

Vehicular Cloud: Stochastic Analysis of Computing Resources in a Road Segment

by

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Abstract

Intelligent transportation systems aim to provide innovative applications and services relating to traffic management and enable ease of access to information for various system users. The intent to utilize the excessive on-board resources in the transportation system, along with the latest computing resource management technology in conventional clouds, has cultivated the concept of the Vehicular Cloud. Evolved from Vehicular Networks, the vehicular cloud can be formed by vehicles autonomously, and provides a large number of applications and services that can benefit the entire transportation system, as well as drivers, passengers, and pedestrians. However, due to high traffic mobility, the vehicular cloud is built on dynamic physical resources; as a result, it experiences several inherent challenges, which increase the complexity of its implementations.

Having a detailed picture of the number of vehicles, as well as 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. The number of vehicles represents the amount of computation capabilities available in this region and the navigation time indicates the period of validity for a specific compute node. Therefore, in this thesis, we carry out a comprehensive stochastic analysis of several traffic characteristics related to the implementation of vehicular cloud inside a road segment by adopting proper traffic models. According to the analytical results, we demonstrate the feasibility of running a certain class of applications or services on the vehicular cloud, even for highly dynamic scenarios.

Specifically, two kinds of traffic scenarios are modeled: free-flow traffic and queueing-up traffic. We use a macroscopic traffic model to investigate the free-flow traffic and analyze the features such as traffic density, the number of vehicles and their residence time. Also, we utilize the queueing theory to model the queueing-up traffic; the queue length and the waiting time in the queue are analyzed. The results show the boundaries on enabling vehicular cloud, allowing to determine a range of parameters for simulating vehicular clouds.

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Publications Related to Thesis

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Chapter 1

Introduction

Due to the advent of cloud computing and the maturity of its technology, various users are able to access services at any point in time and space. The emergence of a new type of cloud—the vehicular cloud—has been a prominent step forward for intelligent transportation systems. The vehicular cloud is formed autonomously by the traffic on the road, and each vehicle serves as a compute node for the cloud, which offers a great number of benefits not only to drivers, passengers, and pedestrians but also to the municipal traffic manager and city planners. Those self-organized clouds can work independently, as well as complementing to the conventional cloud structure and providing processing power to deal with the traffic-related issues. This trend is quite promising, due to the sky-high increase in the rate of the number of vehicles on the road. According to US National Transportation Statistics [95], the number of vehicles in American roadways, has reached 253.6 million. Harnessing the excessive computing power of those vehicles has a profound significance for information technology (IT), the economy and society.

1.1 Background

Thanks to the revolutionary change in the automotive industry, an increasing number of "smart vehicles" are introduced to drivers for daily use. A typical vehicle today is regarded as a "computer-on-wheels" due to the reason that it is likely to equip with a powerful on-board computer, a large capacity storage device, a sensitive radio transceiver, a rear collision radar and a GPS device. Meanwhile, rapid technological advances in cloud computing [77] provide sufficient technical support for building a dynamic cloud in mobile environments. Cloud can provision resources and services on-demand over the Internet, just like a public utility [52]. Amazon Elastic Compute Cloud (Amazon EC2) is now the largest online retailer to provide dynamic compute capacity in the cloud. On the other hand, an increasing number of businesses prefer to rent their servers, platforms or software in an elastic and scalable manner, instead of purchasing and maintaining them by themselves [10]. The reciprocal benefit accelerates the prosperity of cloud computing, whose main features include pay-as-you-go, virtualization technology, resources on demand, scalability and Quality of Service (QoS). As a result, cloud computing is becoming the main technological trend in IT, and enterprises nowadays invest massive effort in migrating their services to the cloud.

Motivated by the above-mentioned facts and opportunities, the vehicular cloud framework was initially proposed in [79]. In general, various underutilized vehicular resources such as computing power, network connectivity, sensing capability, and storage can be shared with car owners. Moreover, the aggregated resources can be rented to potential consumers following a specific business model, similar to the traditional cloud infrastructure.

