IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 7, 2019, accepted August 23, 2019, date of publication August 26, 2019, date of current version September 9, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2937672

Modelling and Analysis of a Novel Vehicular Mobility Management Scheme to Enhance Connectivity in Vehicular Environments

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ABSTRACT Robust end-to-end connectivity in vehicular environments has been a daunting problem standing in the way of the development and provisioning of novel in-transit data communication services envisioned to incur remarkable enhancements on all of the: *a*) road safety, *b*) environment and *c*) welfare of travelling passengers. The establishment of continuous multi-hop data communication paths among arbitrary pairs of vehicular nodes is severely affected by the natural vehicular traffic flow's inherent limitations and obstacles that have been widely investigated in the literature. This present work proposes a novel Vehicular Mobility Management (VMM) scheme that has the objective of regulating the vehicles' navigational parameters in such a way to steadily line these vehicles up in proximity of each other with space headways that do not exceed the coverage range of their respective OnBoard Units. This will allow for establishing robust and long-lived communication links connecting the vehicles together; hence, increasing the probability of existence of multi-hop paths between arbitrary pairs of vehicular nodes. A Mathematical model is formulated herein in order to evaluate the performance of VMM in terms of multiple Quality-of-Service (QoS) metrics (*e.g.* average end-to-end data delivery delay, average throughput, probability of existence of an end-to-end path, etc). A simulation framework is then established for the purpose of verifying the correctness and validity of the proposed model and gauge the merit and advantages of the proposed VMM scheme. The reported results constitute a tangible proof of the validity of the proposed model as well as of the benefits emanating from vehicular flow control in the context of a highly promising step towards the realization of the embraced Internet of Vehicles (IoV).

INDEX TERMS Modelling, performance, connectivity, delay, vehicular networks, multihop, path.

I. INTRODUCTION

A. PRELIMINARIES

Intelligent Transportation Systems (ITSs) and the flurry of services (*e.g.* passenger safety, traffic management, infotainment, on-the-fly Internet access, etc) they offer have appeared at the heart of numerous existing publications in the literature. Compared to their early days of emergence, these systems' current status quo is a tangible proof of their remarkable technological evolution. Truly, the amount of intelligence they have gained over time renders them as one of the facets of today's smart cities. Above and beyond, ITSs today constitute one of the integral industry verticals of the next generation carrier grade networks envisioned by the embraced 5G technology. Fundamental enablers of this latter technology are vehicular networks, which, unsurprisingly, lying at the core of ITSs constitute these systems' driving force supporting both of their operational expenditure as well as the proper functionality of the services they provision. Nowadays, the remarkable upsurge of end-users for novel in-transit services and applications is pushing towards an unparalleled cooperation between the automotive, electronics and telecommunications industries whereby newly manufactured vehicles are being equipped with modern top notch ubiquitous technology (*e.g.* computerized modules, wireless communicating devices, electronic sensors, actuators, etc) that mediate the physical and digital layers of vehicular networks. All of the industrial, governmental and academic investments and efforts endowed in this regard are leading towards the future realization of a groundbreaking network

The associate editor coordinating the review of this article and approving it for publication was Asad Waqar Malik.

of all-time-anywhere connected vehicles nominated, herein, as the Internet of Vehicles (IoV). In turn, IoV will further catalyze the expenditure and empowerment of the current ITSs as it brings to the wheels novel digital services subordinating the elemental data gathering and interchange enabled by the all-famous Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Undeniably, the revolutionary intelligence enhancements characterizing newly manufactured vehicles delineate the novel Vehicle-to-Everything (V2E) communication paradigm enabling these vehicles to communicate with everything around them; hence, raising their real-time awareness of their surroundings. In particular, this allows vehicles to cooperate with each other in a distributed manner and dynamically auto-tune their navigational parameters in order improve performance, reduce energy consumptions and gaseous emissions, increase safety and offer today's sophisticated passengers an enjoyable ride and unparalleled travel experience.

B. LITERATURE SURVEY AND MOTIVATION

IoV is envisioned to provision a multitude of upraised services including but not limited to: *a*) real-time vehicular teleoperation, [1], *b*) on-the-fly streaming of high-quality interruption-free media in autonomous vehicles, [2], *c*) seamless vehicular mobility, [3], *d*) field-limited emergency support and rescuing services, [4], *e*) traffic monitoring and roadway surveying, [5], *f*) improved data routing and dissemination, [6], *g*) vehicular cloud-based services, [7], *h*) safety-related services (*e.g.* see through downstream vehicles, [8]) and so many others. All of these novel revolutionary services pronounce a surge for a stringent all-time-anywhere available connectivity that overcomes the constraints that the built-in physical mobility dynamics of natural vehicular traffic impose on the digital communication layer of ITSs. This, though, is a challenging problem that, regardless of the seminal efforts invested by the research community, continues to stand in the way of the deployment of a full-fledged IoV.

The literature encloses a number of recently published prime work that address the issue of on-the-road connectivity, some of which, also, investigate possible ways of improving it. For instance, the work of [9] studies the feasibility of multi-hop paths originating from isolated vehicles navigating throughout dark areas along certain roadways. These paths traverse multiple intermediate vehicles downstream towards another destination vehicle or, ultimately, a RoadSide Unit (RSU) that happens to be connected to the Internet via a backhaul network. In this context, the authors of [9] model and analyze the performance of data communications taking place over such paths. The stochastic variability of connectivity in Vehicular Ad Hoc Networks (VANETs) (*i.e.* nodal population size, nodal location distribution and cluster formation probability) with user mobility were studied in [14]. The effect of high-speed mobility on inter-vehicular connectivity was investigated in [11].

The authors of [12] observed that the high node mobility and frequent topology changes in VANETs impose new challenges on the maintenance of long-lasting connections between vehicles. They probabilistically analyzed the inter-vehicular communication links under different vehicular density ranges with the objective of determining the lifetime of these links. Then, throughout their work in [13], the authors recognized vehicular clustering as a potential approach to improve the scalability of Vehicular Ad Hoc Networking (VANET) protocols. Nonetheless, natural vehicular traffic flow limitations such as the elevated degree of vehicle mobility and frequent network topology changes incured new challenges that rendered cluster stability one of the most crucial efficiency measures of VANET clustering algorithms. In this regard, the authors in [13] utilized the passage time analysis to derive probability distributions pertaining to time periods of invariant cluster-overlap state and cluster membership as measures of cluster stability. Then, the limiting behaviors of common and unclustered nodes between neighboring clusters were characterized.

The work of [14] presented an in-depth study of the steady-state statistical properties of continuous communication path availability in VANETs. The authors therein considered a network of highways with an arbitrary topology. These highways were assumed to experience vehicular traffic flows having similar characteristics to the one modelled herein in Section IV-A. To this end, their study ultimately aimed at deriving the probability distributions of the number of naturally formed clusters as well as the duration of continuous communication path availability time as a function of natural and uncontrolled vehicular traffic flow parameters. Their results shed the light on the effect that vehicular mobility parameters have on the end-to-end path availability and experienced packet delays.

In [16], a new mobility metric referred to as the Generalized Speed Factor (GSF) was proposed with the objective of relaxing the assumption of vehicles maintaining fixed speeds at all times. This GSF has been used in analyzing three different scenarios of vehicular connectivity, namely: *i*) temporal static connectivity, *ii*) low mobility connectivity and *iii*) high mobility connectivity. The authors of [16] have shown that connectivity may be maintained at an acceptable level up until the average speed of vehicles reaches a certain threshold beyond which interruptions become more frequent.

The authors of [17] noted the inability of existing routing protocols - particularly, the Position-Based Routing (PBR) protocol - to guarantee the existence of a routing path between a source-destination pair of nodes in a vehicular network nor to provide contact time (*i.e.* connection duration) information. This limitation renders these protocols unsuitable for reliable routing and delivery of Internet packets. To this end, they propose iCar-II being a novel infrastructure-based connectivity aware routing protocol that allows vehicles to predict local network connectivity and update location servers with real-time network information with the objective of constructing a global view of the vehicular network topology. iCar-II augments vehicles with real-time connectivity awareness and, hence, allows for dynamic selection of routing paths

