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Analysis of Vehicle-to-Vehicle Basic Safety Message Communication Using Connectivity Characteristic Matrix

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***Abstract*— This work investigates vehicular mobility and the main factors that impact Vehicle-to-Vehicle (V2V) connectivity using Basic Safety Message (BSM). MATLAB simulation used for Vehicular mobility and connectivity characterization under specific road traffic conditions. The simulation covers connectivity between traveling vehicles and a selected target vehicle to monitor communication interaction and establish an envelope within which reliable communication and BSM messages can occur. Another objective of this work is to use BSM exchanges to indicate the level of connectivity used to estimate traffic density, thus enabling congestion prediction. The obtained data contain information describing many vehicles, distance, connectivity time, and traffic density. The simulation results indicate an increase in the number of connected vehicles (connectivity level) as a function of both traffic density and communication range. Extending communication over fixed duration showed increased connectivity levels, allowing more vehicles to interact and exchange BSMs. The rate of change of connectivity per communication range is an indication of the state of traffic. Continuous connectivity proved to be less than general connectivity as vehicles exits through ramps and move from one cluster of vehicles to another. Varying duration per fixed communication range produced evidence of spatial domain change, and cluster variation as threshold values separate vehicles clusters in time and space. This work presented a model to help analyze the impact of vehicular mobility as a function of BSM communication range variation and connectivity duration variation correlated to traffic density.**

***Keywords*— V2V; congestion; wireless communication; routing; intelligent transportation systems; VANETs.**

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I. Introduction

Human mobility and vehicular connectivity are part of the new revolution in transportation due to societal and marketing requirements through urbanization, pollution, and emission regulations. Such changes are driving transportation into the reactive, dynamic, and intelligent corner of system applications, with the main objective is to reduce accidents and congestion and support more efficient vehicle and road utilization with environmental preservation. Current vehicular networks have emerged to facilitate intelligent transportation systems. Communication technologies should connect different transportation elements such as vehicles, pedestrians, infrastructures, roads, cloud computing service platforms.

Vehicle-to-everything (V2X) communications apply advanced networking technologies to enable communication between vehicles and vehicles (V2V), vehicles and infrastructure (V2I), vehicles and pedestrians (V2P), vehicles and grid (V2G), vehicles and cloud (V2C), among other interfaces. All communication applications aim to achieve better human living in a safer and more secure environment [1]–[11].

Vehicle-to-vehicle (V2V) communication systems will reduce the accidents rate through cooperative driving that uses the roadway efficiently. To support such an objective, the used communication system needs to cover a wide range of requirements. V2V systems contribute to improving traffic flow through reducing vehicle-to-vehicle spacing; manage intersections, among many other features, which enable smooth mobility on the roads. The increasing implementation of vehicle automation will change the roles of drivers, as manufacturers adapt to such change supported by new regulations targeting safety and mobility covering the operational, tactical, and strategic vehicle and driver behavior and control in a synchronized human-machine interface [12]–[19]

The Basic Safety Message (BSM) used by vehicles developed for Vehicle-to-Vehicle (V2V) communications uses a simplified algorithm to transmit data such as the position and heading of the vehicle. A reliable On-Board Unit

(OBE), vehicle sensors, and communication channels need optimization to achieve BSM exchange. DSRC based V2V communications enable vehicles to sense nearby vehicles and examine risks through communicating safety messages summing vehicles' current status (position, speed, heading, braking status, and size).

These exchanges deliver information and vehicle sensors data that usually contain information about vehicle mechanics, road condition, driver status, and behavior, among others. The BSM message contributes greatly to the safety and mobility of vehicles by reducing accidents and congestion through exchanging critical information regarding position, speed, and other data such as intersections, blind spots, and pedestrian crossing, among many [20]–[22].

Vehicle-to-vehicle (V2V) communications will increase roadway safety by providing each vehicle with optimum awareness of other vehicles in proximity and using on-board sensors to detect imminent crash scenarios. The vehicle's system depends on continuous DSRC communication. However, it provides potential false data, which might cause accidents, and contributes to traffic congestion. V2V communications must be robust in terms of security and privacy to meet the intra-vehicle and vehicle-to-vehicle communication requirements due to an increasing number of vehicles and accumulating traffic volumes. Dedicated Short-Range Communication (DSRC) supports V2V communications with some bandwidth limitations regarding adding security and privacy signatures to each exchanged Basic Safety Message (BSM) [23]–[27].