Figure 1.1 shows two types of vehicular cloudlet, which is defined as a group of vehicles can share resources with each other via vehicle to vehicle (V2V) communication

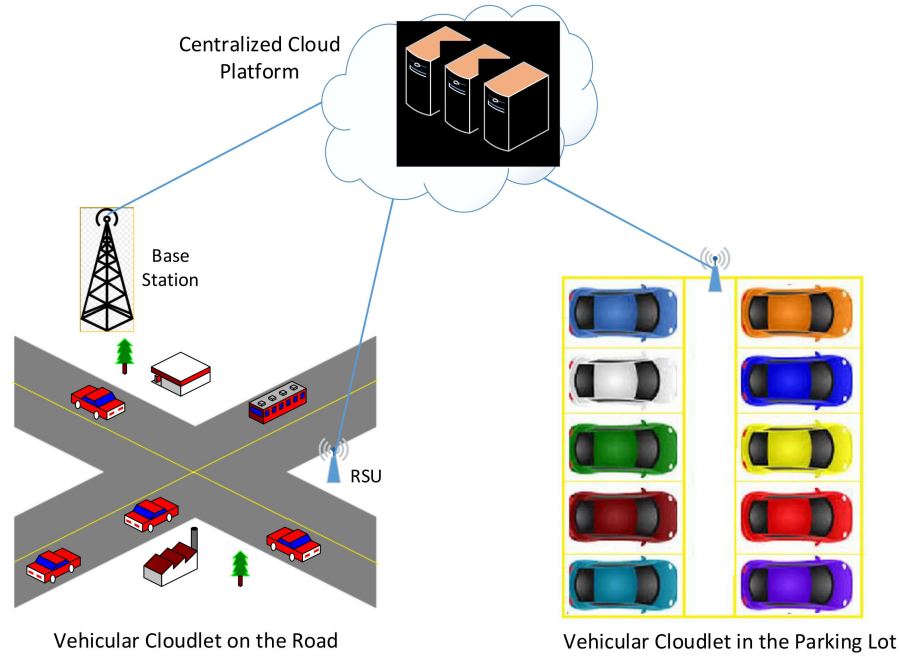


Figure 1.1: Vehicular Clouds

or vehicle to infrastructure (V2I) communication. The vehicular cloudlet on the road (mobile cloudlet) consists of moving vehicles while the cloudlet in the parking lot (static cloudlet) is formed by statically parked ones. Each type of cloudlet is suitable for hosting a series of vehicular cloud services. For example, the mobility of vehicles in the highway makes the mobile vehicular cloudlet ideal for data dissemination service; the vehicle cloud constructed by the vehicles waiting in the queue can be utilized to run the traffic management application in order to ease the traffic congestion; the static vehicular cloudlet has relatively stable computing and storage resources and, therefore, can be used for provisioning the conventional cloud services.

1.2 Problem Statement

Although the functionality of vehicular clouds may be very similar to the conventional clouds from the perspective of utilization, the following distinguishing characteristics

make it unique and not easy to deal with.

- The most challenging aspect of building vehicular cloud is dealing with the highly dynamic availability of the vehicles, which distinguishes the vehicular cloud architecture from traditional cloud models. The autonomous cooperation among vehicles and their “*decentralized*” management contribute to the complexity and uniqueness of the vehicular cloud.
- Accurately determining the amount of vehicles and their available time frame is critical for constructing a vehicular cloud. The analysis of the availability of resources in this particular scenario is totally and directly involved with the perception of the traffic flow for a given area, such as a road segment, during a time span. Nevertheless, the number of vehicles varies continually, since the same vehicles move dynamically, with diverse traveling times, behaviors, and speeds.
- Since the vehicular clouds are not as stable as the conventional clouds, the resource management system (see Fig 1.2) of vehicular cloud should be able to predict the amount of the available computing capabilities, and the task scheduling system needs to schedule the computation tasks on the dynamic resources for the sake of providing consistent service to the authorized customers.