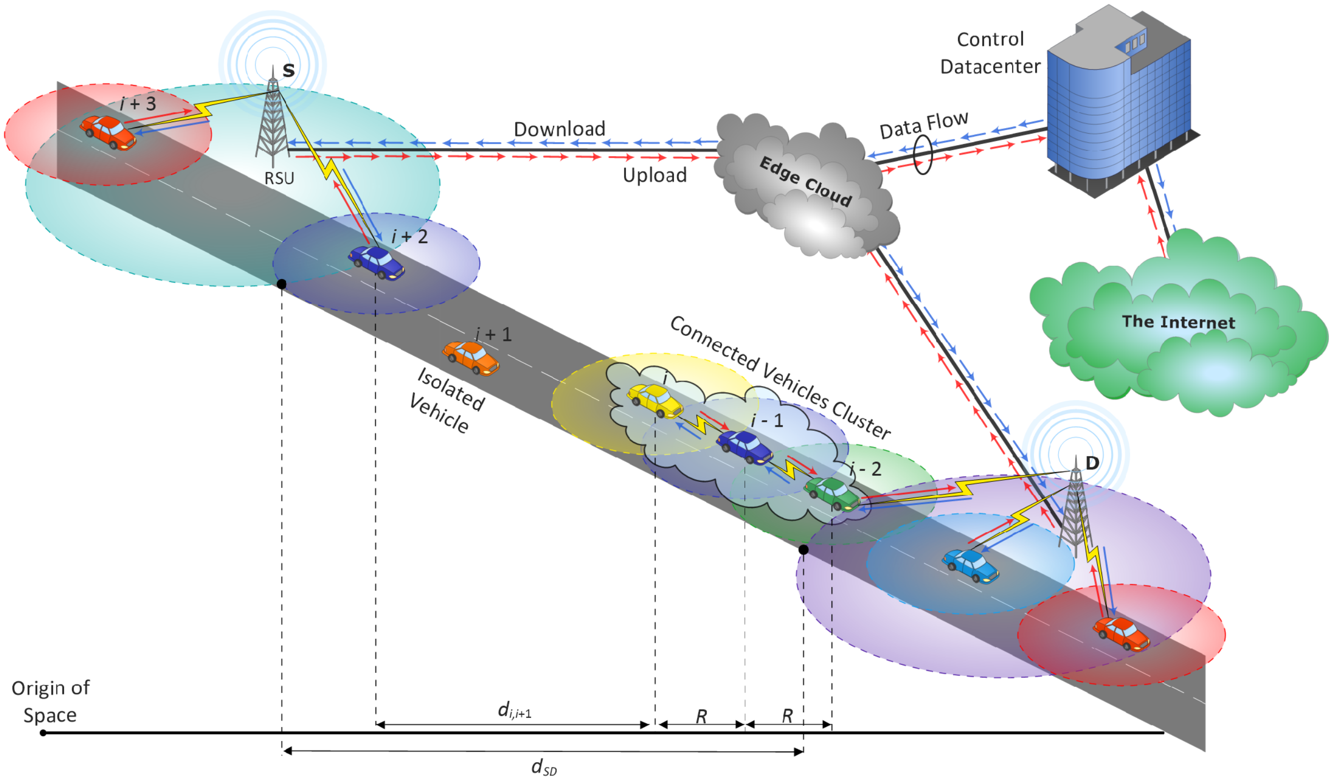

FIGURE 1. Intelligent transportation slice of next generation carrier grade networks.

with best achievable connectivity guarantees under specific vehicular traffic conditions and, thus, improve the packets' delivery ratio and reduce the average end-to-end delivery delay.

The work of [18] revolves around capturing the instantaneous variations of vehicular networks' topologies and structures. Therein, the authors focus on highlighting the fundamental properties of realistic network topologies in the context of two different vehicular networking scenarios in both the cities of Cologne and Zurich respectively in Germany and Switzerland. The presented study in [18] unveils a poorly connected topology with very limited end-to-end path availability and low-level reliability. The authors conclude that the currently employed simplistic mobility models may lead to unrealistic overly connected topologies.

In [19], the authors analyze the information delivery delay between RoadSide Units (RSUs) in the context of a vehicular networking scenario with intermittent connectivity. The underlying networking application therein consists of delivering road condition information via the vehicles allowing them to act as data carriers/forwarders to RSUs that are deployed along the considered roadways. In turn, these RSUs will disseminate the collected information to other unaware vehicles that are passing by. Unarguably, under light vehicular traffic conditions with vehicles sparsely distributed over the considered roadway, inter-vehicular connectivity intermittence becomes a rather severe obstacle that stands in the way of timely information delivery and, thus, considerably reduces the quality of the provided service. For this purpose, the authors of [19] investigate a relationship between the achievable delivery delay and the inter-RSU distance with the objective of optimizing the deployment of RSUs in order to increase connectivity. Complementarily, the authors of [20] highlight the major impact that inter-vehicular distances (*i.e.* the space headway) have on V2V connectivity. For this purpose, they have established an analytical framework that aims at theoretically quantifying the space headway under Free-flow vehicular traffic conditions (*i.e.* low-to-moderate vehicular traffic flow/density). Their presented theoretical foundation appears as a more transparent modelling generalization that asserts the correctness of fundamental assumptions underlying existing traffic models such as the one developed in [21] and that adopted in [22] and, hence, presents a simple theoretical expression for the space headway distribution as a function of Poisson vehicle arrivals and general speed distributions.

Owing to the tremendous impact that the improvement of connectivity will have on the performance of services supported by vehicular networks, the work of [15] revolved around the deployment of extra Mobile Base Stations (MBSs) characterized by higher transmission ranges for the purpose of improving the end-to-end path availability in the context of a vehicular networking scenario that is similar to the one considered herein and illustrated in Figure 1.

Throughout their work the authors accounted for the possible non-cooperativeness of some vehicles as well as the impact that RSUs will have on the network's performance. The optimal number of MBSs and their respective transmission ranges were the fundamental results reported in [15].

The work of [23] revolved around consolidating two of the main pillars of connectivity in vehicular environments, namely: *i*) the availability of end-to-end paths between any pair of nodes and *ii*) the average end-to-end data delivery delay. The authors of [23] ought to investigate the role that things, external to these networks, may play towards improving the performance of vehicular networks in terms of the above-mentioned metrics. For instance, according to [25], the world is currently witnessing explosive interests and investments (*i.e.* top of 2.3 billion dollars by the year of 2027) in the production of Unmanned Aerial Vehicles (UAVs) (*a.k.a* drones) and their envisioned market applications. AMAZON has recently filed a U.S. patent (refer to [26]) that elaborates on the possible use-cases and applications encompassing UAVs as integral core components. In the era of the Internet of Things (IoT), aside from the projected pervasive UAV-based goods delivery infrastructure, every smart device may, virtually, be the target of UAV-supplied value-added services, [27]. On the same note, the authors of [23] proposed to augment UAVs with the capability of buffering data and, hence, given their relatively higher speeds as compared to vehicle speeds, these UAVs may act as express data deliverers to intended vehicular destinations (*e.g.* other vehicles and/or far away RSUs) contributing to reducing data delivery delays.

All of the above surveyed connectivity analyses were conducted in the context of typical roadways experiencing natural vehicular traffic and the limitations thereof. More precisely, the majority of existing work in the literature addressing the problem of connectivity in vehicular environments revolve around capturing the vehicular traffic dynamics with the objective of determining the possibility of establishing end-to-end paths between an arbitrary source-destination pair of nodes and the ability of these paths in improving the communication performance between these communicating nodes (*e.g.* reduce end-to-end data delivery delays, increase the throughput, etc). Under the circumstances of severe vehicular traffic limitations, the way, so far, was to exploit the source node or intermediate nodes (*i.e.* vehicles) along one sub-path towards the destination as Store-Carry-Forward (SCF) nodes capable of physically carrying data until either connecting with another node traversed by another sub-path towards the destination or directly connecting with this latter. Given their higher speeds and flexible trajectories relative to ground vehicles restricted only to navigable roadways, SCF-enabled UAVs constitute better candidates for transporting data from one end to another as shown in [23]. This is especially true since they are also independent of the vehicular traffic and, hence, are not subject to its stringent limitations. Nonetheless, irrespective of their abilities, these UAVs still cannot deliver the data as fast as it gets delivered through electromagnetic transmissions occurring over multi-hop paths connecting the source node to its intended destination. It is important to mention that UAVs may act as intermediate relay nodes that can possibly re-connect two disconnected vehicles and, hence, on-the-fly restore broken links along a disrupted path between two communicating ends. This certainly improves and expedites the data delivery process from an arbitrary source to its intended destination but, nonetheless, persists as an open research problem.

C. NOVEL CONTRIBUTIONS

None of the existing work was able to completely overcome the inherent limitations of natural vehicular traffic flows except when possibly resorting to external factors (*e.g.* UAVs and possibly other things), but, at additional cost. This is not to mention that, until this date, the exploitation of UAVs for data communication, although being a very promising concept, it still faces numerous challenges, [26]. Motivated by all of the above and unlike existing publications, this present work whose preliminaries are rooted in [24] capitalizes on the revolutionary advancements in vehicular technology, particularly on the evolution of the smart identities of vehicles and all of the artificial intelligence being embedded in them as well as in recently manufactured and deployed RSUs, giving birth to highly cooperative networking environments that enable and expedite the deployment of IoV. Under the assumption of fully cooperative vehicles,[1] a Vehicular Mobility Management scheme is developed herein through which an upstream RSU attempts to regulate the speeds of incoming vehicles with the objective of triggering the formation of steady chains (*i.e.* platoons) of these vehicles interconnected by stable links subsidizing the coalescence of multi-hop data communication paths connecting any arbitrary pair of source-destination nodes in vehicular environments. It is expected that, under the controlled behavior of vehicles, such paths will now become more robust with a higher likelihood of availability and, hence, remarkably improve connectivity. Two direct results are: i) an increase in the network's throughput as well as ii) an expedited data delivery process involving different combinations of communicating mobile vehicles and stationary RSUs.

An analytical framework is developed herein and encompasses a tractable stochastic model that has the objective of capturing the dynamics of the proposed VMM scheme and its ability to trigger the relatively rapid formation of end-to-end communication paths among communicating vehicles and RSUs. A thorough simulation study is then conducted for the purpose of verifying the validity of the proposed model as well as to evaluate the performance of the proposed VMM scheme in terms of important Quality-of-Service (QoS) metrics such as the probability of path availability and the average end-to-end delivery delay. A benchmarking scheme is

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[1] It is, of course, possible that not all vehicular nodes be fully cooperative. Indeed, the degree of cooperativeness of nodes has a direct impact on the performance of data communications in vehicular environments. This, however, will be considered in a future work. As a first step, this work assumes complete cooperativeness of all of the network nodes.

borrowed from a previous work (*i.e.* [9]) and, for all purposes of consistency, is referred to herein as the Uncontrolled Vehicular Mobility (UVM) emulates the dynamics of natural uncontrolled vehicular traffic and the achievable data delivery process thereunder. A direct comparison of the path availability and the average data delivery delay that are achieved respectively under VMM and UVM in different vehicular traffic scenarios serves the objective of shedding the light on and gauging the merit of the proposed VMM.

D. PAPER'S ORGANIZATION

The remaining of this paper is organized as follows. Section II presents a sub-networking scenario that aims at motivating the need for explicit vehicular mobility management to trigger the formation of steadily-chained vehicular platoons; hence, improving the data communication and delivery process. Section III is dedicated for the comprehensive presentation of the proposed VMM scheme and the detailed discussion of its inherent dynamics. A brief summary of the adopted vehicular traffic model together with the mathematical formulation of the achieved path availability and average end-to-end delivery delays are presented in Section IV. In Section V a simulation framework is developed with the objective of verifying the validity and accuracy of the proposed VMM scheme as well as evaluating and comparing its performance with another existing scheme in the literature. Finally, concluding remarks are presented in Section VI.

