \propto \frac{1}{u} \left| \frac{da}{dt} \right|. \tag{10}$$

Both (9) and (10) provide a simple and useful means of density estimate. Base on the concept above, we defines a formula to indicate density of one road

$$D_s = \begin{cases} \frac{|a|}{\alpha u_i + (1-\alpha)u_{i-1}} & 1 \leq i \leq n, u_i \neq 0 \\ 1 & u_i = 0 \end{cases}. \tag{11}$$

where i equals to the time value of each time step. The value of a presents the acceleration at time i, while u means the value of speed. A parameter α is introduced to indicate acceleration or deceleration.

$$\alpha = \begin{cases} 0 & decelerate \\ 1 & accelerate \end{cases}. \tag{12}$$

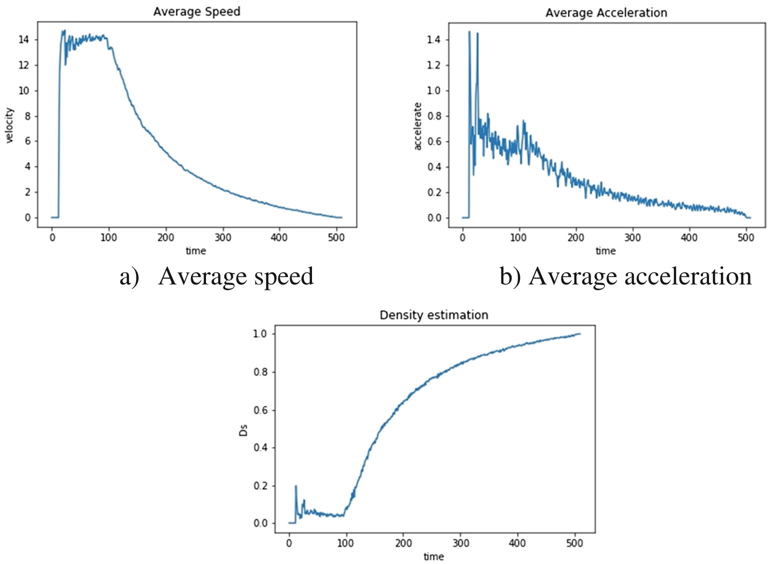
5.2 Evaluation of VAAED

Simulation under the network mentioned above to demonstrate whether Eq. (11) performed well in both free-flow and congested traffic condition, especially whether it can well reflect the communication resource needs. In the simulation, we calculate D_s of each car on the lane between J1 and J2 in each time step, the take the average to represent the road state. The system parameters in the simulation scenario are summarized in Table 2.

From Fig. 3, we can easily obtain the relationship between velocity, acceleration and D_s. Vehicles travel at approximately the maximum speed, while acceleration is

Table 2. Simulation parameters

Parameter	Value
Simulation time	520 s
Time step	1 s



a) Average speed b) Average acceleration

c) Average Ds

Fig. 3. Density estimation

maintained at around 0.6 during time 20 and time 100, and DS is steady in value 0.05. This presents a sparse network with less interactive. As time goes on, road between J1 and J2 is getting denser, as more and more cars come to here without one left. During time 100 and 200, the speed and acceleration rapidly decreased, resulting in a sharp increase in D_s. Large acceleration deviation means frequent interaction between vehicles, which requires more resource to broadcast or unicast. Finally, the road is in a fully congested state with Ds equals to 1.

6 Conclusion

In this paper, we first analysis a classical density estimate algorithm, which is based on its movement pattern. Many VANET protocols, which are depends on traffic conditions can use this estimate to configure parameters. The simulation results show that the algorithm is more accurate when the vehicles are stopped, but fails when the vehicle is running normally.

Velocity and Accelerate Density Estimation (VAADE) was introduced as an estimation technique which only depend on self-information. VAADE can be employed for vehicular dynamic resource allocation based on density estimation, due to the full use of the relationship between acceleration deviation and communication resource demands. According to the simulation result, it was proved that VAADE performed well under free-flow and congested traffic condition.

A future study will involve a performance analysis of vehicular system using dynamic resource allocation based on VADDE.

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