1.3 Contribution

The main contribution of this thesis is a detailed stochastic analysis about the distribution of the vehicles and their available time range within a road segment in an urban area. Two specific traffic scenarios are considered – free flow traffic and queueing-up traffic, as depicted in Figure 1.3. These two scenarios are very common traffic situations nowadays in the urban roadways of metropolitan cities.

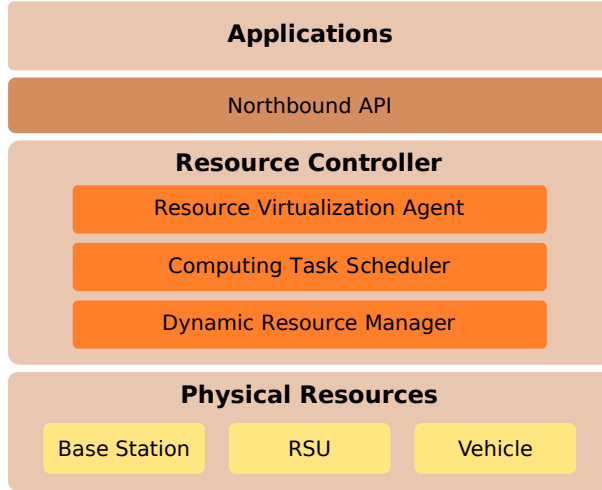


Figure 1.2: Vehicular Cloud Resource Management Layers

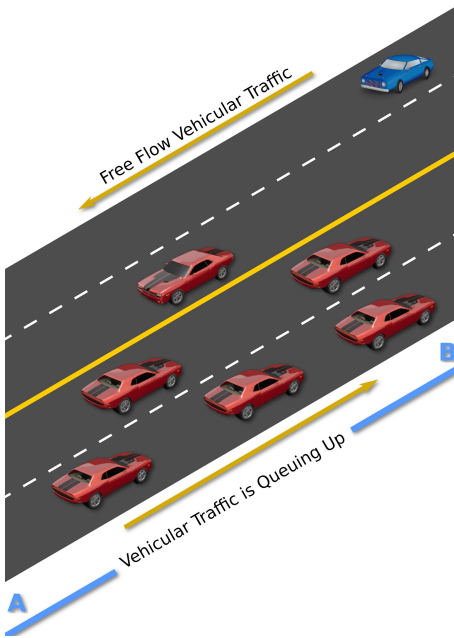


Figure 1.3: Traffic conditions under the flow of vehicles in road segment

This is a preliminary step towards utilizing excessive vehicular resources and constructing the vehicular cloud in a highly dynamic environment. Specifically,

- To analyze the specific features and characteristics of vehicular cloud, we study and classify the existing related works of VANETs, cloud computing and vehicular cloud. Comparison of these technologies reflects the evolution of the concept of vehicular cloud. The information is presented and summarized in an appropriate way.
- A macroscopic model in [60] is utilized as a base to analyze the features of free-flow traffic in a roadway segment. We first obtain the average number of vehicles, then we get the distribution of the number of vehicles inside the road segment.
- We use the queue theory to model the queueing-up traffic. The analytical form of the length of the traffic queue and the waiting time of vehicles are presented. Those two features are important for the reason that they represent the amount of available computation resource and their valid time, respectively.
- Based on the models, we carry out the comprehensive analysis of several traffic characteristics related to the implementation of vehicular clouds for both traffic scenarios.

1.4 Thesis Organization

The remainder of this thesis is organized as follows:

- Chapter 2 surveys the state-of-the-art technology of vehicular cloud computing. We highlight Vehicular Cloud, an extension of traditional Cloud Computing with many inherent new features. In addition, we present a comparative study between

cloud computing and vehicular cloud computing as well as explaining the vehicular cloud computing architecture, autonomous cloud formation, and the potential applications.

