# Urban Traffic Characterization for Enabling Vehicular Clouds†

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***Abstract*—The accelerated growth of applications and services in intelligent transportation systems (ITS) are driven by interests from the public and private sectors. The intent to utilize the on-board resources, along with the advanced methods of managing the available computing capabilities in the conventional cloud, has led to the high popularity of Vehicular Clouds. Likewise in Vehicular Networks, vehicles provide the building blocks for forming these particular clouds, which can enable a large number of applications and services that can benefit the whole transportation system, as well as the drivers, passengers, and pedestrians. However, due to its high mobility, Vehicular Clouds show several inherent challenges, which increase complexity and restrict the design of solutions. Determining the number of vehicles and their time of availability in a given region through a model works as a critical stepping stone for enabling vehicular clouds, as well as any other system involving vehicles moving over the traffic network. Therefore, by implementing proper traffic models, we present a comprehensive stochastic analysis about the distribution of the number of vehicles inside a road segment in this paper. According to real parameters, we show that certain classes of applications are feasible even for highly mobile scenarios.**

## I. Introduction

Vehicular Cloud is shown as a prominent step forward for intelligent transportation systems. Due to the technological development, communication and computation capabilities have enabled the access to cloud services at any time and space. Urban traffic does not escape this trend and contains means together to compose a Vehicular Cloud autonomously, offering a myriad of benefits to drivers, passengers, businesses, pedestrians, and the transportation system. Such clouds can also be integrated into the conventional Cloud and enhance its processing power. This enhancement shows a growing potential since the number of vehicles is increasing steadily in American roadways, currently being composed of approximately 253.6 million vehicles, according to US National Transportation Statistics [1].

On the other hand, Cloud computing has been receiving significant increasing attention over the world [2] due to its flexible, on-demand provisioning of services and resources over the Internet [3]. As its main features, the Cloud mainly includes virtualization technology, resources on demand, scalability, pay as you go, and Quality of Service (QoS). Cloud computing is turning into the main technological trend in information technology (IT) territory, redefining the understanding and business models on data centers and IT investments. However, this growing area presents several challenges that need to be considered and addressed in order to be widely available, mostly on mobile environments.

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Motivated by the advantages in creating a Vehicular Cloud, a framework [4] has been initially proposed. In general, this work introduces a method to exploit vehicular resources that are not being used, such as computation power, network connectivity, and storage. However, building such a Cloud is extremely challenging due to the high mobility constrains of the vehicles, imposing a totally novel perspective in which they are built and maintained.

Determining the amount of resources, or vehicles that possibly can be in cooperation is critical for constructing, supporting, and organizing a Cloud. In this work, we present a detailed analysis about the distribution of the number of vehicles within a road segment in an urban area. Two dynamic traffic models are considered in the analysis – free flow traffic and queuing-up traffic. This model is an initial step towards implementing vehicular cloud in a very dynamic environment.

The remaining of the paper is organized as follows. Section II summarizes the concept and recent work of vehicular clouds. Section III provides the modeling and analytical results of the study; this section is composed of two subsections, the first subsection focuses on the free-flow traffic scenario, and the second one works on the queuing-up traffic scenario. Finally, Section IV concludes the paper and presents remarks for future research directions.

## II. Related Work

Besides the advantages that the access to the Cloud might bring to vehicles, the extra or unused available resources each vehicle contains show a great potential for building or joining Clouds autonomously. This promising feature can allow vehicular clouds to easily access and to generate joint computing capabilities, which are necessary to solve complex issues in real-time. In general sense, Vehicular Clouds have been considered a paradigm shift, being a valuable mechanism that can greatly contribute to the whole society [5].