When considering V2V communication and BSMs, issues of concern can arise, such as traveling area under consideration, connectivity and BSM interaction, duration, road setup, trajectories, and driver's behavior considerations. Applying security to BSMs will result in the actual connectivity level being different from the estimated level, as secure algorithms will remove misbehaving vehicles. In addition, the vehicular area vehicular interaction through which BSMs exchanged comprises vehicles modeled as c dynamic nodes moving in real-time, thus and for the exchange of messages to occur, Vehicular Ad hoc Networks (VANETs) are used for Vehicle-to-Vehicle (V2V) communication. Routing in VANET is very important as it relates to vehicle position, which is highly dynamic, resulting in a continuous change in the network topological map representing vehicles as nodes and is a connectivity function [28]–[31].

Many critical applications employ wireless ad hoc networks, ranging from road traffic management and control, environmental sensing and control, to vehicle communications and autonomous driving, among many other applications. Such work recognizes that routing protocols need particular attention. Routing protocols fall under either pro-active or on-demand, needing to adapt dynamically to the constantly changing network topology.

There is a correlative relationship between routing and path prediction, whereby monitoring path length and related variables, such as consumed energy, number of hops, network lifetime, are indicators of traffic status. Mobility models are required to map the change in pattern for mobile nodes to enable optimization of communication and management [32]–[34]

Vehicular ad hoc networks (VANETs) are a wireless network that does not have the fixed infrastructure and are critical for cooperative vehicle driving, providing essential communication and data exchange mechanism between vehicles and vehicles (V2V), and Vehicles and infrastructure (V2I).

VANETs depend on dynamic and variable topology with many communication impairments, such as buildings and the high mobility of vehicles. VANETs are important in traffic and route planning and congestion control, emphasizing accident prevention and environmental pollution limitation through route optimization. In addition, VANETs are important in autonomous and cooperative driving, emphasizing driver behavior analysis and service provision to vehicles through data sharing[35], [36].

The networking of Vehicles is an essential and critical component of smart transportation systems. There is increasing work on more efficient communication channels, which will enhance vehicular communication.

Two main communication platforms exist for vehicular networking:

- Vehicle-to-vehicle (V2V)
- Vehicle-to-infrastructure (V2I)

Where V2I enables vehicular communication using Road Side Units (RSUs), V2V communication is radio-based communication and uses technologies such as Dedicated Short Range Communication (DSRC).

Recent development in vehicular applications covering critical issues such as reliability, efficiency, and safety requires vehicular networks to provide high-quality services with minimum delay. However, vehicular networks are hindered by channel and infrastructure setups and designs. In addition, the mobility of vehicles and location change requires complex routing and monitoring algorithms.

Advanced safety applications make use of BSMs in assessing risk and predicting scenarios related situations; such applications cover many aspects of vehicle driving and maneuver, such as:

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Lane Change Warning (LCW)
- Do Not Pass Warning (DNPW)
- Intersection Movement Assist (IMA)
- Control Loss Warning (CLW)

Traffic congestion and too many vehicles in a limited area will cause degraded communication channel performance due to the accumulated BSMs exchanged between vehicles. On the other hand, slow mobility when traffic congestion exists will lead to less efficiency in the exchanges BSMs as the vehicle's mobility reduces and does not require high-speed communication within the vehicular network formed in the congested area [37]–[41]. Thus, routing, number of hops per route, and number of exchanged messages are indicators of traffic congestion building up and time stamps. Consideration of these enables better traffic management systems.

In this work, a simulation approach is carried out to establish a correlative relationship describing traffic density, communication range, and communication duration and the subsequent effect on connectivity of V2V using BSM messaging and DSRC.

II. MATERIALS AND METHODS

Vehicular Ad Hoc Networks' existence is particularly important in achieving safety, reliability, security, and efficiency under the umbrella of intelligent transportation systems (ITS). Vehicles must be able to communicate with other vehicles in an efficient and with minimum latency or delay in signal transmission carrying Basic Safety Messages in-between vehicles. Thus, the dependent and reliable exchange of BSMs is of prime importance for vehicle-installed applications to enable safety and to prevent accidents, which are a major contributor to congestions. Therefore, traffic management needs to avoid congestion regardless of the cause, and vehicle communication can be a solution to avoid such problems [42]–[45].

