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On the Connectivity of Vehicular Ad Hoc Network Under Various Mobility Scenarios

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ABSTRACT In this paper, a new mobility metric called generalized speed factor (GSF) is proposed by extending the existing speed factor, which assumes that all vehicles have the same speed at all times. The GSF defines an actual relationship between the inter-vehicle spacing and the relative speed of consecutive vehicles. The vehicle connectivity in three different mobile environments based on GSF is analyzed, i.e., temporal static connectivity, low mobility connectivity, and high mobility connectivity. It is shown that the connectivity probability P_c is directly proportional to the mean velocity μ_v up-to a specific threshold μ_τ, and after μ_τ the connectivity starts going down. Finally, network connectivity is extended to the best route selecting metric for the most strongly connected route. Simulation results show that a congested network is strongly connected as compared with sparse vehicular ad hoc network.

INDEX TERMS Connectivity model, inter-vehicle spacing, freeway highway, generalized speed factor, best route, most strongly connected.

I. INTRODUCTION

The concept of connectivity in VANETs is to measure the effectiveness of vehicles communication on highways. VANETs technology is growing exponentially with its integration with the concept of 5G [1], [2], mobile cloud computing [3], [4], connected vehicles (CV) [5], IoV (Internet of vehicles) [6], big data and social networking [7]. The combination of IoT (Internet of things) and VANET is called IoV [1].

By combining vehicles with sensor, Internet, and road infrastructure, VANETs comes with many flavors [5]. Communication is an essential research theme in VANETs. The main purpose of VANET technology is to introduce safety and non-safety applications by using V2V and V2I. Multihop ad-hoc connections are used among vehicles to get connect them with each other on highway. A robust and reliable connection is the demand of efficient VANETs connectivity.

The study of connectivity diverts to another direction with the introduction of VANETs. The subject of network connectivity examination has increased exponentially and attracted the consideration of many research groups [8]–[15]. Two vehicles on highway are said to be connected, if they belong to the transmission range of each other. In order to get optimal distribution of real time data, a reliable and strongly connected network is required [16].

Many authors have discussed the connectivity of vehicles and its impacts in different environments [12], [16]–[18]. Vehicular Cloud Computing (VCC) is an extended version of conventional cloud technology, which maximize the advantages of vehicular network [3], [19].

In VANETs domain, most of connectivity models are based on simple assumptions that, all vehicles have same velocities at all times or either different from others, but same for a given vehicle during the whole journey [11], [12], [20]–[22]. The same speed supposition will further affect the distribution model of vehicle inter-spacing significantly. Relative speed is a good parameter to measure the mobility situation of two connected vehicles. Vehicles V_i and V_j may have very fast speed, but their relative speed will be very small, therefore their connectivity will not be affected too much.

The authors of [12] proposed a new mobility metric called speed factor, which measures the relationship between vehicles speed and inter-vehicle spacing. The authors considered constant speed of vehicles at all times. They ignored the relationship between arrival rate and vehicle speed. Normally speed depends on the drivers intention and arrival rate to the road segment. Suppose at every time, if the speed remains constant to a specific traffic condition, then the inter-vehicle distances will not be fully independent and identically