This perspective of paradigm shift is originated from the concept that vehicular cloud is a natural evolution from vehicular networks (VANETs) [6]. In the scope of ITS, vehicular networks has steeply grown in popularity with advancements of technologies and the extensive array of applications it can enable. Expanding Mobile Ad-hod Networks, VANETs present some diversities on its structure [7], ranging on V2I and V2V. Initially, VANETs have focused on solutions for early notifications to avoid traffic hazards or unpleasant driving experience [8] wherein vehicles by themselves work on gathering real-time data and disseminating to the rest of the network [9]. VANETs have extended the scope of the safety to a wide range of applications, such as in entertainment and security.

Vehicular Cloud has been first introduced in [10], [4], [5], however, most of the works in this area aim at discussing taxonomies, open issues, possible applications, architectures, and development challenges [11]. On the other hand, there are many significant speculations on several applications [5] and services. Vehicular cloud can offer primary services classified as Storage as a Service (STaaS) [12], [13], [14], Network as a Service (NaaS) [15], Computation as a Service [12], and Cooperation as a Service (CaaS) [16].

In terms of Vehicular Cloud applications, by harnessing vehicle's excessive computation capability, a datacenter can be built from the vehicles resting in a parking lot. A dynamic traffic management system is another known conceptual application that can be created using vehicles [4]. This system can support the mitigation of traffic congestion by utilizing the computational power of vehicles located at the traffic jam. Based on these examples, the applications are divided into two large categories [14]: less-dynamic vehicular cloudlets and highly-dynamic vehicular clouds.

A work [12] has been developed in the context of less-dynamic vehicular clouds by estimating the time vehicles stay in long-term parking lot an airport. In this context, vehicular cloud are very similar to the conventional clouds, which just aggregates still available resources. The work summarizes in determining a stochastic process with time-varying arrival and departure rates, which are used to model the number of computing nodes for a datacenter. On the other hand, there is no work that attempt to implement a dynamic vehicular cloud, so an initial step has been taken to model the expected number of vehicles in a road segment in [17], providing means to determine the feasibility of the model in real environments. However, a deeper analysis is needed to define the amount of resources and their availability for better harnessing their power for building a cloud.

## III. Stochastic Modeling and Analytical Results

The ability to predict the amount of available computational resources within a roadway segment, given the random arrivals and departures, is one of the fundamental requirements for building and maintaining a dynamic Vehicular Cloud. Two traffic scenarios shaped by different conditions are observed: free flow traffic and queuing-up traffic.

The vehicular density in free-flow traffic tends to be low or medium since there are no factors hampering the movement of vehicles in the segment; consequently, vehicles are more likely to be vastly isolated, composing a scattered display on roads. In other words, the vehicle arrivals to a specific geographical reference point is represented according to an independent identical distribution (i.i.d). On the other hand, the queuing-up traffic scenario usually appears in a downtown area, showing a higher chance of high vehicle density in the road segment.

### A. Free Flow Traffic

To have an approximate estimation about computing resources in Vehicular Cloud, it is essential to characterize the dynamics of the number of cars inside the road segment. The quantity of vehicles can be modeled by a counting process $\{N(t)|t \geq 0\}$ of continuous time parameter $t$. The event $\{N(t) = i\}$ stands for the road segment containing $i$ vehicles at time $t$, and the probability that this situation happens is denoted as $P_i(t) = P\{N(t) = i|t \geq 0\}$. Assume that $s$ is the total number of arrivals during the time range $(0, t)$ and that $p(t)$ is the probability that a vehicle is still in the road segment $[SD]$ at time $t$. Using the theorem on total probability, the distribution of number of vehicles contained in the road segment $[SD]$ can be expressed as described in Formula 1.

$$P_n(t) = \sum_{s=0}^{\infty} P_{n|s}(t) \cdot M_s(t) = \frac{[\mu t \cdot p(t)]^n e^{-\mu t \cdot p(t)}}{n!} \tag{1}$$

where $M_s(t)$ denotes the probability of $s$ vehicles that arrived in the interval $(0, t)$; $P_{n|s}(t)$ represents the probability of $n$ vehicles within the road segment at time $t$ provided the total number of $s$ vehicle arrivals during the time period $(0, t)$; and $\mu$ (*veh/s*) designates the arrival rate of vehicles in the road segment.