The objective is to apply vehicular mobility to predict connectivity under different communication ranges, road, and traffic conditions, affecting routing protocols and vehicle safety applications. The approach in this work is to examine vehicular mobility through simulation as a function of Traffic Density, Communication Range, Communication Duration to determine availability for vehicular connectivity exchanging Basic Safety Messages (BSMs). The adopted mobility monitoring process is shown in Fig. 1.

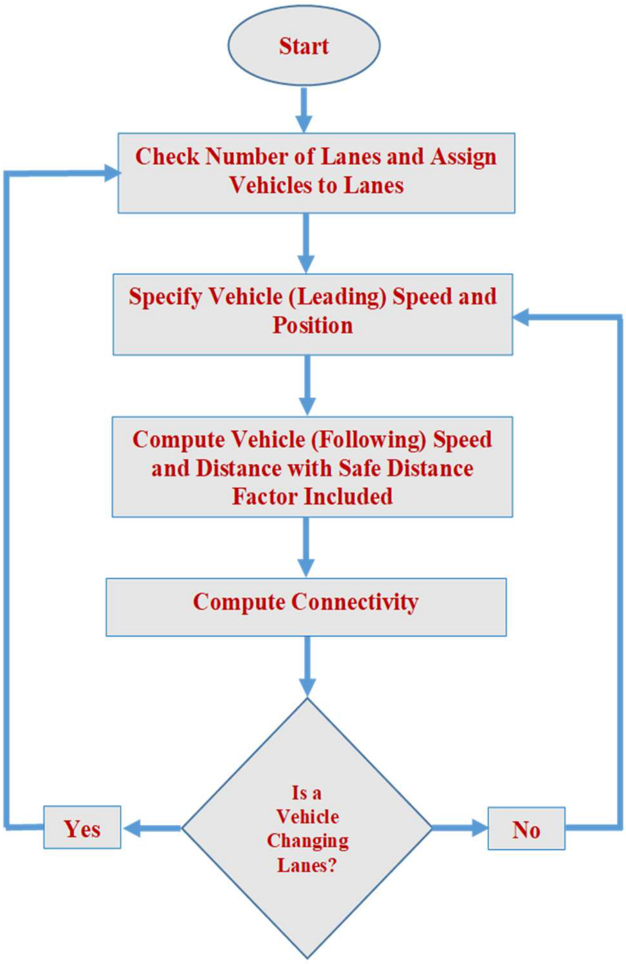

Fig. 1 Mobility monitoring process

The road layout under consideration consists of four lanes; each has a length of 4Km with three entry/exit ramps. All lanes in the simulation can use such ramps. Each lane has a varying number of vehicles making up its traffic ranging from 80 to 400 vehicles. Communication ranges for safety and normal V2V transmission are set to the values of 40 m, 80m, and 120 m, while communication duration for a group of vehicles exchanging information is set to the values of 20 secs, 40 secs, and 60 secs. Equal arrival departure rates (0.333) are considered for up to 1200 vehicles.

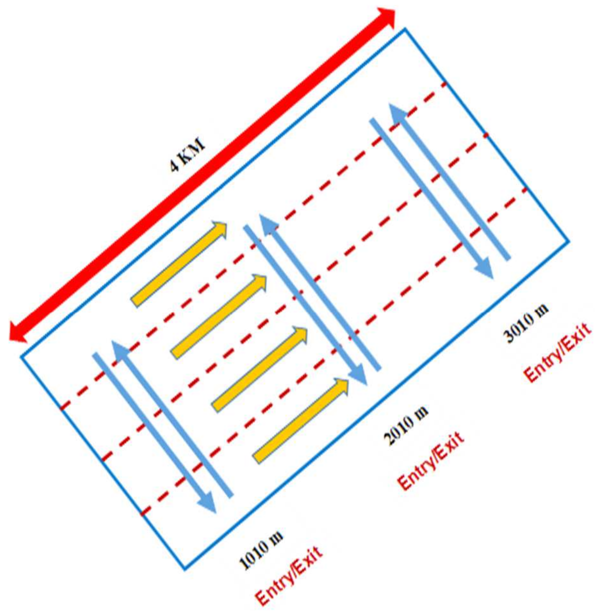

Fig. 2 Simulated vehicular network layout

III. RESULTS AND DISCUSSION

Tables 1-3 and present the simulated and computed results for the setup shown in Fig. 2.