II. VEHICULAR SUB-NETWORKING SCENARIO

Consider the intelligent transportation sub-slice of a next generation carrier grade network (*e.g.* 5G network) scenario that is illustrated in Figure 1. The objective of this illustration is to assist the reader in visualizing the main components involved in the process of supporting intelligent transportation services and applications such as those mentioned in Section I-B (*e.g.* vehicle tele-operation, media streaming and other infotainment applications, etc). Figure 1 shows two RSUs, namely, S and D, located along the sides of a large one-dimensional and uninterrupted highway segment (*e.g.* inter-city highway). These RSUs are connected to an Edge Computing (EC) mini-cloud, which, in turn, is connected to a control datacenter. The control datacenter itself is also connected to the Internet via a backbone metropolitan area network while the Edge Cloud is intended to bring some real-time intelligent transport services and content closer to the network's edge in order to improve the response time and save bandwidth. Each of the RSUs S and D has a communication range having a radius that covers a distance of R (*meters*) of the considered highway. Being located at the respective edges of this highway, the distance separating S from D is equivalent to the highway's length, which is denoted, herein, by d_{SD} and is such that $d_{SD} \gg R$. Vehicles cruising along the considered highway, will encounter (*i.e.*, enter the coverage range) either RSU at random times. Throughout their respective residence periods within an RSU's range, vehicles may directly communicate with that RSU and take advantage from the ITS services it provides.[2] For instance, semi-autonomous electric vehicles will be connected to the control datacenter through a path that traverses the EC and connects the RSUs on one side to the control datacenter on the other side. Being equipped with various sensors and multi-dimensional cameras, these vehicles are can sense their environment, capture snapshots and/or record live videos of the road, which they will communicate in a real-time manner to the control center. Based on the acquired data from the vehicles, operators at the control center may manually tele-operate and/or download navigation instructions to the vehicles. On a different note, onboard passenger entertainment is becoming more and more popular. While traveling, passengers may require uninterrupted media streaming services in order to watch a movie. In this context, vehicles residing within the coverage range of RSUs may download and store media files within their respective OnBoard Units' (OBUs') buffers in anticipation of their playback throughout these vehicles' travel durations. Nonetheless, the sojourn time of moving vehicles within the RSUs communication range is limited and, usually, insufficient for downloading enough data for media playback throughout the vehicles' navigation in dark areas (*i.e.* areas that have no connectivity/RSU coverage) all the way until they encounter the next downstream RSU. Here, it is important to mention that the existence of dark areas is mainly due to the elevated communication infrastructure deployment and setup costs over large highways such as the one considered in the context of the scenario illustrated in Figure 1. At this point, arguably, vehicles navigating in dark areas may reconnect to the Internet through the cellular network (*i.e.* 5G, 4G, LTE, LTE-A, etc). Nonetheless, the earlier-mentioned revolutionary services are bandwidth intensive as they induce massive data downloads/uploads (often in real-time). Here, cellular-based data communication becomes remarkably costly from both the end-user's perspective (*e.g.* elevated costs of large data plans) and the operator's perspective (*e.g.* over-utilization of network resources). As such, under the circumstances where only the roadside networking infrastructure is used, at some point, commuting passengers may experience service outage until their conveying vehicles get in contact with another RSU (*e.g.* RSU D). Now, the severity of the interruption differs from one service to another. For example, speaking of temporary interruption in media streaming services may not sound as critical, but, it surely affects the Quality-of-Service (QoS) as perceived by end-users (*i.e.* the onboard passengers). However, criticality is magnified by several orders of magnitude when safety-related service interruptions occur (*e.g.* tele-operation, warning message dissemination, field-limited emergency support and rescuing, traffic monitoring, roadway surveying, etc). Indeed, robust data communication services may remarkably

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[2] Here, any newly incoming vehicle to the considered roadway segment may potentially communication with the RSU to request some service. Hence, in the sequel, without loss of generality, all incoming vehicles are assumed to require digital connectivity throughout their navigation along the considered roadway segment.

contribute to improving road/passenger safety through avoiding life-threatening vehicle collisions and accidents that are highly likely occur especially under extreme driving conditions (*e.g.* severe snow storms) leading to catastrophic losses such as those that have been recently witnessed in Canada, [27]. Truly, such tragic incidents vociferate a surge for immediate vehicular connectivity improvements in response to the urgent need for circumventing the limitations imposed by dark areas. Hereafter, this paper presents a possible alternative enabled by IoV, which, more precisely, exploits V2E communications and vehicular mobility management for the purpose of establishing robust multi-hop data communication paths to connect remote vehicles navigating through dark areas (vehicle $i+1$ in Figure 1) to RSUs disposed alongside roads and highways.

III. VEHICULAR MOBILITY MANAGEMENT SCHEME: A DETAILED DESCRIPTION

In view of the scenario depicted in Figure 1, the Vehicular Mobility Management (VMM) scheme presented herein is intended to autonomously regulate the navigational parameters of cruising vehicles for the purpose of stimulating the genesis of steady-state vehicular clusters. Such clusters[3] exhibit navigational steadiness and regularity in such a way that vehicles will autonomously be whizzing along at equal space headways (*i.e.* constant inter-vehicular distances) and constant velocities behind a certain lead vehicle. Over the past years (*e.g.* [29]), lining up vehicles into train-like platoons was being fantasized as the future of freeways offering salient benefits including but not limited to: *a*) reduced consumption of fossil fuel (energy), *b*) increased road capacities and *c*) improved safety, *d*) reduced average travel times, and, *e*) reduced CO_2 emissions. Herein, VMM has the fundamental objective of overlaying on top of these physical benefits a digital layer that exploits IoV's V2E communications for the purpose of bringing to the wheels a remarkably enhanced broadband connectivity; hence, supporting the proper operation and functionality of revolutionary novel services such as those mentioned in Section I-B; particularly, reaching out for isolated vehicles navigating through dark areas (*e.g.* vehicle $i + 1$ in Figure 1) and reconnecting them to far away RSUs. For this to happen, it becomes a necessity to work around the obstacles and limitations imposed by the natural flow of vehicular traffic - these having been identified and widely investigated in the literature (*e.g.* [9], [14] and [23]) - that stand in the way of establishing multi-hop data communication paths between any arbitrary set of nodes in vehicular environments. In other words, the formation of such paths is not always naturally feasible. Consequently, in order to increase the probability of their existence, vehicular flow control must be invoked to regulate the vehicles' navigational parameters in such a way to steadily line these vehicles up in proximity of each other at a distance that does not exceed the communication range of their respective OBUs; hence, allowing for robust communication links to be established between them. On the long run, the longer the chain of interconnected vehicles becomes the larger the probability that an arriving vehicle to the considered highway segment will find a multi-hop data communication path that leads to any downstream destination node be it a vehicle or an RSU.

The key element in VMM is the RSU such as, for example, RSU S shown in Figure 1. Precisely, nowadays, RSUs as well as vehicles being equipped with modern ubiquitous technology (*e.g.* sensors, radios, computerized modules, data buffers, etc) are capable of communicating with each other and exchange traffic information in a real-time manner. In particular, as a vehicle, say vehicle i, enters the coverage range of RSU S at a certain time τ_i, this latter RSU will become aware of that vehicle's presence, speed, V_i, and direction of navigation. Accordingly, RSU S can compute the vehicle's sojourn time, S_i, within its coverage range as well as estimate the respective downstream location of that vehicle within the considered highway segment at any future point in time (*i.e.* $\tau > \tau_i$); particularly, RSU S will be able to determine the time instant at which vehicle i will arrive to the destination RSU D and cross the middle of its range; a point at which vehicle i is hereafter considered to have departed from the considered highway. Here, RSU S will register a record for vehicle i and store it in its Vehicle Information Table (VIT) for as long as that vehicle continues to navigate along the considered highway. Vehicle i's record will be deleted from RSU S's VIT as soon as this vehicle exits the highway segment. It follows that each record stored in the VIT of an RSU has a very well-defined lifetime as the VIT is continuously updated in a dynamic manner by adding new records corresponding to newly arriving vehicles and deleting the records of those vehicles that depart from the considered highway segment. Now, assume that at a time $\tau_{i+1} > \tau_i$, a subsequent vehicle $i + 1$ arrives and happens to be navigating at a speed V_{i+1}. Now, given vehicle i's record, RSU S will determine the position of that vehicle at time τ_{i+1} and determine the appropriate speed, $V^*_{i+1} \neq V_{i+1}$ at which vehicle $i + 1$ must navigate to reach and connect to vehicle i before this latter exits the highway. Connectivity between the two consecutive vehicles i and $i + 1$ can be established whenever their space headway is no larger than a distance that allows both of these vehicles to be within each other's mutual communication ranges. Assuming that all vehicles' OBUs are identical and having equal communication ranges with radii of R, then connectivity can only be established between vehicles i and $i + 1$ if their space headway is no larger than R. Accordingly, RSU S will instruct vehicle $i + 1$ to navigate at speed V^*_{i+1} up until a connection with vehicle i is established. Upon establishing the connection with vehicle i, vehicle $i + 1$ will, then, reduce its speed to that of vehicle i and both vehicles will continue to navigate throughout the remaining of the highway segment at equal speeds and space headways. RSU S will repetitively instruct all consecutively arriving vehicles to navigate at the individual appropriate speeds that it

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[3] In the sequel, the terms cluster and platoon are used interchangeably but are intended to have the same meaning.