Based on the model described in [17], a vehicle might arrive at the segment [SD] in the interval $\tau(0 < \tau \leq t)$. The probability of finding this vehicle in [SD] at time $t$ is delimited by Formula 2.

$$P(u > t - \tau) = 1 - P(u \leq t - \tau) = 1 - F_T(t - \tau) \tag{2}$$

Therefore, in the long term represented by $t \to \infty$, we can obtain the tendency described in Formula 3.

$$t \cdot p(t) = t \cdot \int_0^t [1 - F_T(t - \tau)] \cdot \frac{1}{t}\, d\tau = E(T) \tag{3}$$

In Formula 3, we employed the property of Poisson process. This allows us to determine that if the number of arrivals in the interval $(0, t)$ is $s$. Therefore, the arrival times of individual vehicles are distributed independently and uniformly in the time interval. The closed form of probability mass function (pmf) of number of vehicles within the road segment can be derived by substituting Formula 3 into Formula 1, which is shown in Formula 4.

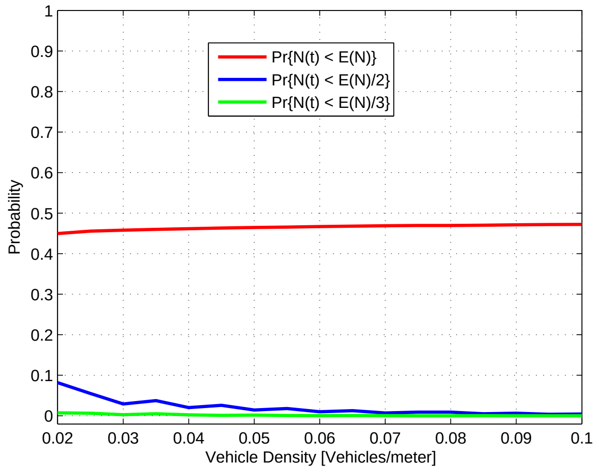


Fig. 1: The Probablity $P[N(t)]$

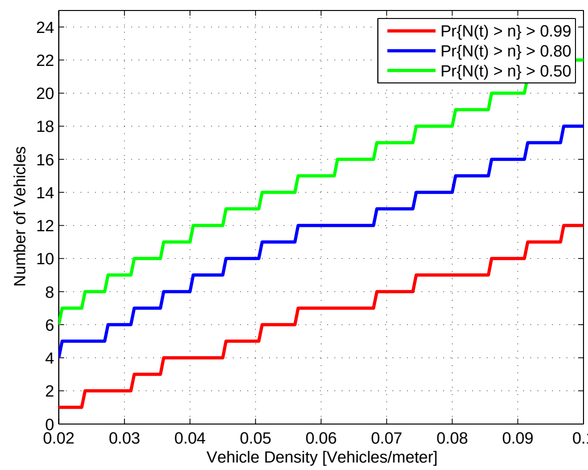


Fig. 2: Number of Vehicles vs Vehicular Density

$$P_n = \frac{[\mu E(T))]^n e^{-\mu E(T)}}{n!} \tag{4}$$

where $E(T)$ denotes the expected value of residence time of a vehicle in the segment.

From Formula 4, it can be noticed and assured that the number of vehicles in a road segment follows a Poisson process in the long run. Moreover, this process is totally independent of the velocities of vehicles; no matter what velocity distribution is employed to represent the mobility within the road segment, the number of vehicles is Poisson distributed. This distribution is consistent with the results in [17], which describes the expected number of vehicles in a [SD]. It is also important to investigate the limiting behaviour of the variance of the stochastic process $\{N(t)|t \geq 0\}$. In other words, when $t \rightarrow \infty$ and the effect of the initial conditions has worn off, based on the properties of Poisson distribution, the variance $VAR(N)$ tends to be stable and can be expressed as $VAR(N) = \mu E(T)$.