- Chapter 3 provides the mathematical modeling of the study. This chapter is composed of two sections; the first focuses on the free-flow traffic scenario and the second works on the queueing-up traffic scenario.
- Chapter 4 demonstrates the analytical results, and presents the detailed analysis of each scenario.
- Chapter 5 concludes the results and describes our future directions of research.

Chapter 2

Related Work

Evolved from Vehicular Ad-Hoc Network (VANET), presently, vehicular cloud computing (VCC) has received much attention. VCC is an attractive technology, which takes advantage of cloud computing to support many novel applications. Therefore, the objectives of VCC are to offer various computational services at low cost to the authorized users, to ease traffic congestion and to improve road safety. In this chapter, we provide a survey of VCC and our aim is to help readers better understand the fundamental vehicular cloud computing mechanisms.

The flow chart 2.1 classifies existing techniques that are contributing towards the generation of vehicular cloud computing, which can be seen as a combination of two technical paradigms i.e., ad hoc network and cloud computing.

All nodes in wireless ad hoc networks can be dynamically connected in an arbitrary manner. As the transmission range of each node is limited and different [29] [28], the sender may need the aid of its neighboring nodes to forward the packets to the receiver. Since wireless ad hoc networks do not rely on pre-installed static infrastructure for communication, the localization of the nodes becomes one of the major issues [17] [36] [21] [80] [18] [14], especially in MANETs where the nodes are mobile. All nodes in the ad

hoc networks behave as routers, which discover and maintain the routes to the next hop in the network. Therefore, the routing protocols are vital for enhancing the efficiency and reliability of the dissemination of packets [98] [26] [31] [25] [19]. Other challenges of ad hoc network include security [15] and energy consumption [91] [30]. Compared to the traditional ad hoc networks, mobile ad hoc networks (MANET) are more dynamic since the nodes are not fixed [22] [23] and the Vehicular Ad-hoc Network (VANET) primarily adapts from Mobile Ad hoc Networks (MANETs) [24] [88] where the communication among the nodes is generally single hop or multi-hop based.

On the other side, distributed computing and grid computing [6] [27] [16] have enormously contributed to the emergence and prosperity of cloud computing; and the concept of VCC originates from Mobile Cloud Computing (MCC) where the main concern is to access traditional cloud services provided by Infrastructural-Cloud in a way similar to access telecommunication and other data based services.