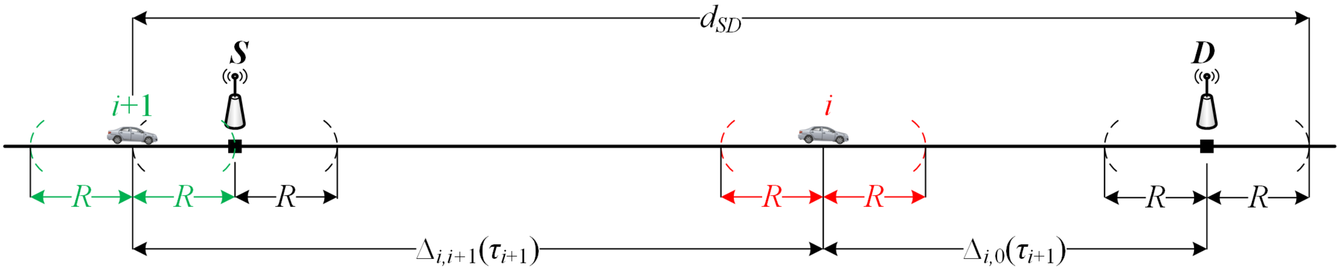

FIGURE 2. Case 1 of connectivity establishment feasibility analysis.

computes in an attempt to enlarge the vehicular chain as much as possible. With such traffic regulation and control, the number of connected vehicles on the considered highway will increase and, hence, the probability of existence of a multi-hop data communication path that connects an arbitrary pair of vehicular source-destination nodes will increase. Indeed, a traffic control scheme such as VMM will therefore contribute to expediting the data exchange and delivery process from an upstream source node to a downstream destination node; hence, reducing the average end-to-end data delivery delay.

IV. MODELLING OF PATH AVAILABILITY AND AVERAGE DATA DELIVERY DELAY UNDER VMM

A. VEHICULAR TRAFFIC MODEL

The highway segment considered in Figure 1 is assumed to be one-dimensional, uninterrupted and, naturally, experiencing Free-Flow vehicular traffic (*i.e.* medium-to-low vehicular densities). This type of traffic has been extensively considered in the literature (*e.g.* [9], [21], [23]). In this work, the macroscopic Free-Flow traffic model presented in [21] will be adopted. Accordingly, vehicle arrivals to the segment $[SD]$ follow a Poisson process with a parameter $\Lambda_V\ \left(\frac{vehicles}{second}\right)$. Denote by $\Im_{i+1,i} = \tau_{i+1} - \tau_i$ the inter-arrival time interval between two consecutive vehicles i and $i+1$ (*seconds*). The vehicle inter-arrival time intervals $\{\Im_{1,0}; \Im_{2,1}; \Im_{3,2}; \ldots\}$ constitute a sequence of independent and identically distributed (i.i.d.) exponential random variables (r.v.s) having a probability density function (p.d.f.) $f_{\Im}(\tau)$ given by:

$$f_{\Im}(\tau) = \frac{1}{\Lambda_V} e^{-\frac{\tau}{\Lambda_V}} \quad , \tau \geq 0 \tag{1}$$

In addition, let the r.v. V_i denote the speed $\left(\frac{meters}{second}\right)$ of the arriving vehicle i, which is defined over the range $[V_m; V_M]$ where V_m and V_M denote, respectively, the minimum and maximum vehicle speeds. The average and standard deviation of the vehicle speeds were respectively derived in [21] as $\overline{V} = V_M(1 - \rho_V \cdot \rho_{\max}^{-1})$ and $\sigma_V = \xi \cdot \overline{V}$ where ρ_V and $\rho_{\max}$ denote, respectively, the mean and maximum vehicular densities and ξ was a parameter whose value is correlated to the ongoing vehicular traffic activity and was determined based on experimental data. It is shown in [21] that $\{V_0, V_1, V_2, \ldots\}$ constitutes a sequence of i.i.d. per-vehicle speeds having a truncated Normal distribution whose p.d.f. was given by:

$$\widehat{f_V}(v) = \frac{\zeta}{\sigma_V\sqrt{2\pi}} e^{-\left(\frac{v-\overline{V}}{\sigma_V\sqrt{2}}\right)^2} \quad , v \in [V_m; V_M] \tag{2}$$

where ζ was defined and derived as a normalization constant.

B. MULTI-HOP PATH AVAILABILITY ANALYSIS

When it comes to studying the feasibility of connectivity path establishment between newly arriving vehicles to the considered segment $[SD]$, several cases may be distinguished. In the very first case illustrated in Figure 2, assume that a vehicle i navigating at a speed V_i enters the communication range of RSU S at time t_i and, upon its arrival, happens to be navigating at a speed of V_i. Without loss of generality, assume that, initially, no vehicles are navigating along $[SD]$. As such, vehicle v_i being the first to arrive to $[SD]$ is referred to as the lead vehicle and will preserve a constant speed of V_i all the way throughout its navigation downstream towards RSU D until it exits the range of this latter and, hence, departs from $[SD]$. At a subsequent time τ_{i+1} vehicle $i+1$ arrives and happens to be navigating at a speed V_{i+1}. Upon its arrival, the RSU S being knowledgeable about the arrival time and speed of vehicle i will determine whether or not, following the calibration of vehicle $i+1$'s speed, this vehicle will be able to reach vehicle i and establish connectivity with it before this latter crosses the middle of the range of RSU D. This is especially true since, a space headway of R (meters) between two consecutive vehicles is required for these vehicles to be within each other's mutual communication ranges and, hence, be able to inter-communicate. As such, in the case where two consecutive vehicles spaced by a distance of R are navigating at equal and constant speeds, whenever the lead vehicle enters the range of an RSU and navigates a distance of R inward within that range, its direct successor vehicle will then be found at the edge of the RSU's range and able to establish direct connectivity with that RSU. Under such circumstances, the connectivity with the lead vehicle will become of marginal utility. This is why the interest here lies in determining whether or not it is feasible for vehicle $i+1$, following the calibration of its speed, to reach out and connect with vehicle i (and, hence, possibly expedite its data delivery to RSU D through a multi-hop path via v_i) before this latter

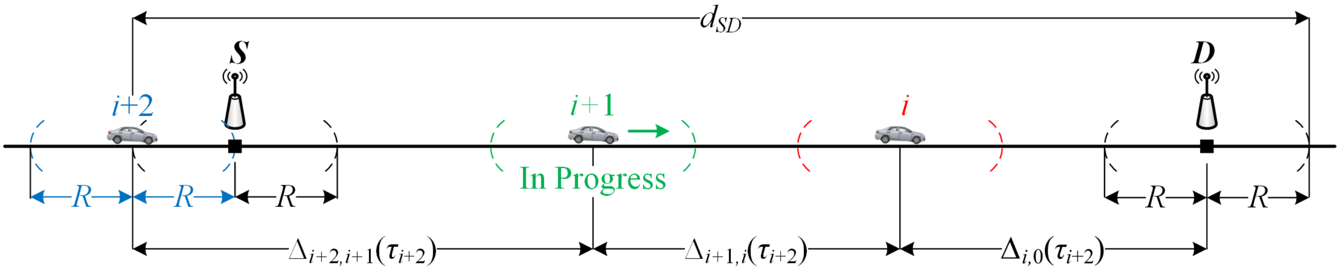

FIGURE 3. **Case 2 of connectivity establishment feasibility analysis.**

enters the range of (*i.e.* establishes direct connectivity with) RSU D. At this point, it is important to recall that, herein, the ultimate objective consists of determining the possibility of the most expedited formation of multi-hop paths through which data will be delivered from an arbitrary source vehicle to the destination RSU D; thus minimizing the data delivery delay. Consequently, if ever feasible, RSU S will instruct a newly arriving vehicle (here vehicle $i+1$) to navigate at the maximum possible/allowable speed (*i.e.* V_M as mentioned in section III-B) throughout its approach phase to a leading downstream vehicle (here vehicle i). Upon reaching the leading vehicle i, the approaching vehicle $i+1$ will then reduce its speed to that of vehicle i and maintain this speed constant throughout its residual navigation time downstream along $[SD]$ until it finally exits the range of RSU D and, hence depart from $[SD]$. To this end, in studying the feasibility of establishing connectivity between vehicles i and $i+1$ before this latter enters the range of RSU D and establishes direct connectivity with it, it is required to determine the initial distance that separates these two vehicles at the time of arrival of vehicle $i+1$. This distance is denoted herein by $\Delta_{i+1,i}(\tau_{i+1})$ and is given by:

$$\Delta_{i+1,i}(\tau_{i+1}) = (\tau_{i+1} - \tau_i)V_i = \Im_{i+1,i}V_i \tag{3}$$

Denote by $\Gamma^c_{i+1,i}$ the shortest possible time interval required for vehicle $i+1$, once its speed is calibrated to the maximum allowable speed, V_M, in order to reach (*i.e.* travel a distance of $\Delta_{i+1,i}(\tau_{i+1}) - R$) and establish connectivity with vehicle i. $\Gamma^c_{i+1,i}$ is given by:

$$\Gamma^c_{i+1,i} = \left(\Delta_{i+1,i}(\tau_{i+1}) - R\right)(V_M - V_i)^{-1} \tag{4}$$

Now, at the time of arrival of vehicle $i+1$ (*i.e.* at time τ_{i+1}), $\Delta_{i,0}(\tau_{i+1}) = d_{SD} - \Delta_{i,i+1}(\tau_{i+1}) - R$ is the distance that separates vehicle i from RSU D's middle range. Given vehicle i's speed (*i.e.*, V_i, vehicle i will, therefore, bypass RSU D's middle range (referred to as the time of departure of vehicle i from the system since, at this time, this vehicle will no longer contribute to the multi-hop path formation and expedited data delivery process) can be expressed as:

$$\begin{aligned}\Gamma^d_i &= \Delta_{i,0}(\tau_{i+1})\cdot V_i^{-1} = \left[d_{SD} - \Delta_{i+1,i}(\tau_{i+1}) - R\right]\cdot V_i^{-1}\\ &= (d_{SD} - R)\cdot V_i^{-1} - \Im_{i+1,i}\end{aligned} \tag{5}$$