When $VAR(N)$ is compared with the expected value in [17], it is observed that the limiting behaviour of expected value $E(N)$ and variance $VAR(N)$ correspond to the same value. For instance, from *"Average Number of Vehicles versus Road Length"* in [17], we can see that the average number of vehicles is approximately 14 when the vehicle density of the road segment is $\rho = 0.05$. At the same time, the variance is stabilized at 14, which is considerably large if considering the case that the expected value is also 14. Therefore, we need to demonstrate that there is a negligible probability that the number of vehicles in a road segment is low, despite the large variance of $N(t)$.

We investigate the three sets of probabilities in our analysis. For each analysis, we adopt the same experimental parameters as those in [17] and compute the probability values according to the free-flow scenario. Figure 1 shows that the probability $Pr[N(t) < E(N)]$ tends to 0.5 as the vehicle density in the road segment increases. This tendency is an expected result because $VAR(N)$ and $E(N)$ are both equal to $\mu E(T)$ for the defined Poisson process. The probability that the number of vehicles within [SD] is less than half of the expected value, which is the value of 0.08 when the vehicle density in the segment corresponds to $\rho = 0.02$ (*vehicles/meter*). The expected value quickly decreases to 0 with the increase of vehicle density ($\rho$). For instance, if the expected value of $N(t)$ is delimited as 12 when the vehicle density is $\rho = 0.04$, then the probability $Pr[N(t) < 6]$ is equal to 0.02. This means that we can assure with probability of 0.98 that there are more than 5 vehicles within [SD]. Furthermore, $Pr[N(t) < E(N)/3]$ remains close to 0 for any value of vehicle density in the road segment. This implies that the probability of the event that there are at least $E(N)/3$ vehicles in the road segment is 100%. In other words, it is guaranteed that there are at least $E(N)/3$ vehicles within [SD] at any time for our utilization.

Figure 2 demonstrates the probability of the number of vehicles running inside the segment, which represents the amount of available computing resources within [SD]. For instance, when the vehicle density is equivalent to $\rho = 0.06$, there are at least 7 vehicles within [SD] for the reason that $Pr[N(t) > 7] > 0.99$. In addition, with probability 0.80, the number of vehicles is more than 12 within [SD]. Furthermore, the event that more than 15 cars navigate in [SD] occurs with probability 0.5.

### B. Queuing-up Traffic

From the stochastic process perspective, when the arrival rate is greater than the departure rate, the queue is bound to form up. Queuing process [18] is used to model the queuing-up traffic and thus to calculate the mean number of vehicles in the queue.

Considering an one-lane roadway segment, we assume that the arrival of vehicles can be represented as a Poisson process with rate $\lambda$, so the inter-arrival times are exponential random variables with mean $1/\lambda$. Assume that the time it takes for a vehicle to pass by the endpoint of the segment, such as an intersection, a construction site, or any distinguishable point on the segment, follows a general distribution, and we call this period of time as the leaving time ($\tau$) of a vehicle.

The steady-state queuing system is considered in this scenario, which means that the state probabilities for this queuing system do not depend on initial conditions. In this case, the