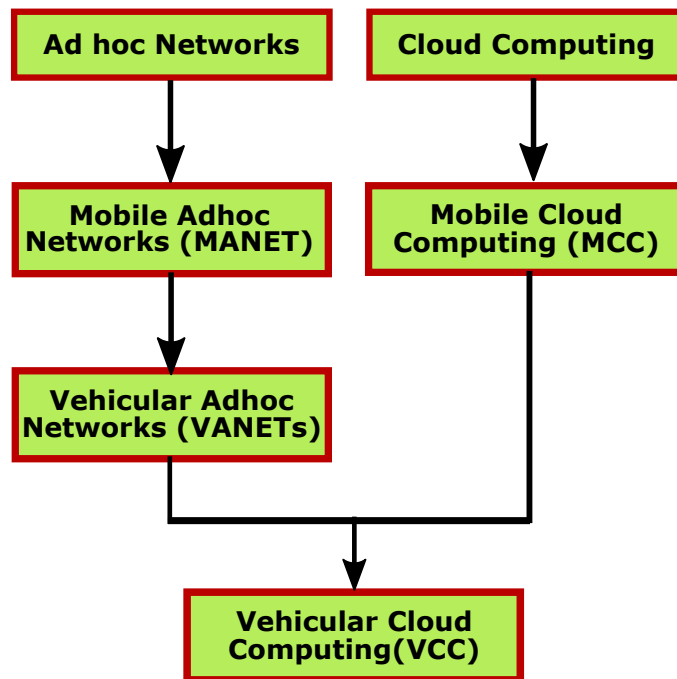


Figure 2.1: Technologies Contributing Towards Vehicular Cloud Computing

2.1 Vehicular Network

Traffic congestion in the urban area is a daily event, the growth in the number of vehicles on the road has put huge stress on transportation systems and this tremendous growth of vehicles has lead to unsafe and unpleasant driving experience. Most of the time, we are not alerted by beforehand notification of congestion. Thus, existing transportation infrastructure requires improvements in traffic safety and efficiency. The municipal traffic management department has planned various solutions such as expanding lanes on highways and reducing the number of stop signs and traffic lights to reduce traffic congestion. However, those solutions are ineffective and may even increase congestion and pollution levels. The cutting edge technological advancements have been considered to enable such diverse traffic applications as traffic hazard detection, cooperative traffic monitoring, and control of traffic flow. Inspired by Mobile Ad-hoc Networks [68], a new kind of network, which incorporate Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication, is named as Vehicular Ad Hoc Network (VANET), which has been considered as an excellent network environment for Intelligent Transportation System (ITS).

2.1.1 Architecture of VANET

Figure 2.2 shows the architecture of VANET. The V2V and V2I communication are achieved through a device called Wireless Access in Vehicular Environment (WAVE). Specifically,

- V2V are communications between vehicles in ad hoc mode [58]. A vehicle can transmit or receive useful traffic-related messages such as traffic accidents and road conditions to/from other vehicles.
- V2I is used for the valuable information exchange between vehicles and fixed net-

work infrastructure [58]. In this mode, a vehicle could communicate with external networks such as the Internet by utilizing RSU as a gateway. V2I links are more secure and require more bandwidth than V2V links.

In addition, the 5.9 GHz frequency spectrum band has been allocated for Short Range Communication (DSRC) between vehicles [7]. The main components of the architecture are on-board units (OBUs), road side units (RSUs) and certification authorities (CAs).

- OBU, along with a set of sensors, resides in each vehicle and it collects the information of the vehicle and transmits information such as the position, speed and acceleration/deceleration to other vehicles or RSUs through the wireless medium. At the same time, OBU also receives the messages from other sources and has the ability to verify the incoming message and avoid security attacks.
- RSU is a physical communication equipment at a fixed location and responsible for collecting and disseminating traffic-related information such as the length of the traffic queue, accident spot ahead and nearest parking lots and gas stations. RSU is equipped with at least one network device for the Internet and short-range wireless communication. RSU acts as a gateway for the OBU to access the Internet, which also enables vehicles within the communication range to establish Internet connections. RSU can be deployed along the road to monitor the traffic flow or in the road intersections to offer help in coordinating the traffic lights and collecting information about vehicle activities.
- To prevent the possible security problems in VANETs [74], CA has the information of all vehicles in order to verify that the source of the message is a valid entity. It is vital for the performance of VANET and should be a fully trusted party; for instance, the municipal transportation department could play the role as a CA.

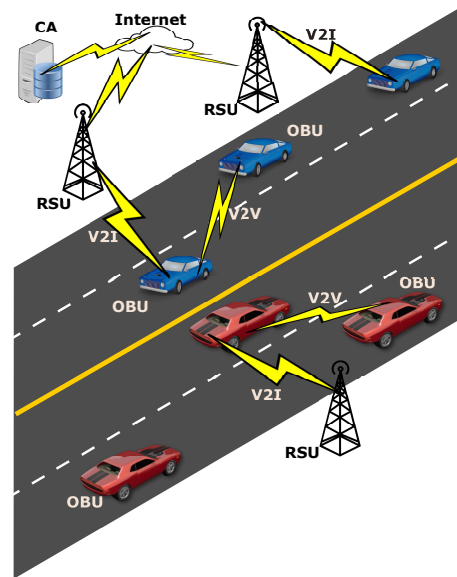


Figure 2.2: Architecture of VANET

2.1.2 Comparison of VANET and MANET

VANET is evolved from MANET and it is a subclass of MANET [85]. From MANET perspective, the ad-hoc domain is composed by RSU and OBU, which are considered as the static (fixed) node and the mobile node, respectively. Moreover, they are both based on IEEE 802.11p protocol.