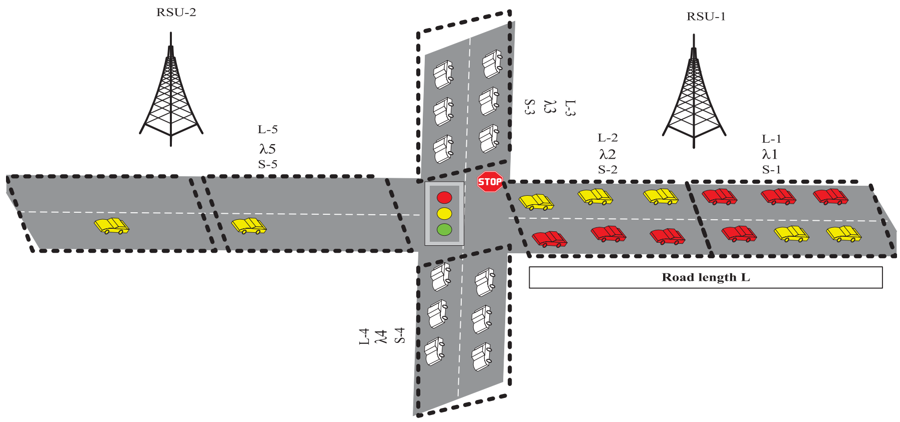

FIGURE 1. Generalized Speed Factor System Model.

distributed *(i.i.d)* and the distribution will not be fully modeled as exponential [12], [16]–[18].

In [17] and [18] the authors proposed a new protocol for platoon structure called MAC connectivity-aware. In their model, connectivity was considered as a function of node density and its impact was investigated in both single and multi-lane highway. On the basis of the results of [17], it was concluded that throughput increases with increase in connectivity up-to some level, but after that level, throughput goes down. The model presented in [17] and [18] was based on the ideas and methodology offered by [16], but focused on considering vehicular platoons.

In this paper a new mobility metric called Generalized Speed Factor (GSF) is proposed by using relative speed of connected vehicles. The proposed GSF defines an actual relationship between relative speed and vehicle connectivity. The performance of GSF is analyzed in three different scenarios that is temporal connectivity of static traffic, low mobility connectivity at [20-40]km/h and high mobility case. The connectivity base on GSF further used as a metric for the best route selection called Most Strongly Connected (MSC) route. Simulation results show that a highly congested network will be more connected as compare to the sparse network.

The rest of paper is organized as follows, Section II describes the system model in detail, III explains VANET connectivity for different mobility scenarios, Section VI describes how connectivity can be used as metric for optimal route selection. Section V gives simulation results along with discussion and finally VI concludes the paper on the basis of simulation results.

II. GENERALIZED SPEED FACTOR (GSF)

Vehicular connectivity model follows the same distribution as that of queuing system model [23]. Suppose a unidirectional road of length L having sub segment $S = \{s_1, s_2, \cdots s_n\}$ as shown in Figure 1. The vehicles arrival at a highway follows Poisson distribution with mean $1/\lambda$ per unit time. Each road segment s_i having constant arrival rate $\lambda_i (i = 1, 2, 3, \cdots N)$ with unit veh/h. It is assumed that $\lambda_1 = \lambda_2 = \lambda_5$ and $\lambda_3 = \lambda_4$. The inter-arrival time and inter-vehicle spacing of two consecutive vehicles are modeled as exponential distribution. In Figure 1, the movement of vehicles is restricted due to the intersection. The vehicles on segment $S-1$ and $S-2$ will follow $S-5$'s direction after crossing intersection. Similarly segment $S-3$'s vehicles will follow $S-4$ as depicted in Figure 1.

Suppose that every vehicle enters a road segment s with different velocity. The authors of [12], [21], and [23] considered the steady state distribution of vehicles, where speed is modeled as Gaussian distribution with supposition that velocity will be constant for a specific duration. If v is a random speed assigned to a vehicle, then PDF of Gaussian distribution is [16]–[18], [24]

$$f(v) = \frac{1}{\sigma.\sqrt{2\pi}} e^{-\frac{(v-u)^2}{2\sigma^2}} \tag{1}$$

where μ and σ represent the mean and standard deviation of velocity v. The authors in [12] introduced a new parameter called speed factor A. The parameter A shows the intensity of vehicles on highway with measuring unit h/km or s/m and reflects the impact of velocity on inter vehicle spacing as given below mathematically

$$A = \int_{v_{min}}^{v_{max}} \frac{\hat{f}_v(v)}{v} d(v) \tag{2}$$

$$\hat{f}_v(v) = \frac{f_v(v)}{\int_{v_{min}}^{v_{max}} f_v(S) d(S)} \tag{3}$$

where v_{min} and v_{max} are the upper and lower limits of vehicles speed. Limitation: All the vehicles are considered to have same speed which follows Gaussian distribution with same mean μ and standard deviation σ. The same speed at time t also affects the inter-vehicle spacing on highway. The inter-distance among vehicles will become steady as far as the speed remains constant and the situation will lead to unrealistic scenario.