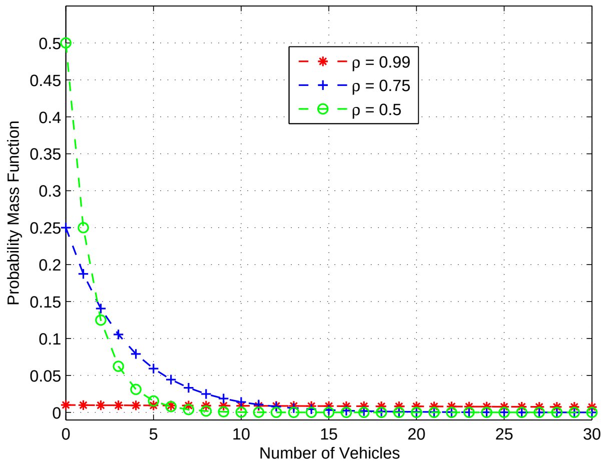


Fig. 3: PMF of No. of Vehicles-Exponential Leaving Time

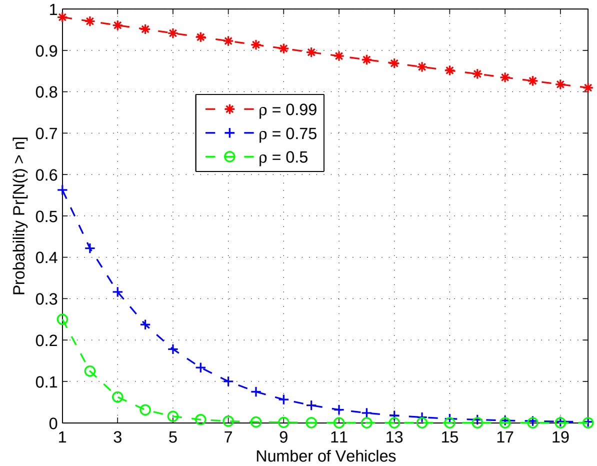


Fig. 4: Pr[N(t)>n] with Exponential Leaving Time

average length of the queue maintains a constant value. We defined $\rho$ as the traffic intensity, which means the expected number of vehicular arrivals $E(V)$ during the mean leaving time $E(\tau)$. Since the arrival process $V$ is a Poisson with an average of $\lambda$ arrivals in unit of time for a given $\tau$, the variable $V$ presents a Poisson distribution with mean $\lambda\tau$.

In order to have a full image of the number of vehicles in the queue, we have decided to investigate, experimentally, the distribution of queue length and waiting-time. We use Pollackzek-Khinchin transform formula to derive the explicit form of the distribution in this particular case.

$$G_N(z) = \frac{(1-\rho)(z-1)b^*(\lambda(1-z))}{z - b^*(\lambda(1-z))} \tag{5}$$

where $G_N(z) = \sum_{k=0}^{\infty} Pr[N = k]z^k$ is the generating function for $N$, $\rho$ is the traffic intensity, $\lambda$ is the arrival rate, and $b^*(s)$ is the Laplace transform of the leaving time probability density function (pdf). If the leaving time, $\tau$, is exponentially distributed with mean value $1/\mu$, the pdf can be expressed as $f_\tau(t) = \mu e^{-\mu t}$, so the Laplace transform of $f_\tau(t)$ is

$$b^*(s) = \int_0^\infty e^{-st} f_\tau(t)\, dt = \frac{\mu}{s+\mu} \tag{6}$$

$G_N(z)$ can be derived by combining Formula 5 and Formula 6.

$$G_N(z) = \frac{(1-\rho)(z-1)\frac{\mu}{\lambda(1-z)+\mu}}{z - \frac{\mu}{\lambda(1-z)+\mu}} = \sum_{n=0}^{\infty}(1-\rho)\rho^n z^n \tag{7}$$

where we used the condition that ($\rho < 1$ and $|z| < 1$). Formula 7 implies the pmf of the number of vehicles $N(t)$ is

$$p_n = (1-\rho)\rho^n \; (n \geq 0) \tag{8}$$

Figure 3 shows the probability mass function (pmf) of number of vehicles in the queue when the leaving time is exponentially distributed; this probability includes the departing vehicles in the segment. Given that we are focusing on the equilibrium scenario, the traffic density has to satisfy the condition $\rho = \frac{\lambda}{\mu} < 1$. If $\rho = 0.5$, which means the departure