Consequently, the combination of Equations (3) and (4) allows for establishing the necessary and sufficient condition for a newly incoming vehicle (*i.e.* vehicle $i+1$) to connect to its immediate predecessor (*i.e.* vehicle i) as follows:

$$\begin{aligned}\Gamma^c_{i+1,i} \le \Gamma^d_i &\Rightarrow \frac{\Im_{i+1,i}V_i - R}{V_M - V_i} \le (d_{SD} - R)\cdot V_i^{-1} - \Im_{i+1,i}\\ &\Rightarrow \Im_{i+1,i} \le \frac{(d_{SD} - R)(V_M - V_i)}{V_M\cdot V_i} + \frac{R}{V_M}\end{aligned} \tag{6}$$

Next, consider a second case which is illustrated herein in Figure 3. In this case, a newly arriving vehicle $i+2$ arrives at time $\tau_{i+2} > \tau_{i+1}$. At this time, vehicles i and $i+1$ are found to be navigating downstream with vehicle $i+1$ approaching vehicle i at a speed of V_M.[4] At τ_{i+2}, the relative distance separating vehicle $i+2$ from vehicle $i+1$ is $\Delta_{i+2,i+1}(\tau_{i+2}) = \Im_{i+2,i+1}\cdot V_M$. This is especially true knowing that ever since its arrival, vehicle $i+1$ had calibrated its speed to V_M to navigate downstream with the objective of reaching vehicle i during the shortest time possible. To this end, if vehicle $i+2$ increases its speed to V_M, it will begin approaching vehicle $i+1$ only at the time when this latter enters in contact with vehicle i and decreases its speed to V_i. As such, there exists a certain interval of time (*i.e.* basically equivalent to the residual time period needed for vehicle $i+1$ to connect to vehicle i) during which both vehicles $i+2$ and $i+1$ navigate at a speed of V_M. This time is given by:

$$\Gamma^r_{i+1,i} = \left(\Im_{i+1,i}\cdot V_i - R\right)(V_M - V_i)^{-1} - \Im_{i+2,i+1} \tag{7}$$

At this level, following the same reasoning used to establish Equation (4), the time for vehicle $i+2$ to connect to vehicle $i+1$ can be easily derived as:

$$\begin{aligned}\Gamma^c_{i+2,i+1} &= \left(\Delta_{i+2,i+1}(\tau_{i+2}) - R\right)(V_M - V_i)^{-1} + \Gamma^r_{i+1,i}\\ &= \frac{\Im_{i+2,i+1}V_M + \Im_{i+1,i}V_i - 2R}{V_M - V_i} - \Im_{i+2,i+1}\end{aligned} \tag{8}$$

Hence, an expression for vehicle $i+1$'s departure time of can be derived in view of the fact that following that vehicle's connection to vehicle i, it will decrease and sustain a constant speed of V_i allowing it to conserve with vehicle i a constant

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[4] Here, it is important to mention that, if condition (6) was not satisfied, or, at time τ_{i+2}, vehicle $i+1$ was found to be already connected to vehicle i, then the same events depicted in Figure 2 will take turn again.

space headway of R. Thence, whenever vehicle i departs, vehicle $i+1$ will be located just at the edge of RSU D's range and will, therefore, depart after it steers an additional downstream distance of R. It follows that the departure time of vehicle $i+1$ is:

$$\Gamma^d_{i+1} = \Gamma^d_i + R \cdot V_i^{-1} = d_{SD} \cdot V_i^{-1} - \Im_{i+1,i} \tag{9}$$

Consequently, for vehicle $i+2$ to connect to vehicle $i+1$, the following condition has to be satisfied:

$$\begin{aligned} \Gamma^c_{i+2,i+1} \leq \Gamma^d_{i+1} &\Rightarrow \frac{\Im_{i+2,i+1} V_M + \Im_{i+1,i} V_i - 2R}{V_M - V_i} \\ -\Im_{i+2,i+1} &\leq \frac{d_{SD}}{V_i} - \Im_{i+1,i} \end{aligned} \tag{10}$$

A simple mathematical arrangement of Equation (10), leads to reducing this condition to:

$$\frac{V_i}{V_M} \cdot \Im_{i+2,i+1} + \Im_{i+1,i} \leq \frac{d_{SD}(V_M - V_i)}{V_M \cdot V_i} + \frac{2R}{V_M} \tag{11}$$

A reasoning akin the one above and further considering the arrival of vehicle $i+3$ at τ_{i+3}, it becomes easy to identify the necessary condition for this latter vehicle to connect to its immediate downstream successor (*i.e.* vehicle $i+2$). This condition is:

$$\begin{aligned} \Gamma^c_{i+3,i+2} \leq \Gamma^d_{i+2} &\Rightarrow \frac{V_i}{V_M} \cdot \Im_{i+3,i+2} + \Im_{i+1,i} \\ &\leq \frac{d_{SD}(V_M - V_i)}{V_M V_i} + \frac{3R}{V_M} \end{aligned} \tag{12}$$

At this point, a generalization of conditions (6) through (12) can be established. First, recall that the speed V_i is actually the speed of vehicle i, which, without loss of generality, was initially assumed to be the first vehicle to arrive to the considered road segment $[SD]$. Consequently, all subsequently arriving vehicles will be forming a platoon that is led by vehicle i. In other words, whenever a vehicular platoon is formed, vehicle i will play the role of the lead vehicle. Hereafter a lead vehicle will be referred to as vehicle L and its speed will be denoted by V_L. In all of Equations (6), (11) and (12) a common factor being a function of V_L appears in both the right and left hand sides of the inequalities. It is:

$$\Phi(V_L) = V_L \cdot V_M^{-1} \tag{13}$$

Also, the inter-arrival time interval $\Im_{i+1,i}$ representing the time period delimited by the arrival time of the lead vehicle L and its direct successor. It will be, in the sequel, generally denoted by $\Im_L$. Consequently, given the lead vehicle's speed, V_L, and the reference inter-arrival time interval $\Im_L$, the necessary and sufficient condition for an arbitrary arriving vehicle k to reach out and establish a multi-hop connectivity path to RSU D through a downstream cluster of vehicles reduces to:

$$\Im_k \leq \left(\Phi^{-1}(V_L) - 1\right) d_{SD} V_L^{-1} - \Phi^{-1}(V_L)\left(\Im_L + kRV_M^{-1}\right) \tag{14}$$

where $\Im_k$ denotes the k^{th} vehicle inter-arrival time bounded by the arrival times of vehicle $k-1$ and its direct successor vehicle k. Consequently, the conditional probability of a multi-hop path formation from vehicle k to RSU D is derived in Equation (15), as shown at the bottom of this page, where $F_\Im(\psi) = 1 - e^{-\frac{1}{\Lambda_V}\psi}$ is the cumulative distribution function (c.d.f.) of $\Im$. It follows that the unconditional probability of path availability is:

$$\mathcal{P}_k = \int_{V_m}^{V_M} \int_0^{\infty} \left[\mathcal{P}_k(v,\tau) \cdot \widehat{f_V}(v) \cdot f_\Im(\tau)\right] \mathrm{d}v\mathrm{d}\tau \tag{16}$$

where $f_\Im(\tau)$ and $\widehat{f_V}(v)$ are derived respectively in Equations (1) and (2). Unfortunately, $\mathcal{P}_k$ has no closed-form solution and will be evaluated numerically.

C. DELIVERY DELAY ANALYSIS

Without loss of generality, assume that a vehicle k arrives at time τ_k. Recall from Section IV-C that, with a probability of $\mathcal{P}_k$, this vehicle will be able to reach and join (*i.e.* connect with) a downstream cluster and, hence, establish a multi-hop connectivity with RSU D through downstream intermediate vehicles. In contrast, with a probability of $1 - \mathcal{P}_k$, vehicle k will have to physically navigate at speed V_k all the way down towards RSU D and deliver its data directly to it upon entering its range. Consequently, the mean data delivery delay, $\overline{\mathcal{D}_k}$, achieved by vehicle k consists of two integrants, namely: *i*) $\overline{\mathcal{D}^c_k}$ being the mean delay achieved whenever vehicle k gets connected to a downstream cluster, and *ii*) $\overline{\mathcal{D}^{nc}_k}$ being the mean delay achieved by vehicle k as it carries its data all the way down and delivers it to RSU D through a direct connection. It follows that, in general, $\overline{\mathcal{D}_k}$ is given by:

$$\overline{\mathcal{D}_k} = \mathcal{P}_k \cdot \overline{\mathcal{D}^c_k} + (1 - \mathcal{P}_k) \cdot \overline{\mathcal{D}^{nc}_k} \tag{17}$$

Given the above and knowing that vehicle k will enter RSU D's range upon travelling a distance of $d_{SD} - 2R$ (refer to Figures 2 and 3), it is easy to establish that:

$$\overline{\mathcal{D}^{nc}_k} = \int_{V_m}^{V_M} \left(\frac{d_{SD} - 2R}{v}\right) \cdot \widehat{f_V}(v)\mathrm{d}v \tag{18}$$

Next, in deriving $\overline{\mathcal{D}^c_k}$ it is important to keep in mind that, in this case, vehicle k is deemed able to catch up and

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$$\begin{aligned} \mathcal{P}_k(v,\tau) &= \Pr\left[\Im_k \leq \left(\frac{1}{\Phi(V_L)} - 1\right)\frac{d_{SD}}{V_L} - \frac{1}{\Phi(V_L)}\left(\Im_L + \frac{kR}{V_M}\right) \middle| V_L = v, \Im_L = \tau\right] \\ &= F_\Im\left[\left(\frac{1}{\Phi(v)} - 1\right)\frac{d_{SD}}{v} - \frac{1}{\Phi(v)}\left(\tau + \frac{kR}{V_M}\right)\right] \end{aligned} \tag{15}$$

connect to downstream cluster. Here, there are two cases to distinguish, namely:

- **Case 1:** vehicle k connects to the downstream cluster before the lead vehicle of this latter enters RSU D's range.
- **Case 2:** vehicle k connects to the downstream cluster after that latter's lead vehicle enters RSU D's range.