The definition of A revised with GSF, which shows the intensity of vehicles on a sub-segment of road s with measuring unit h/km or s/m and reflects the impacts of relative speed on inter vehicle spacing. The proposed GSF metric is based on relative speed with unique mean μ and standard deviation σ, as given below.

$$\begin{aligned} V_1 &\sim N(\mu_1, \sigma_1^2) \\ V_2 &\sim N(\mu_2, \sigma_2^2) \\ V_3 &\sim N(\mu_3, \sigma_3^2) \\ &\vdots \\ &\vdots \\ V_{N-1} &\sim N(\mu_{N-1}, \sigma_{N-1}^2) \\ V_N &\sim N(\mu_N, \sigma_N^2) \end{aligned} \tag{4}$$

where $\{V_1, V_2 \cdots V_{N-1}, V_N\}$ are vehicles on highway. Every vehicle follows Normal distribution with different mean and variance, because of the drivers intention and the road condition. The pdfs of relative velocities will be $f(v_{12}) \sim N(\mu_{12}, \sigma_{12}^2)$, where $v_{12} = v_1 - v_2, \mu_{12} = \mu_1 - \mu_2$ and $\sigma_{12}^2 = \sigma_1^2 + \sigma_2^2$. If v is the differential velocity of two vehicles i and j, then

$$f(v_{rel}) = \frac{1}{\sqrt{\sigma_i^2 + \sigma_j^2} \cdot \sqrt{2\pi}} e^{-\frac{(v-(v_i-v_j))^2}{2(\sigma_i^2+\sigma_j^2)}} \tag{5}$$

where σ_i and σ_j are the deviations of vehicle i and j. The PDF $f(v_{rel})$ represents the relative normal distribution of speed. On the basis of (5), the definition of GSF becomes.

$$G_{SF} = \int_{v_{min}}^{v_{max}} \frac{f_{v_{rel}}^*(v)}{v} d(v) \tag{6}$$

$$f_v^*(v_{rel}) = \frac{f_v(v_{rel})}{\int_{v_{min}}^{v_{max}} (S) d(S)} \tag{7}$$

where v_{min} and v_{max} are the truncated velocities. GSF uses fully exponential distribution based on variable arrival rate [16]–[18] as given in (8).

$$f(s/\mu) = \frac{1}{\mu} e^{\frac{-s}{\mu}} \tag{8}$$

(8) gives probability of s unit inter-spacing for a given mean μ.

III. VANET CONNECTIVITY FOR DIFFERENT MOBILITY SCENARIOS

This paper mainly concerns with connectivity probability P_c of vehicles in high speed scenarios using the proposed GSF. Since connectivity is a function of vehicle density, hence spatial density in both static and mobile environment should be estimated.

A. VEHICLE DENSITY ESTIMATION

Vehicle spatial density defines the intensity of vehicles on road [17], [18]. The road length L has an inverse relation with node spatial density. Suppose a road segment s of length L_s with vehicles arriving rate λ from t_0 to t_1. Then vehicle spatial density ρ on road segment s is

$$\rho = \frac{(t_1 - t_0)\lambda}{L_s} \tag{9}$$

where ρ is vehicle spatial density in the time interval $[t_0 - t_1]$. In case of mobility, suppose vehicles are arriving at λ rate to a road segment s with average relative speed factor G_{SF}, then average number of vehicle N at time t is

$$N = L_s \lambda.(G_{SF}) \tag{10}$$

In (10), G_{SF} is the average speed factor as derived in (6). The proof of (10) is shown in Appendix along with the proposed connectivity definition.