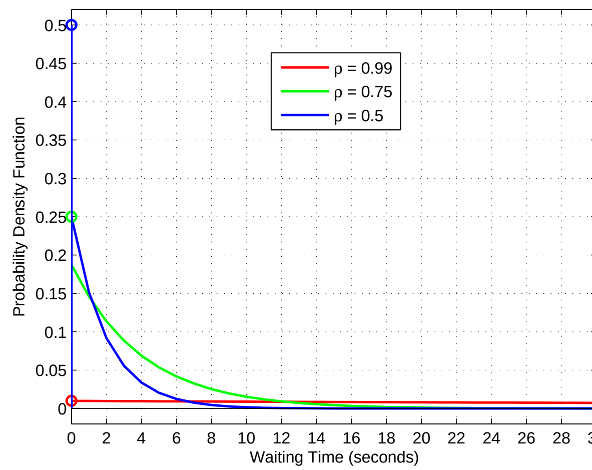


Fig. 5: PDF of Waiting Time with Exponential Leaving Time

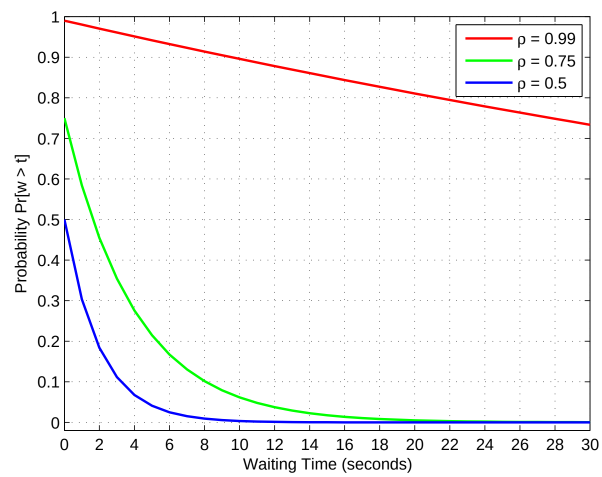


Fig. 6: Pr[W(w)> t] with Exponential Leaving Time

rate is twice as much as the arrival rate, the traffic queue is less likely to be built up. From the graph of the figure, it is noticeable that with probability $0.5$ the number of vehicles in the queue is $0$. When the arrival rate is very close to but less than the departure rate ($\rho = 0.99$), the pmf presents itself similar to a uniform distribution. Therefore, the number of vehicles in the queue could be very large since it shows the same probability of the event that the small number of vehicles waiting in the queue. Figure 4 demonstrates the probability of the number of queuing vehicles is more than a specific number. For instance, when $\rho = 0.5$, it is impossible to have more than 5 cars in the queue, and $P[N(t) > 13]$ is close to 0 when $\rho = 0.75$. In the other hand, if $\rho = 0.99$, the event that the number of cars in the queue is more than 20 occurs with the probability 0.82. It is reasonable to infer that the traffic queue is forming up in this case, and we have higher chance to reach more computing resources in the roadway segment.

Similarly, we can get the probability density function of waiting time by using the Pollackzek-Khinchin transform formula 9 related to waiting time in the queue.

$$c^*(s) = \frac{(1-\rho)s}{s-\lambda+\lambda b^*(s)} \tag{9}$$

where $c^*(s)$ is the Laplace transform of the waiting time pdf $f_W(w)$. Substituting $b^*(s)$ with Formula 6, we have

$$c^*(s) = (1-\rho)\frac{s+\mu}{s+\mu-\lambda} = (1-\rho)\left(1+\frac{\lambda}{s+\mu-\lambda}\right) \tag{10}$$

Then, we obtain the pdf of waiting time by conducting the reverse Laplace transform of Formula 10.

$$f_W(w) = (1-\rho)\delta(w) + \rho(\mu-\lambda)e^{-(\mu-\lambda)w} \quad w > 0 \tag{11}$$

where the delta function at $w = 0$ corresponds to the fact that a car has zero waiting time with probability $1-\rho$.