Let $\Gamma^{r}_{L,D}(\tau_k)$ denote the residual time by the end of which the lead vehicle L will get connected (*i.e.* will enter the range of) to RSU D. It is given by:

$$\Gamma^{r}_{L,D}(\tau_k) = \frac{d_{SD} - 2R - \Delta_{S,L}(\tau_k)}{V_L} \tag{19}$$

where $\Delta_{S,L}(\tau_k) = \left(\sum_{n=1}^{k} \Im_{n,n-1}\right) V_L$ represents the distance that separates the special origin (*i.e.* entry point to segment $[SD]$) from the location of vehicle L at the time of arrival of vehicle k. In what follows, define a random variable $\mathcal{I}_k = \sum_{n=1}^{k} \Im_{n,n-1}$. It is clear that $\mathcal{I}_k$ is the sum of k (i.i.d.) exponential random variables with the same p.d.f. as given in Equation (1). As such, $\mathcal{I}_k$ follows an Erlang-k distribution that has a p.d.f. $f_{\mathcal{I}}(\tau)$ and a c.d.f. $F_{\mathcal{I}}(\Gamma)$ which are given by:

$$\begin{aligned} f_{\mathcal{I}}(\tau) &= \frac{\tau^{k-1} e^{-\frac{\tau}{\Lambda_V}}}{\Lambda_V (k-1)!} \quad, \tau \leq 0 \\ F_{\mathcal{I}}(\Gamma) &= \frac{\gamma\left(k, \frac{\Gamma}{\Lambda_V}\right)}{(k-1)!} = 1 - \sum_{m=0}^{k-1} \frac{1}{m!} \left(\frac{\Gamma}{\Lambda_V}\right)^m e^{-\frac{\Gamma}{\Lambda_V}}, \ \Gamma \geq 0 \end{aligned} \tag{20}$$

As such Equation (19) can be re-written as:

$$\Gamma^{r}_{L,D}(\tau_k) = \frac{d_{SD} - 2R}{V_L} - \mathcal{I}_k \tag{21}$$

Following a similar analytical reasoning as that in Section IV-B, it becomes straightforward to establish that the time for an arbitrary arriving vehicle k to connect to a downstream cluster is given by:

$$\Gamma^{c}_{k,k-1}(\tau_k) = \left(\frac{V_L}{V_M - V_L}\right) \mathcal{I}_k - \frac{kR}{V_M - V_L} \tag{22}$$

Consequently, a necessary and sufficient condition for the above-mentioned Case 1 to occur is given by:

$$\begin{aligned} &\Gamma^{c}_{k,k-1}(\tau_k) \leq \Gamma^{r}_{L,D}(\tau_k) \\ &\quad \Rightarrow \mathcal{I}_k \leq (d_{SD} - 2R) V_L^{-1} [1 - \Phi(V_L)] + kRV_M^{-1} \end{aligned} \tag{23}$$

where $\Phi(V_L)$ is given in Equation (13). If condition (23) is satisfied, then, given $V_L = v$ and $\mathcal{I}_k = \tau$, the conditional data delivery delay endured by vehicle k is derived as:

$$\mathcal{D}^{c'}_{k}(v, \tau) = (d_{SD} - 2R)\, v^{-1} - \tau \tag{24}$$

where $v \in [V_m; V_M]$, $\tau \in [0; \Im_l(v)]$ with $\Im_l(v) = (d_{SD} - 2R)\, v^{-1}[1 - \Phi(v)] + kRV_M^{-1}$. Alternatively, the earlier-mentioned Case 2 will take place and, thus, $\mathcal{D}^{c''}_{k}(v, \tau)$ being the conditional delay endured by vehicle k will be equivalent to the amount of time required for that vehicle to reach out and connect to the downstream cluster since this latter will have been already connected through a multi-hop path with a last hop consisting of a link connecting the lead vehicle L to RSU D. Thus, $\mathcal{D}^{c''}_{k}(v, \tau)$ is given by:

$$D^{c''}_{k}(v, \tau) = v\tau (V_M - v)^{-1} - kR(V_M - v)^{-1} \tag{25}$$

where $v \in [V_m; V_M]$, $\tau \in [\Im_l(v); \infty]$. At this point, the mean delivery delays experienced by vehicle k unconditioned on V_L and $\mathcal{I}_k$ are:

$$\begin{aligned} \overline{\mathcal{D}^{c'}_{k}} &= \int_{V_m}^{V_M} \int_{0}^{\Im_l(v)} \left[\mathcal{D}^{c'}_{k}(v, \tau) \cdot f_{\mathcal{I}}(\tau) \cdot \widehat{f_V}(v)\right] \mathrm{d}\tau \mathrm{d}v \\ \overline{\mathcal{D}^{c''}_{k}} &= \int_{V_m}^{V_M} \int_{\Im_l(v)}^{\infty} \left[\mathcal{D}^{c''}_{k}(v, \tau) \cdot f_{\mathcal{I}}(\tau) \cdot \widehat{f_V}(v)\right] \mathrm{d}\tau \mathrm{d}v \end{aligned} \tag{26}$$

Now, let $\mathcal{Q}_k$ denote the unconditional probability that condition (23) is satisfied. It is derived as:

$$\mathcal{Q}_k = \int_{V_m}^{V_M} F_{\mathcal{I}} \left[\frac{d_{SD} - 2R}{v}[1 - \Phi(v)] + \frac{kR}{V_M}\right] \cdot \widehat{f_V}(v) \mathrm{d}v \tag{27}$$

Consequently, the delay experienced vehicle k in the case where it is able to connect to a downstream cluster is:

$$\overline{\mathcal{D}^{c}_{k}} = \mathcal{Q}_k \overline{\mathcal{D}^{c'}_{k}} + (1 - \mathcal{Q}_k) \overline{\mathcal{D}^{c''}_{k}} \tag{28}$$

Final Remark: It is worthwhile mentioning that the delay, $\overline{\mathcal{D}_k}$, encountered by a generated packet lies within the range $\left[0; d_{SD} V_m^{-1}\right]$. This is especially true since, a generated packet by an already connected vehicle will be immediately cleared out and delivered to RSU D through the established multi-hop path. Alternatively, the highest possible delay will be encountered whenever the packet is generated by a vehicle navigating at the lowest speed, V_m, and stands no chance to be connected to a platoon. In this latter case, the vehicle will have to carry the packet all the way along the distance d_{SD} and have it directly delivered to RSU D in a time that is equal to $d_{SD} V_m^{-1}$.

V. SIMULATIONS AND NUMERICAL ANALYSIS FRAMEWORK

A. SIMULATION FRAMEWORK

Discrete-event simulations are carried out for the purpose of evaluating the performance of a vehicular network operating under the proposed VMM scheme herein. An Uncontrolled Vehicular Mobility (UVM) scheme that emulates the natural vehicular dynamics and the data forwarding process presented in our previous work [9] is adopted herein as a benchmark. The performances of these two schemes are respectively assessed in terms of two fundamental QoS metrics, namely: *i*) the mean packet delivery delay and *ii*) the end-to-end multi-hop data communication path availability. Real-world vehicular mobility traces were generated using the Simulation for Urban MObility (SUMO) simulator [29] and fed as inputs to a custom-developed PYTHON-based discrete-event simulator aiming at the evaluation of the impact that vehicular mobility regulation has on the data communication performance in a real-world vehicular networking scenario. The simulator's input parameters and their values are: *a*) following the recommendation of [9], [21], the vehicular traffic flow rate $\Lambda_V \in [0.1; 0.2777]$ (veh/s), the minimum speed is $V_m = 10$ (m/s) while the maximum speed is $V_M = 50$ (m/s), *b*) the RSUs' and vehicles' communication range radii $R = [150; 250; 500]$ (m), and *c*) the considered road segment's length $d_{SD} = [2; 5; 10; 20]$ (km). A total number of 10^6 vehicles were allowed to arrive to the considered road segment. Simulations were stopped following the departure of all of these vehicles from this segment. Throughout each run of the simulator, end-to-end delivery delay and multi-hop path availability measurements were recorded for each generated packet by each of the vehicles arriving/navigating along the considered roadway and then averaged out over all of the generated packets. Results reported herein in Figures 4 through 7 are the averages for each of the above-mentioned performance metrics taken over multiple runs of the simulator in order to establish a 95% confidence interval.

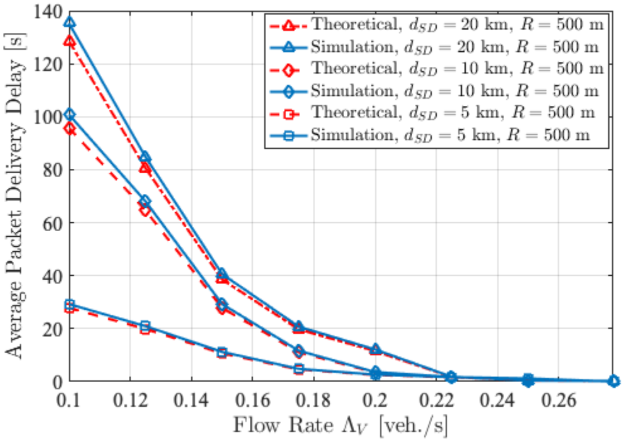

FIGURE 4. **Average packet delivery delay V.S. flow rate - Theo. V.S. Sim.**

B. NUMERICAL ANALYSIS AND PERFORMANCE EVALUATION

Figures 4 and 5 concurrently plot the theoretically computed mean packet delivery delay and multi-hop path availability probability together with their simulated counterparts as a function of the vehicular flow rate for the different values of d_{SD} and R.[5] These figures manifest themselves as a tactile proof of the correctness and validity of the derived mathematical formulas in Section IV as well as the accuracy of the developed simulator. Indeed, the figures show that all of the theoretical curves almost overlap with their simulation counterparts. In what follows the developed simulator herein will be used to evaluate the performance of VMM and compare it to UVM with the objective of providing further insights into the dynamics of VMM, highlight and gauge its merit.