B. STATIC CONNECTIVITY

In a static scenario, vehicles on road segment s will form static platoon. Let at time slot t, vehicles form a sorted queue by location denoted as $\{V_1, V_2, V_3 \ldots V_N\}$ on road segment of length L. Let X_i be a random variable representing the inter-distance between vehicles V_i and V_{i+1} [16]–[18]. The VANET will be connected if there is a path connecting any pair of vehicles. This shows that the distance between any two consecutive vehicles should be smaller than the transmission range of the vehicles R. Let P_c be the connectivity probability of vehicles in a sub-segment s [16]–[18], then

$$P_c = Pro\{X_1 < R, X_2 < R \ldots Nd_{N-1} < R\} \tag{11}$$

where R is the transmission range of vehicle and X_i is an $i.i.d$ random variable. The connectivity probability P_c, that at-least k vehicles are connected on road segment s is given as

$$\begin{aligned} P_c(k) = P(N \geq k) &= \sum_{i=k}^{\infty} P(N = i) = \sum_{i=k}^{\infty} (F_s(R))^i \\ &= (1 - e^{-\rho R})^{k-1} \end{aligned} \tag{12}$$

In (12), $F_s(.)$ is the distribution function of inter vehicle spacing. N is the total number of vehicles and k represents connected vehicles at time t. The definition of ρ is given in (9). The mobility of nodes is ignored in (12). Once the mobility is introduced, the connectivity will start increase, which is the main motivation and contribution of the proposed work.

C. MOBILE CASE CONNECTIVITY

Free flow connectivity is the main concern of this paper. Mobility is the core parameter to affect the performance of VANETs in every perspective [25]. The probability that at-least k vehicles will be connected in a road segment s with arriving rate λ_i and radio range R is given as

$$P_c(k) = P(N \geq k) = \sum_{i=k}^{\infty} (1 - e^{-L_s \lambda_i (G_{SF}) \frac{R}{L}}) \tag{13}$$

where N is the total number of vehicles and G_{SF} is the proposed GSF given in (6). The proof of (13) is shown in Appendix. By using (10), the definition becomes

$$P_c(k) = P(N \geq k) = \sum_{i=k}^{\infty}(1 - e^{-N_s \frac{R}{L}}) \tag{14}$$

where N_s is the average number of vehicles, R is the fix radio transmission range of each vehicle and L represents length of highway.

IV. CONNECTIVITY AS A METRIC FOR OPTIMAL ROUTE SELECTION

The selection of optimal route is an NP problem [26]. Many existing protocols [27] are using different criteria to select best route. Most Strongly Connected (MSC) Route aims to find the strongly connected route from source to destination in VANETs. Due to the instantaneous change in topology, the normal Dijkstra algorithm [28] is not adopted in VANET. The modify EG-Dijkstra aims to find the strongest connected route as given below [29]

$$C_{edges}(J(S_r, D)) = \prod_{w=1}^{k} C_t(e_w) \quad \text{where} \quad e_w \epsilon J(u, v) \tag{15}$$

Eq. (15) shows the product of link's connectivity P_c between source S_r and destination D at time t. The EG-Dijkstra integrates an array of Connected Routes CR. MSC obtains from CR as given by (16)

$$\arg \quad max_{J \epsilon CR(S_r, D)} C_{edges}(J) \tag{16}$$

Initially EG-Dijkstra assigns CR(S_r)=1 and CR(D) $= \Phi$ to source and all other vehicles respectively as MSCs. Then by (15) all connected routes are calculated from source S_r to destination D. At the end, the route with the higher connectivity value will be selected as a MSC.