Assuming $\mu = 1$ vehicle/second, Figure 5 shows the pdf of the waiting time in the queue when the leaving time is a random variable with exponential distribution. It is consistent with pmf in Figure 3, in which 50% of the vehicles pass the road segment without waiting in the queue when traffic intensity is $\rho = 0.5$. Even if there is a queue on the road, the waiting time seems to be trivial. On the contrary, the waiting time is uniformly distributed within a large time frame when $\rho = 0.99$, which means the waiting time could be very large since the arrival rate is almost the same as the the departure rate. Similarly, Figure 6 describes the probability that the waiting time is longer than a specific period of time. For instance, the probability that the waiting time for a vehicle in the queue is longer than 8 seconds is zero when $\rho = 0.5$, and the vehicle necessarily needs to wait for more than 30 seconds in order to pass the road segment when $\rho = 0.99$ with probability 0.75.

Next, we focus on the deterministic leaving time and assume leaving rate is 1 vehicle/second. Therefore, $\rho = \frac{\lambda}{\mu} = \lambda$. By Formula 5, we have

$$G_N(z) = \frac{(1-\lambda)(z-1)exp(\lambda(z-1))}{z-exp(\lambda(z-1))} \tag{12}$$

where we use the fact that the pdf of constant random variable, a degenerate distribution, is a delta function at $t = 1s$ (first vehicle leaves at $1s$).

Based on deduction process in [19], the explicit form of pmf of the $N(t)$ is given by the Taylor expansion of Formula 12.

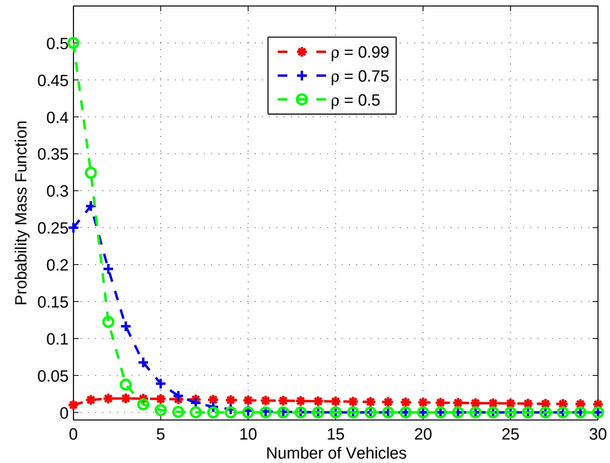


Fig. 7: PMF of No. of Vehicles-Fixed Leaving Time

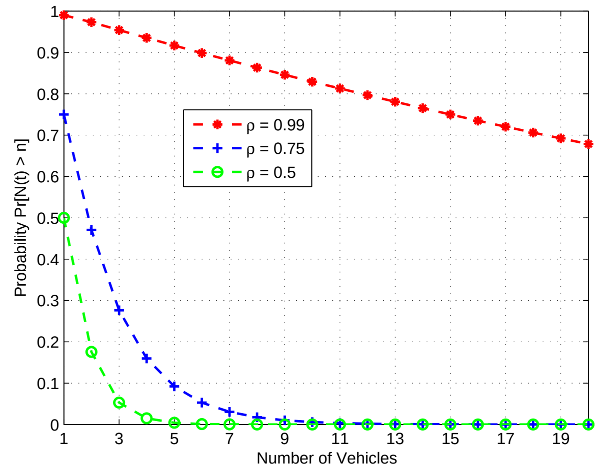


Fig. 8: Pr[N(t)>n] with Fixed Leaving Time

Figure 7 and Figure 8 demonstrate the distribution of the number of vehicles in the queue when the leaving time is a constant. We can compare this case with the scenario in which the leaving time is exponentially distributed. When the value of $\rho$ is low, there is not too much difference between these two scenarios. When the traffic intensity is high, with $\rho = 0.99$, and when the leaving time is fixed, the probability that the number of cars in the road segment is larger than 20 is 68%, and the corresponding probability for the exponentially distributed leaving time scenario is 82%. The result matches with [17], which states that the average number of vehicles for the exponentially distributed leaving time scenario is larger than that of the fixed leaving time scenario.