- In the ad-hoc network, every wireless transmission has distance coverage limitation, wireless node will use its neighboring nodes to forward the packet beyond its coverage [111]. To improve the reliability, MANET nodes require ad-hoc types routing protocols such as table-driven routing, on-demand routing, and hybrid routing [112]. The routing protocols of MANET can not simply apply to VANET network as MANET has fast changing ad-hoc network topology.
- The size of VANET is much larger than that of MANET. Each vehicle represents a valid mobile node in VANET and there are a considerable number of vehicles within an area, especially in the urban area. Therefore, we normally divide VANET into

small pieces and design protocols and applications which are fit for local traffic situation. At the same time, those partitions of VANET are able to communicate with each other via the stationary RSU.

- The topology of VANET is more or less determined by the layout of the roads and the traffic conditions. The mobile nodes cannot move around arbitrarily as in MANET and their possible routes are restricted within the roadway segment. Therefore, the position of the mobile node in VANET is more predictable than that in MANET.
- When it comes to designing MANET, we should pay the utmost attention to the power consumption of each node. Usually, we need to compromise the system throughput due to node's power capacity, which actually becomes a bottleneck for the entire MANET system. Contrarily, VANET nodes (OBU) are not subject to storage and power limitation because they reside in vehicles, which provides enough power to support all the tasks in OBU.
- Without the power limitation, the computation system of OBU can be more sophisticated and more complex computation tasks can be assigned to this VANET distributed system.
- Since vehicles are fast-moving on the road, the nodes in VANET are highly mobile and the network topology changes constantly. As a result, the VANETs are ephemeral networks [86] and this is the most significant difference between VANET and MANET. The node distribution density highly depends on the traffic. Typically it is lower during the night time and much higher during the rush hours. It is apparent that vehicles' navigation speeds and directions are unpredictable, therefore, sometimes the connection time between two vehicles could be very short. It

needs to be considered when designing the protocols [2] and algorithms in order to increase the reliability [4] and decrease the packet dropping probability.

2.1.3 VANET Applications

The main VANET applications can be categorized into three classes [76] [74] [96]:

- Applications for road safety. VANET applications provide valuable messages [20] such as collision avoidance, notification danger of the road and warnings of harsh weather for the sake of improving road safety and reducing traffic accidents.
- Applications for traffic efficiency. These applications aim to help drivers make better use of the road and assist the driver in certain situations such as overtaking vehicles, warning of potential traffic jams, detection of vehicle queue, etc.
- Applications of passengers comfort. They are value added applications and for the comfort of the driver and passengers with on-board services such as infotainment, messaging, Internet access, etc.

2.2 Cloud Computing

Thanks to the revolutionary change of computation and networking technologies, the past few years have witnessed the tremendous advancement of Cloud Computing (CC)[62][12][40], which is a paradigm shift in information technology (IT) industry all over the world. Based on [75], CC is defined as "cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." Compared to the traditional local systems, CC has several novel characteristics:

- It provides computational resources, storage, and IT services on demand. From user's perspective, it has infinite computing resources available; thus, they don't need to plan ahead for physical resource provisioning.
- Various users may rent the amount of services they need at the moment. CC allows them to purchase extra hardware resources only when there is an increase in their needs. It is really helpful for the start-ups as they don't need to set up big financial commitments for building up the IT infrastructure in advance.
- CC also gives users the ability to rent computing resources in a short period of time as needed. For example, the users can rent the resources based on the length of a project; after the completion the project, they can release them. It will be a huge waste of money if they buy their own physical servers for the project instead of renting them from CC.

An increasing number of individual users and enterprises have migrated their data and IT services to remote cloud servers. Amazon elastic computing cloud (EC2) is the one of the largest cloud services platform, which has attracted millions of users all over the world.