At time t, vehicles V_i and V_j either communicates direct or indirect way. In direct communication both vehicles communicate with absence of any relay node [12] as given by (17)

$$DirCom(V_i, t) = \sum_{v_j t} p(hops = 1, v_i \longleftrightarrow v_j t) \tag{17}$$

If hops between any two communication pair are larger than 2, then

$$InDirCom(V_i, t) = \sum_{v_j t} \sum_{n} p(hops = n, v_i \longleftrightarrow v_j t) \tag{18}$$

To find MSC, Floyd warshal algorithm [30] will be executed on every vehicle to investigate either direct or in-direct link will be optimal.

Floyd-Warshall algorithm belongs to all pair shortest path category of graph theory, which calculates shortest distances of all vehicles as shown in Algorithm 1. In each iteration, Floyd-Warshall algorithm checks all possible routes passing through specific node, if the indirect route passing through node i is stronger connected that directed route, then indirect route information is stored instead of directed route.

Algorithm 1 Optimal Route Selection Algorithm

```
Result: Optimal Route Selection
DirectCon ← Conn[v][u]
 InDirectCon ← Conn[v][k]Conn[k][u]
 while each neighbor vehicle u of v do
   if DirectCon ≤ InDirectCon then
   |  OptimalConn ← InDirectCon
   else
   |  OptimalConn ← DirectCon
   end
end
```

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, the performance of the proposed GSF is compared with existing technique [12] in the context of connectivity and also examined its possibility and effectiveness in various simulation environments.

This section is divided into two sub parts. The first part represents static and congested scenario along with its comparison with the existing technique. The second part represents the simulation performance of GSF in high mobility scenario.

A. STATIC AND LOW MOBILITY CASE ANALYSIS

First, the scenario in Figure 1, where vehicles on intersections are considered static is analyzed. Since all the vehicles are static, the proposed GSF is ignored and the relationship between node spatial density ρ and connectivity P_c is analyzed by (12).

The temporal spatial density ρ is considered given in (9) with arrival rate $\lambda = \{0.1, 0.5, 1\}$ veh/sec. The relationship between temporal spatial density ρ and connectivity is shown in Figure 2.

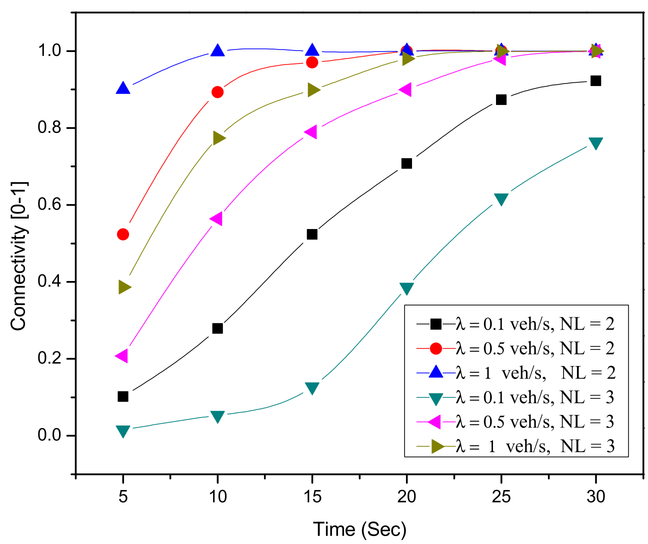

FIGURE 2. Spatial node density versus connectivity (road length L = 10 km, static scenario, NL: number of lanes).

The results show that under various arrival rate ($\lambda = 0.1$ veh/sec, $\lambda = 0.5$veh/sec, $\lambda = 1$ veh/sec), connectivity increases with increase in arrival rate. Road lane also impacts on connectivity of vehicles. The connectivity of a two lanes road will be greater than three lane by keeping same arrival rate as shown in Figure 2.

Now considering low mobility with mean velocity μ 20 km/h and 40 km/h. The GSFs of 20 km/h and 40 km/h are 0.07271 h/km and 0.07096 h/km respectively using (6) with $\sigma = 21$ km/h and $\mu_d = 21m$.