Similarly, we can also use Formula 9 to determine the waiting time distribution if the leaving time is a constant value.

$$c^*(s) = \frac{(1-\lambda)s}{s-\lambda+\lambda e^{-s}} \tag{13}$$

where we assume the leaving rate $\mu$ is 1 vehicle/second and $b^*(s) = e^{-s}$ due to the pdf of the leaving time is a delta function $\delta(t-1)$. It is hard to get the closed-form expressions for the pdf of waiting time since $c^*(s)$ is not a rational function of $s$. However, Formula 13 can be inverted numerically using fast Fourier transform methods.

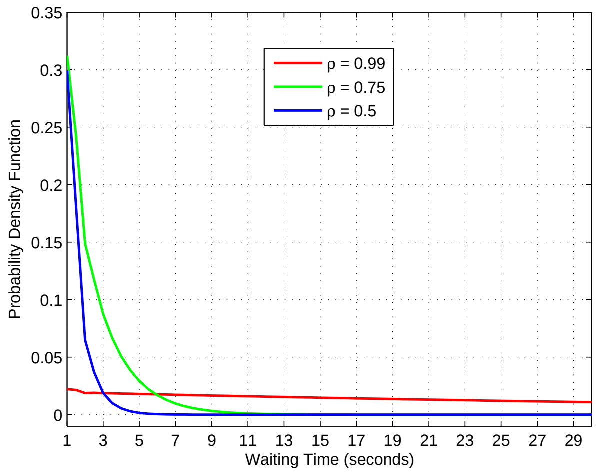


Fig. 9: PDF of Queue Waiting Time with Fixed Leaving Time

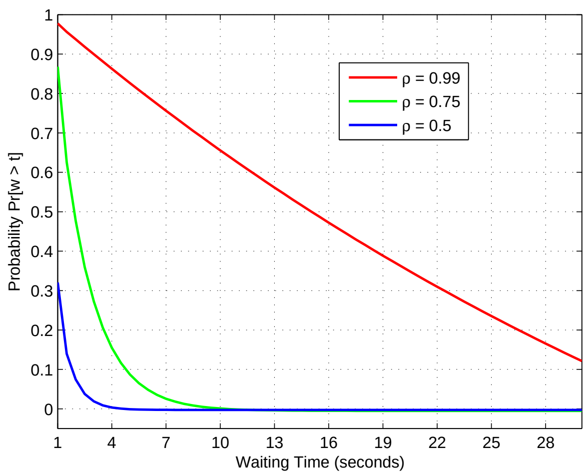


Fig. 10: Pr[W(w)>t] with Fixed Leaving Time

Figure 9 and 10 are the numerical results of the waiting time distribution. When compared to the exponential leaving time scenario, it shows that the waiting time is shorter, which is consistent with the average waiting time information in [17].

## IV. Conclusion And Directions For Future Work

In this paper, we described an work on the modeling of the possible traffic scenarios taking a significant step towards the implementation of a Vehicular Cloud, namely collecting the computing resources of moving vehicles in a rather dynamic environment, a roadway segment. We analyzed free-flow traffic and queuing-up traffic scenarios in order to cover the most common situation in an urban environment. The main objective of this work is to provide the distribution of the number of vehicles inside a road segment and the corresponding analytical results concerning the availability of computational resources and capabilities in such scenarios. The analysis demonstrated that conditions in which favour most the utilization of resources of vehicles. These results can also be employed in several other contexts in which the mobility of vehicles is crucial for delivering services and applications.

There are a couple of interesting directions for future work. For the free-flow traffic, we shall move on to simulations using a third-party simulation tool to determine the process of distribution of the computational tasks to the available vehicles in a roadway segment. For the queuing-up traffic, we focused on causes and consequences derived from queuing-up vehicles in a road segment. An one-lane road segment was used where the equilibrium was achieved. We shall explore scenarios composed of roadway segments with multiple lanes, also covering a non-equilibrium queue, which would substantially grow the complexity of the model.

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