TABLE I
CONNECTIVITY DATA FOR COMMUNICATION: 20 SECONDS

Traffic Density	Connected Vehicles to $V_{selected}$			Continuous Vehicles Connectivity to $V_{selected}$		
	40m	80m	120m	40m	80m	120m
80	9	18	23	8	16	22
120	12	24	33	11	23	30
160	18	34	45	16	31	40
200	17	37	62	16	33	56
240	17	45	80	16	42	73
280	25	55	87	22	51	79
320	22	54	113	20	49	103
360	39	76	103	36	68	95
400	41	87	110	37	78	101

TABLE II
CONNECTIVITY DATA FOR COMMUNICATION: 40 SECONDS

Traffic Density	Connected Vehicles to $V_{selected}$			Continuous Vehicles Connectivity to $V_{selected}$		
	40m	80m	120m	40m	80m	120m
80	7	16	25	6	14	23
120	11	23	38	10	21	35
160	16	30	51	15	27	47
200	19	45	50	17	41	47
240	27	50	68	24	45	65
280	19	53	89	18	49	81
320	31	60	96	28	55	86
360	37	57	108	33	53	98
400	37	77	119	34	71	109

TABLE III
CONNECTIVITY DATA FOR COMMUNICATION: 60 SECONDS

Traffic Density	Connected Vehicles to $V_{selected}$			Continuous Vehicles Connectivity to $V_{selected}$		
	40m	80m	120m	40m	80m	120m
80	9	17	24	8	15	22
120	13	28	36	11	25	32
160	15	36	43	14	32	39
200	17	39	58	16	36	53
240	22	40	62	20	37	57
280	28	53	80	26	47	75
320	32	62	96	29	57	87
360	37	72	96	33	65	86
400	38	85	97	35	76	90

Figs. 3-5 present a relationship between traffic density and vehicle connectivity in terms of the overall number of connected vehicles to a selected and monitored vehicle (target node). The plots show an increase in the connectivity level as a function of a steady increase in traffic density. The variation in the linearity of the plots, which is due to the model used in the simulation, allows vehicles to change lanes within a safe distance of other vehicles and allows vehicles to overtake other leading vehicles. The plots also show a marked increase in the connectivity level as a function of extending communication range.

The initial observations are due to the increasing number of vehicles with equal arrival - departure rate and an increase in the spatial domain, which enable more vehicles to be part of the communication cluster. Thus, more BSMs exchanged over the provided duration and communication range.

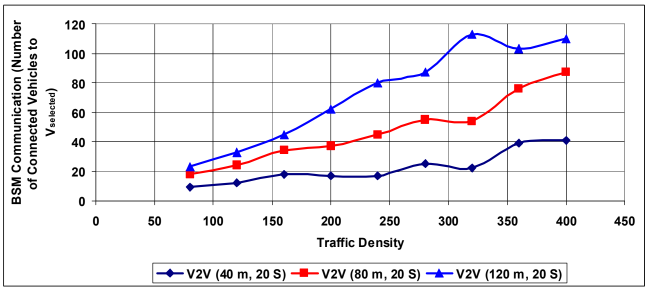

Fig. 3 Connectivity of vehicles to $V_{selected}$

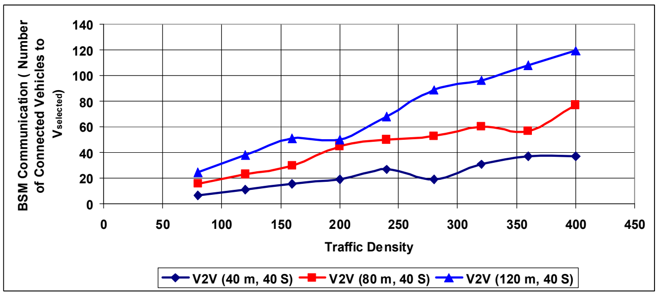

Fig. 4 Connectivity of vehicles to $V_{selected}$

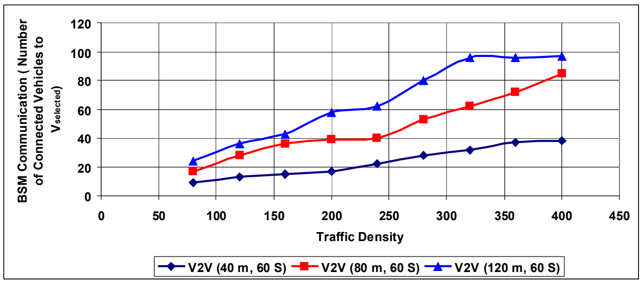

Fig. 5 Connectivity of vehicles to $V_{selected}$

Figs. 6-8 present a relationship between the average number of connected vehicles to the selected and monitored vehicle (target node) and an available communication range. The plots prove that extending the communication range over a specific duration increases the connectivity level to the selected vehicle. This is due to more vehicles communicating their BSMs over a duration of time.