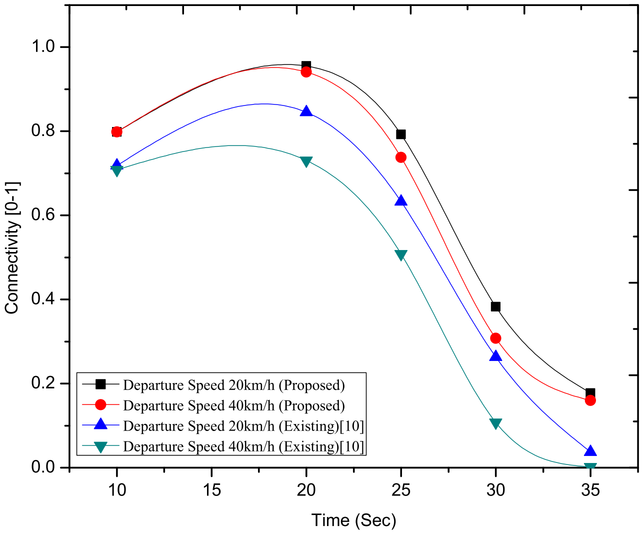

FIGURE 3. Low mobility and Spatial node density impact on connectivity (road length L = 1 km, R = 500 m).

The mobility affects the connectivity as shown in Figure 3. The results suggest the GSF improves the connectivity probability by roughly 10-20 percent. The line graph shows that the proposed GSF outperform than existing model [12] in the case of low mobile scenario.

It is concluded that, using relative speed and exponential distribution as inter-vehicle spacing can improve the overall connectivity of vehicles.

B. HIGH MOBILITY SCENARIO ANALYSIS

In mobile environment, the connectivity is a function of GSF as defined in (6) along with arrival rate and transmission range R.

In high speed scenarios, it is shown that mobility affects the connectivity P_c positively up-to μ_τ and once the mean velocity exceeds μ_τ, the connectivity starts going down as shown in Figure 4 and 5. The μ_τ in Figure 4 is 80 km/h and 85 km/h with vehicle density 100 and 200 respectively. The impact of transmission range R and speed factor on connectivity is also shown in Figure 5. In the case of transmission range R, μ_τ becomes 85 km/h and 90 km/h as shown in Figure 5.

By adding GSF, simulation shows better connectivity as compare to the existing model as shown in Figure 4 and 5.

In the simulation section, both low and high mobility scenarios are analyzed. On the basis of results, it is concluded that in low mobility scenarios, the connectivity going down very slowly after crossing the threshold limit. On the other

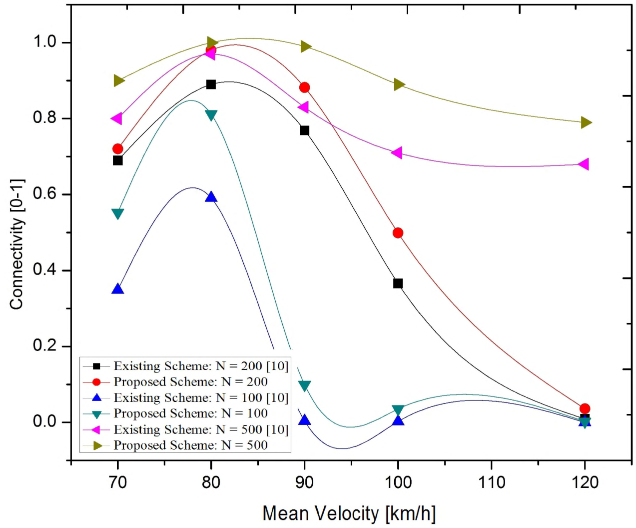

FIGURE 4. Proposed connectivity approach versus existing connectivity approach (standard deviation $\sigma = 40$ km/h, exponential mean $\mu_d = 100$ m, R = 500 m, road length = 5 km, N: number of vehicles).