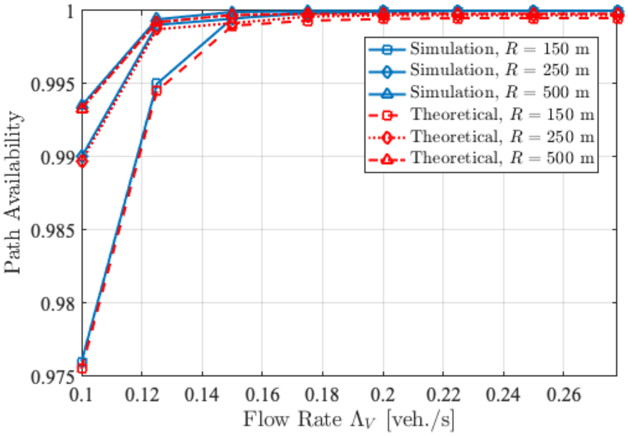

FIGURE 5. **Path availability V.S. flow rate - Theo. V.S. Sim.**

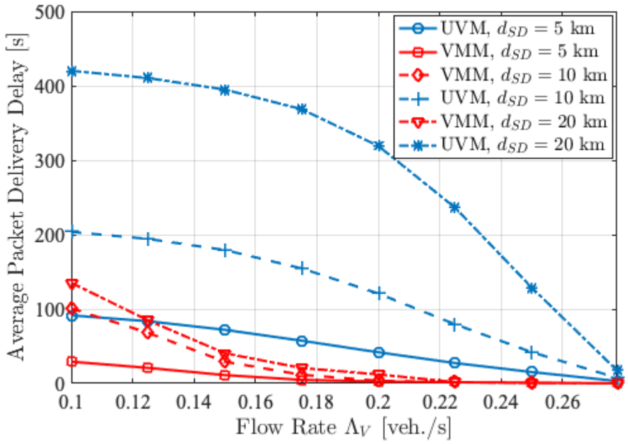

FIGURE 6. **Average packet delivery delay V.S. flow rate - Perf. Eval.**

Figure 6 plots the average packet end-to-end delivery delay as a function of the vehicular flow rate for each of the three above-mentioned road segment lengths. The figure shows that, as the flow rate increases, the average packet end-to-end delivery delay decreases. This is especially true since the vehicular density on the considered roadway segment is, as mentioned in Section III-B proportional to the vehicular flow rate. Consequently, as the flow rate increases, the vehicular density increases and hence, a vehicle with packets to transmit is more likely to find a path through which packets can be forwarded to their ultimate destination RSU, *D* as opposed to getting buffered and physically carried by the vehicle and, then, delivered through direct V2I communication with *D*. This, as shown Figure 6, allows VMM to outperform UVM in terms of mean end-to-end packet delivery delay. This is especially true since, VMM controls the flow

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[5] **Remark:** In Figure 5, the adopted value for $d_{SD} = 2$ (km) whereas the values for *R* where varied in the range specified earlier and shown in the figure. Choosing this small value for d_{SD} has the objective of simulating the worst case scenario, where, with small vehicle coverage ranges such as $R = 150$ (m) and $R = 250$ (m) vehicles newly arriving vehicles might not have enough time to reach downstream vehicles before these latter depart. Hence, establishing multi-hop connectivity paths will become harder under such conditions. Nonetheless, irrespective of these harsh conditions, VMM is shown to be able to achieve a high path availability of 97% under the lowest possible vehicular density.

of vehicles and instructs vehicles to calibrate their speeds in such a way to expedite the formation of steady long-chained clusters that allow for packets to be rapidly forwarded from a source vehicle to the RSU through multi-hop V2V communication paths. Observe that the achieved delay is relatively higher at lower vehicular flow rates/densities. This is because, after calibration of their speeds, newly incoming vehicles have to retain and carry packets while navigating downstream at for a certain period of time until they encounter a connected cluster enabling them to forward these packets to RSU D through an end-to-end path.

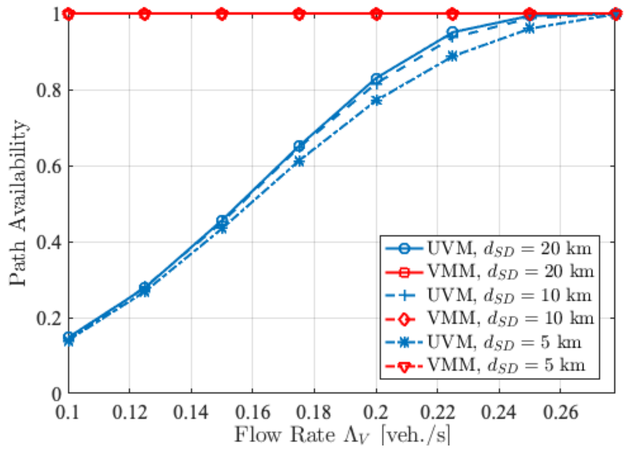

FIGURE 7. **Average packet delivery delay V.S. flow rate - Perf. Eval.**

Figure 7, plots the long-term multi-hop path availability as a function of the vehicular flow rate. The figure clearly shows that VMM remarkably outperforms UVM especially that this former achieves a quasi-constant path availability of 100% compared to the 11% (at low vehicular flow rates) to 98% (at high vehicular flow rates) counterparts achieved by UVM. Truly, under VMM, vehicular speeds are tuned in such a way to instruct vehicles to navigate at relatively higher speeds until they encounter downstream connected clusters. At that point, vehicles will decrease their speeds harmonically with the mobility of the cluster they join and maintain this constant speed until they depart from the considered roadway segment. This enhances the likelihood of steady long-chained vehicular cluster (*i.e.* multi-hop path) formation through which data packets may be routed towards the destination RSU, D. The long-term turn of similar such circumstances, enable newly incoming vehicles to readily find a path towards RSU D by means of which they can accelerate the delivery of their packets. Contrarily, under UVM, the formation of multi-hop end-to-end paths is more challenging especially whenever the considered road segment experiences lower vehicular densities (*i.e.* larger spacing among consecutive vehicles leading to the increased likelihood of link disruptions). Nonetheless, an increase in the vehicular flow rate causes a parallel increase in the path availability as vehicles become more likely to be found within each others' mutual ranges; hence, forming connected clusters.

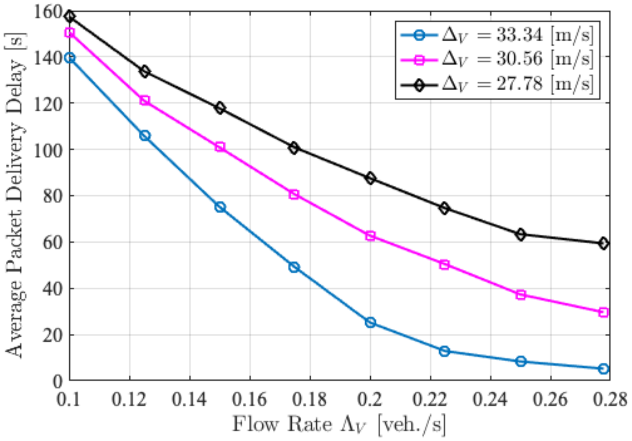

FIGURE 8. **VMM delay performance evaluation as a function of Δ_V.**

Before ending this subsection, it is important to note that, under VMM, since the speed of an arriving vehicle is temporarily increased to the maximum speed V_M (in such a way to expedite the connectivity of this vehicle to a downstream platoon), it is important to mention that the vehicle speed range $\Delta_V = V_M - V_m$ affect's the delay performance. Hence, in order to provision further insights into the delay performance variations as a function of Δ_V, the minimum speed V_m has been varied in the range [16.66; 19.44; 22.22] (m/s) to correspond to minimum speeds of 60 (km/h), 70 (km/h) and 80 (km/h) respectively (here the considered roadway will witness a relatively faster vehicular flow); hence, the values of Δ_V reported in Figure 8. It is worthwhile mentioning that similar values of Δ_V can be obtained in decreasing V_M and hence the vehicular flow will be relatively slower. Notice in this figure that the average packet delivery delay increases (*i.e. the delay performance worsens*) whenever the value of Δ_V becomes smaller. Indeed, this is because, in this case, arriving vehicles will be navigating at relatively faster (slower) speeds (since V_m/V_m increased/decreased) and hence, the contribution of the proposed VMM scheme in expediting the data delivery will become smaller but still much better than UVM. This is especially true since, under VMM, there is always room to temporarily increase the speed of arriving vehicles in such a way that they join downstream vehicular platoons faster. Obviously, in an unrealistic extreme case where all vehicles navigate at the maximum (minimum) speed, VMM will have absolutely no contribution in expediting the data delivery process since no vehicle will be able to reach a downstream vehicular platoon and hence, in this case, each and every vehicle will have to carry its own packets and deliver them through direct contact with the downstream destination RSU. The achieved delay performance in these two latter extreme cases constitute only theoretical lower and upper bounds.

C. FUTURE WORK AND PRELIMINARY RESULTS

Throughout all of the above-presented analysis it is assumed that any arriving vehicle had only one packet to transmit.