Moreover, the average number of continuously connected vehicles to the target node is also incrementing in proportion to the communication range and increasing the spatial communication for nearby vehicles.

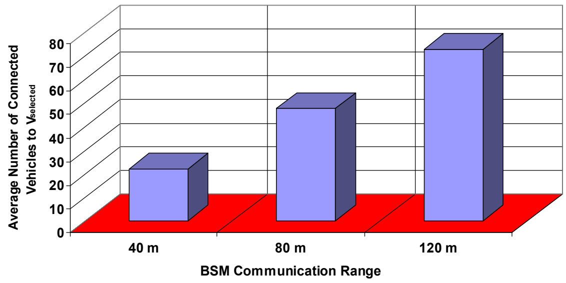

Fig. 6 Effect of communication range on connectivity over 20 seconds period

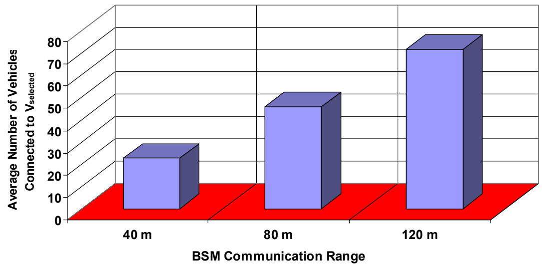

Fig. 7 Effect of communication range on connectivity over 40 seconds period

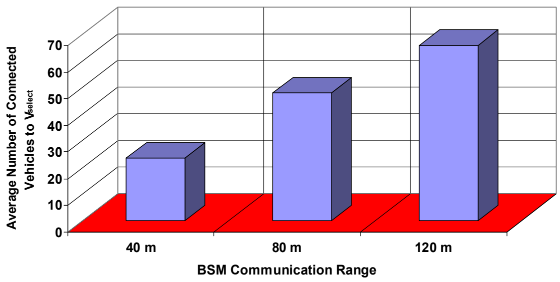

Fig. 8 Effect of communication range on connectivity over 60 seconds period

Figs. 9-11 present an important correlation between the selected vehicle (target node) and the communication duration, covering 40m, 80m, and 120m ranges.