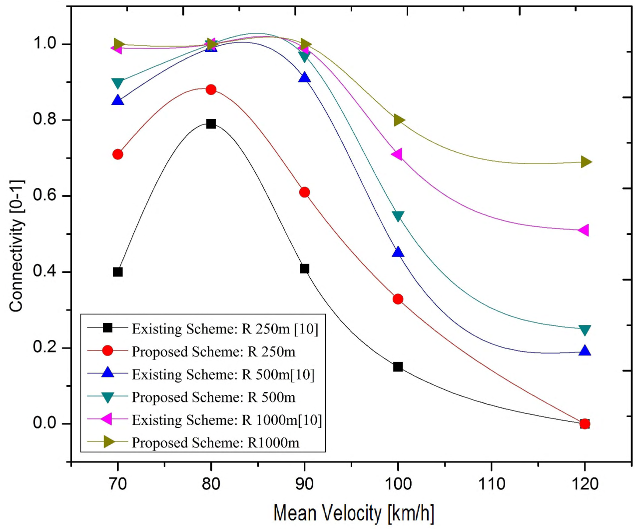

FIGURE 5. Proposed connectivity approach versus existing connectivity approach (standard deviation $\sigma = 40$ km/h, exponential mean $\mu_d = 100$ m, number of vehicles = 500, road length = 5 km).

hand, in high mobility case scenarios, connectivity decreases very fast after crossing μ_τ.

VI. CONCLUSIONS

The improved mobility factor GSF not only provides better stochastic connectivity of vehicles, but also a metric for the best route selection. Connectivity is a function of node density, mobility and transmission range. All the parameters are directly related to connectivity. A highly congested traffic scenario will be strongly connected. The connectivity will increase up-to specific threshold, but will start going down after that threshold.

Stochastic connectivity is an optimal metric for best route selection and optimal vehicular cloud selection. A route is said to be optimal, if the connectivity of that route is maximum among all available routes. A road segment having better connectivity for a period of time will be an optimal choice for vehicular cloud data storage.

APPENDIX
PROOF OF MOBILE CONNECTIVITY EQ. (13)

Suppose N vehicles with radio propagation range R are moving on a road segment s of length L with vehicle arrival rate λ from time t_0 to t_1. Assume that the road condition is normal, then only two depended parameters are left such as arrival rate and speed.

Case I: Connectivity and Time-Variant Arrival Rate: The number of vehicle passing through road segment s in the time interval $[t_i t_j]$ with time variant intensity rate λ is calculated as below.

$$V = \sum_{k=i}^{j} (T_k \lambda_k) \tag{19}$$

Consider the departure rate λ^*(fixed at every time interval), then spatial density ρ will be

$$\rho = \frac{\sum_{k=i}^{j} (T_k \lambda_k - \lambda^*)}{L} \tag{20}$$

Hence the definition of connectivity will change to time variant arrival of vehicles by putting (20) in (13).

Case II: Connectivity and Vehicle Speed: Suppose all vehicles speed follow Gaussian distribution $N(\mu, \sigma^2)$ having unique mean μ and standard deviation σ. In literature [15], the authors introduced a parameter which shows the inter-distances and speed relationship by $\frac{\lambda}{\mu}$. To find the number of vehicle, it is known that, Number of vehicles = length of highway × vehicle density. Hence

$$N = \frac{L_s \lambda}{\mu} \tag{21}$$

In the proposed case, the GSF is considered as given in (6) instead of fixed speed and vehicle arrival rate. Since GSF parameter is an inverse of normal speed, which correlate the inter-vehicle spacing with relative speed.

$$\begin{aligned} \text{Veh Density } (d) &= (G_{SF}).\lambda \\ \text{Number of Vehicles } (N) &= (G_{SF})\lambda L_s \end{aligned} \tag{22}$$

Spatial density ρ can be calculated as below

$$\rho = \frac{(G_{SF})\lambda L_s}{L} \tag{23}$$

G_{SF} is the proposed speed factor. Hence by putting (23) in (13), new definition based on vehicle mobility is obtained.

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