This, obviously, is a restrictive assumption that is only justified throughout the course of presenting a proof of concept. A future extension of this present work that is currently under development aims at relaxing this assumption as a first step. Indeed, realistically, vehicles may have multiple packets to transmit. As a matter of fact, the number of packets that each vehicle may require to transmit is a random variable that varies from one vehicle to another and also depends on the type of service and the duration of service required. Hence, in order to provide further realistic insights into the performance of the proposed VMM scheme herein in the context of real world sub-networking scenarios, preliminary simulations where conducted throughout which vehicles were equipped with OBUs having equal buffer sizes. The maximum buffer size is denoted by B and is varied in the range [300; 400; 500] (packets). For instance, vehicle i's buffer is initialized to be holding a random number of packets, denoted by N_P^i, that were generated upon the arrival of that vehicle to the considered roadway segment (*i.e.* upon entering the source RSU's range, a vehicle is found to be carrying a random number of packets in its buffer). N_P^i is assumed to be uniformly distributed in the range [1; B]. In addition, as a second step, this work's extension aims at catering for the necessity of servicing vehicles in a real-time manner, each packet in the vehicle's buffer is assigned a deadline being the amount of time during which the packet can tolerate being queued (ultimately waiting until it gets serviced). The per-packet deadline is drawn from an exponential distribution with average, $\overline{D} \in [100; 400; 1000]$ (seconds). The earlier presented simulator in Section V-A is used here after being amended to implement the vehicle buffers and packet deadlines. With regards to the other simulation parameters such as the vehicular traffic flow, source-destination distance and the communication range for vehicles the following values (similar to Section V-A) are used: *a*) $\Lambda_V \in [0.1; 0.2777]$ (veh/s), *b*) $d_{SD} = 10$ (km) and *c*) $R = 500$ (meters). The adopted transmission rate is 3 (Mbps) and the used MAC protocol is the IEEE 802.11p. At this point, it is important to mention that the path availability is independent of the number of packets carried by each vehicle and the respective deadlines of these packets. Hence, in terms of path availability similar results as those shown in Figure 7 apply here as well. Nonetheless, the average packet delivery delay varies and due to packets deadline expiries, packet losses may be experienced. Hence, in what follows, the system's performance will be evaluated in terms the average end-to-end packet delivery delay and the packet loss probability. Results are reported hereafter in Figures 9 through 12.

Figure 9 plots the packet loss probability versus the vehicular flow rate for the different buffer sizes that are considered. The figure shows that the packet loss probability decreases as a function of the vehicular flow rate under both VMM and UVM. However, the loss probability achieved under UVM is remarkably higher than its VMM counterpart due to the much higher path unavailability experienced by vehicles under VMM. This causes packets to queue at the vehicle buffers much longer which makes their deadlines more prone to getting expired. Now, with respect to the curves trends, indeed, as the vehicular flow rate increases the vehicular

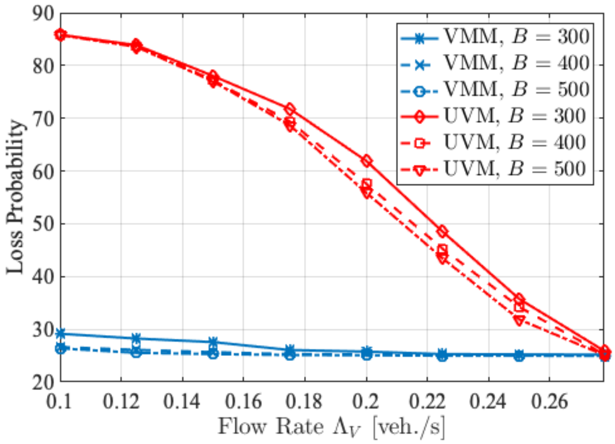

FIGURE 9. Loss probability V.S. flow rate - multiple packets with variable vehicle buffer size.

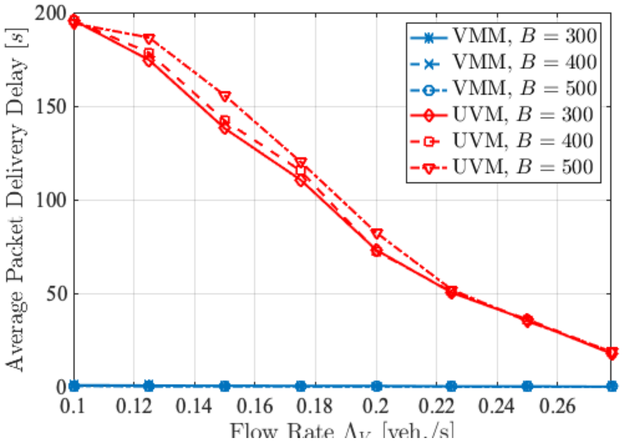

FIGURE 10. Average packet delivery delay V.S. flow rate - multiple packets with variable vehicle buffer size.

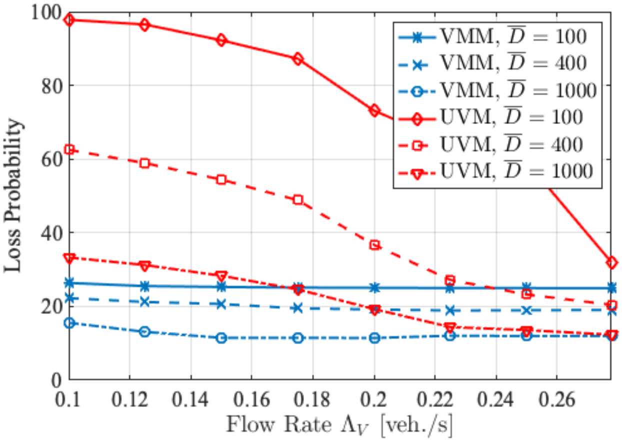

FIGURE 11. Loss probability V.S. flow rate - multiple packets with variable mean packet deadline.

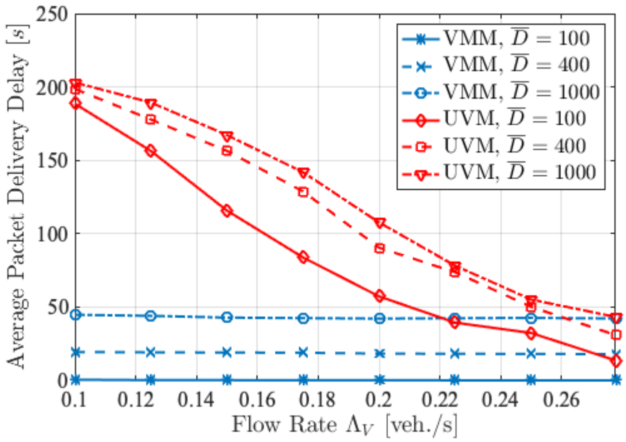

FIGURE 12. **Average packet delivery delay V.S. flow rate - multiple packets with variable mean packet deadline.**

density increases and the probability that a newly arriving vehicle will rapidly find a path to forward its packets to the destination RSU D increases. As such, packets are less likely to suffer from deadline expiries and, hence, the probability of prematurely dropping a packet (*i.e.* dropping a packet before it arrives to its ultimate destination) decreases. In addition, the figure shows that the packet loss probability decreases as the vehicles' buffer sizes increase. This is especially true since as a vehicle's buffer size increases this vehicle will have more room to accommodate original packets (if this vehicle is the source vehicle) as well as other packets that arrive from other upstream vehicles (if this vehicle is an intermediate vehicle). As a result, the probability of buffer overflow will decrease (i.e. the probability of discarding packet due to unavailable buffer space). Observe that the packet loss probability evaluated for the different values of B will converge at high vehicular flow rates (*i.e.* $\Lambda_V > 0.225$). This is because, at high vehicular flow rates, since the path availability increases, packets are less likely to accumulate in buffers. As such, buffers are less likely to be exhausted. Hence, the only factor affecting the loss probability is the probability of deadline expiry. It follows that, at high vehicular flow-rates, the buffer size has a marginal effect. Here notice that VMM outperforms UVM in terms of the packet loss probability for a variable buffer size by almost 57%.

Figure 10, concurrently plots the average end-to-end delay versus the vehicular flow rate for the various considered values of the maximum buffer size B. In addition to the fact that the average packet end-to-end delay decreases as a function of the vehicular flow rate (as discussed in Section V-B), the figure shows that the three different curves corresponding to the different maximum buffer sizes converge to almost a delay of zero under VMM. This is due to the fact that, at high flow rates, the established vehicular chains will be way longer in such a way that newly arriving vehicles will readily find a path connecting them to the destination RSU D. As such, the number of rapidly delivered packets remarkably increases versus the number of packets that have to be explicitly carried and delivered by their respective source vehicles to the RSU D through direct V2I contact. In this sense, the number of packets that are immediately (i.e. almost zero delay) delivered through multi-hop paths from a source vehicle to the RSU D is remarkably larger than the number of packets that are physically carried downstream towards the RSU. Hence the nullified average packet delivery delay. Now, under UVM the delay is much higher than VMM due to the lower path availability as explained earlier. It is worthwhile noting that VMM outperforms UVM in terms of the average end-to-end packet delivery delay by a maximum of 200%.

Figures 11 and 12 respectively plot the packet loss probability and the average end-to-end packet delivery delay achieved under both VMM and UVM versus the vehicular flow rate for the different considered average deadlines. Figure 11 shows that the loss rate decreases as a function of the vehicular flow rate. However, this decrease, under VMM, is not as pronounced when it comes to evaluating it as a function of the average deadline. Indeed, as packets are associated with larger deadlines, they will become less likely to be dropped before they arrive to their intended ultimate destination (*i.e.* RSU D). Under UVM the experienced loss probability is much higher than that achieved under VMM due to the remarkably lower path availability under UVM, which causes packets to queue for way longer times at the vehicle buffers which makes them highly prone to expiring. Figure 12 is a direct result of Figure 11, as a matter of fact, as packet deadlines are increased, this means that these packets will further extend their stay in the vehicle buffers before being delivered. This, in turn, increases the average queueing delay (an integral component of the average end-to-end delivery delay). As such, it becomes clear that the average end-to-end packet delivery delay and the packet loss probability are quasi-inversely proportional.

VI. CONCLUSION

The future of novel and revolutionary on-the-fly data communication services in intelligent transportation systems is dominated by the stringent need for end-to-end connectivity paths that will expedite the data exchange process between any arbitrary pair of communicating vehicular nodes. In this regard, this paper presents a cost-minimal Vehicular Mobility Management (VMM) scheme that stimulates the formation of steady long-chained vehicular clusters; hence, catalyzing the establishment of end-to-end data communication paths exhibiting an expedited data delivery process among pairs of communicating vehicular entities. It is demonstrated herein that the deployment of such a scheme contributes to the achievement of almost all-time data communication path availability and, thus, considerably improve the mean end-to-end data delivery delay in comparison with existing schemes. This reckons VMM's utility in promoting the steady interconnection of vehicular nodes that, in turn, provides support to a plethora of cutting edge intelligent transport services.

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