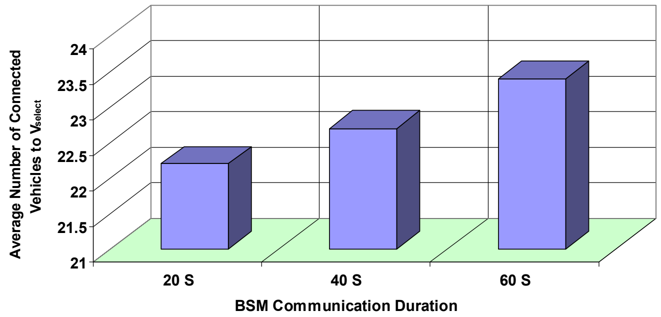

Fig. 9 Effect of communication duration on connectivity over 40 meters range

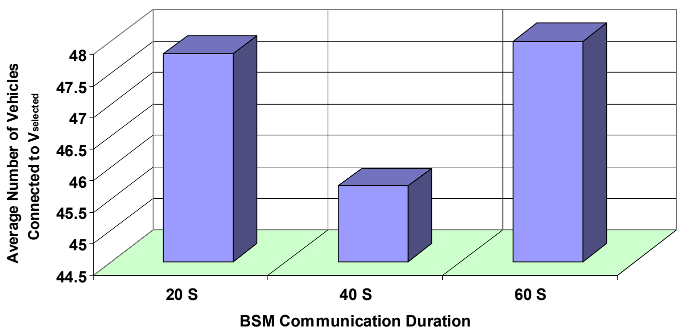

Fig. 10 Effect of communication duration on connectivity over 80 meters range

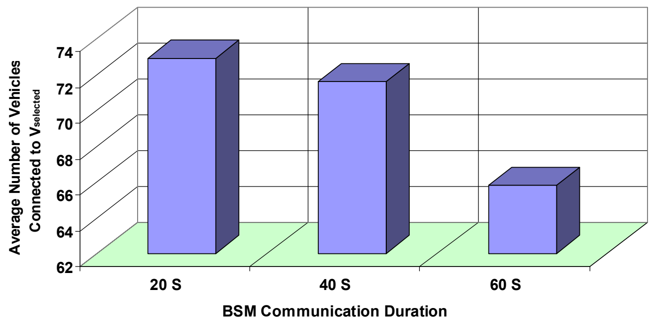

Fig. 11 Effect of communication duration on connectivity over 120 meters range

The results in Figures 8-10 appear to contradict the previous observations that as spatial and temporal domains increase, connectivity levels per target node occur. Equation (1) represents a model for the contradicting results in Figs. 8-10, where it correlates available to message communication time to available to message transmission range.

$$Connectivity\ Charaterisitic(T,L) = \begin{bmatrix} \frac{T_{1,1}}{L_1} & \frac{T_{1,2}}{L_1} & \frac{T_{1,3}}{L_1} \\ \frac{T_{2,1}}{L_2} & \frac{T_{2,2}}{L_2} & \frac{T_{2,3}}{L_{23}} \\ \frac{T_{3,1}}{L_3} & \frac{T_{3,2}}{L_3} & \frac{T_{3,3}}{L_3} \end{bmatrix} \quad (1)$$

Where,
T: Communication Duration is Seconds
L: Communication Range in meters.
Substituting the used values in Equation (1) yields:

$$Connectivity\ Charaterisitic(T,L) = \begin{bmatrix} \frac{20}{40} & \frac{40}{40} & \frac{60}{40} \\ \frac{20}{80} & \frac{40}{80} & \frac{60}{80} \\ \frac{20}{120} & \frac{40}{120} & \frac{60}{120} \end{bmatrix} \quad (2)$$

Which, when computed results in the values in Equation (3)

$$Connectivity\ Charaterisitic(T,L) = \begin{bmatrix} 0.5 & 1.0 & 1.5 \\ 0.25 & 0.5 & 0.75 \\ 0.17 & 0.33 & 0.5 \end{bmatrix} \quad (3)$$

Values appearing in Equation (3) provide the following deductions:

- Whenever the ratio of communication duration to communication range reaches 0.5, the connectivity level associated with that duration per range shifts and moves to another cluster, resulting in lower connectivity at that particular duration as it already moved 0.5 of the available communication range for the selected and monitored vehicle or node.
- Values below and above 0.5: These are for clusters of connected cares that lost connectivity and others that gained connectivity as the monitored vehicle ($V_{selected}$) travels over the 4 km road with a possible lane change. Thus, 0.5, in this case, is the threshold value for the simulated model.

The effect represented by the connectivity characteristic matrix is not applicable to different communication ranges with a fixed duration, proving that the spatial feature is the critical parameter in a BSM communication mechanism as a function of neighboring nodes or vehicles. However, due to ramp exits over traveled distances and lane changing, together with speed change, it is noticed that the continuous connectivity level for $V_{selected}$ is less than the general connectivity level as connections is lost over traveling distance. This is evident in Tables 1-3. The connectivity levels will subsequently influence the overall number of exchanged BSMs, which will definitely affect the available communication bandwidth.

Assuming that transmission of BSM occurs every τ ms; $V_{selected}$ should receive and transmit messages according to equation (4).

$$Total\ BSM(V_{selected}) = \left(\frac{2 * T * V_{Connected}}{\tau}\right) \quad (4)$$

Where,
$V_{connected}$: Number of continuously connected vehicles to $V_{selected}$ for a particular duration.
The factor of 2 account for bidirectional transmission (connected vehicles sending message to $V_{selected}$ and $V_{selected}$ sending message to connected vehicles).

IV. Conclusion

This work presents using simulation, analysis of critical factors affecting V2V connectivity and subsequently roads safety. The obtained and analyzed results indicate that connectivity level increases as a function of both traffic density and communication range, with lower numbers for continuous connectivity as vehicles move between spatial domains over a fixed duration. Critical results obtained when different durations used per fixed BSM communication range show the existence of a threshold value, which allows the assumption of a time slot allocation per fixed transmission range that dynamically shifts as vehicles move in-between spatial domains or clusters. Such change in connectivity proved to affect the total number of BSM messages exchanged and subsequently affect allocated bandwidth.

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