Figure 2.3 illustrates the EC2 architecture [41]. An authorized user can access the cloud services by the client web API and EC2 platform can provide the elastic computing resources (EC2 instances) and storage (Elastic Block Storage and Ephemeral Storage). Cloud Watch monitors the resource usage of the customers and reports the results to Auto Scaling system, which is a decision-maker and has the ability to scale up or scale down the quota of resources for the users. Essentially, there are three types of technologically mature cloud services [62][66]. Namely, Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS).

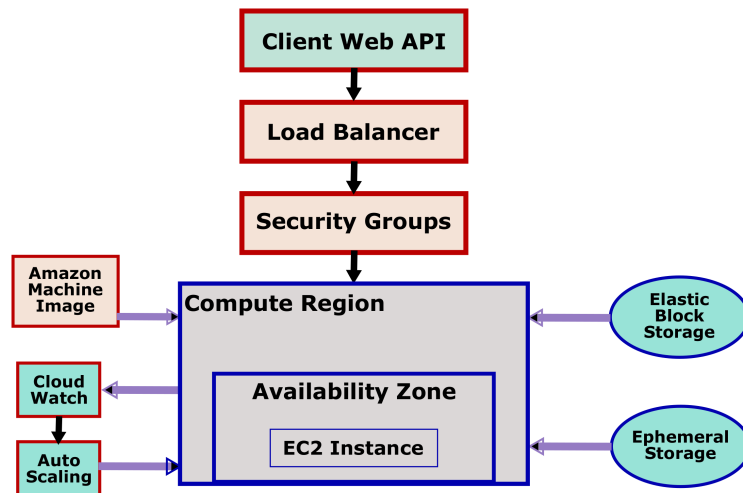


Figure 2.3: Architecture of Amazon EC2

2.2.1 IaaS: Infrastructure as a Service

Based on virtualization technology, the cloud service provider offers its customers elastic resources such as computing capabilities, network connections, and storage capacity [45]. Amazon EC2 [8] is a very good example of this category. For the open-source project, OpenStack is one of the most popular software platforms for cloud computing, mostly deployed as an infrastructure-as-a-service [102]. There are several interrelated components in this software platform. For instance, Nova controls hardware pools of processing; Neutron deals with networking resources, Cinder manages block storage and Swift administers the object storage. Users either manage it through a web-based dashboard (Horizon), through command-line tools, or through a RESTful API.

2.2.2 PaaS: Platform as a Service

PaaS provides a platform where applications can be developed, run and managed by authorized users without worrying about some of the lower-level details of the environment. In other words, the consumer have the control over configuration settings and

software deployment, and the service provider offers the servers, the networks, storage and other services to host the consumer's application. Microsoft Azure [104] and Google AppEngine [109] are typical service platforms of this category.

2.2.3 SaaS: Software as a Service

In SaaS model, software resides in the service provider's datacenter and is maintained by the provider [70], who licenses various applications, including office and messaging software, database management system (DBMS) software, CAD software, customer relationship management (CRM) software, antivirus, etc., to customers as a service on demand. SaaS is subscription based, this allows customers to rent rather than purchase the software. In addition, there is no need for customers to worry about the compatibility between the software and their operating system since the user can access the service simply by launching their browsers and log on during the terms of the subscription. IBM SmartCloud [54] platform is an example of SaaS model.

2.3 Mobile Cloud Computing

The popularity and portability of mobile devices such as tablets, PDAs and smartphones have brought a new research area called Mobile Cloud Computing (MCC) [92][37], where the mobile devices normally provide the input and the computation tasks are performed by the virtual machines on a remote cloud server. The MCC forum defines MCC as follows [72]: "Mobile cloud computing at its simplest refers to an infrastructure where both the data storage and data processing happen outside of the mobile device. Mobile cloud applications move the computing power and data storage away from mobile phones and into the cloud, bringing applications and mobile computing to not just smartphone

users but a much broader range of mobile subscribers” MCC is known to be a promising technology in the IT arena due to its incomparable features such as mobility, portability, and communication. Several features are unique in MCC [37]:

- Prolonging battery lifetime. One of the main concerns for mobile devices is the battery life. Short battery life means the user has to charge them more frequently, which is definitely a weak point of those electronic products. Many methods have been proposed to tackle this issue by enhancing CPU performance and managing the screen and disk in an intelligent manner to lower down their power consumption. However, those solutions are expensive due to the requirements of the fundamental change in the structure of mobile devices, such as a new circuit layout design or an upgraded hardware. It may not be practicable for all mobile devices, especially for products which are already in customers’ hand. In MCC, computation offloading technique is utilized to migrate the heavy computation tasks and complex processing from mobile devices to remote servers in the cloud. It will significantly reduce the application execution time on mobile devices and, consequently, extend the battery life.
- Improving processing capability and storage capacity. MCC is able to reduce the running cost for compute-intensive applications in terms of time and energy consumption. It is obvious that each mobile device has limited physical resources such as processing power and storage capacity. MCC can efficiently support heavy and complex applications on portable mobile devices since it enables mobile users to run the computation tasks online and store the large data on the cloud through wireless networks.
- Improving reliability. MCC can effectively improve the reliability of mobile devices by running applications or storing data on clouds because the data and processing

results are stored and backed up on remote servers. This feature can greatly reduce the risk of data and application loss on the mobile devices. In addition, different data security models can be applied in MCC to provide stronger data protection for both service providers and users. For example, cloud-based mobile digital rights management (DRM) schemes can be used to protect mass of unstructured digital contents (e.g., video, audio, and music) from being pirated and unauthorized distribution [114].

Moreover, MCC also inherits some advantages of CC for mobile services as follows [75] [37]:

- **Dynamic provisioning.** MCC provides authorized users the facility of unlimited resources on a fine-grained, self-service basis. This enables service providers and mobile users to run their applications without early planning of resource provisioning. In addition, the flexible resource provisioning also permits service providers to deploy their mobile applications on a minimum amount of resources at the beginning and scale up their hardware resources based on the popularity of the applications.
- **Ease of access.** Mobile application services can be accessed from anywhere in the world and the users are capable of accessing the resources at any time as long as they have internet access on the mobile devices.
- **Ease of integration.** By resource pooling, service providers can share resources and costs to support a multitude of applications and meet the user demand.

2.4 Vehicular Cloud Computing

The concept of vehicular cloud has been first proposed in recent works [3] [79] [78]. The key point of vehicular cloud comprehends the collection, utilization, and allocation of the excessive on-board resources, such as computing capabilities, sensors, storage, and communication resources, in a dynamic group of vehicles under the authorization of the vehicle owners. Combining such resources together and enabling them to provide cloud services to the public benefit both the cloud and owner of vehicles. The services that vehicular clouds can offer are non-trivial and complementary to the conventional cloud computing. According to the proposal in [78], VC refers to *a group of largely autonomous vehicles whose corporate computing, sensing, communication, and physical resources can be coordinated and dynamically allocated to authorized users*. Table 2.1 compares the features of CC, MCC, and VCC from different perspectives.

Table 2.1: Comparison of CC, MCC and VCC

Feature	Cloud Computing	Mobile Cloud Computing	Vehicular Cloud Computing
<i>Computation Capability</i>	Highest	Lowest	Medium sized
<i>Supports Mobile Resources</i>	No	Yes	Yes
<i>Storage Capacity</i>	Highest	Lowest	Medium sized
<i>Battery Limitation</i>	No	Yes	No
<i>Physical Resources</i>	Local or Remote Servers	Local Mobile Devices or Remote Server	Local Vehicles or Remote Servers
<i>Network Architecture</i>	Client-Server based	Client-Server based	Peer to Peer or Client-Server based
<i>Resource Flexibility</i>	Static	Static	Highly Dynamic
<i>Autonomous Cloud Formation</i>	No	No	Yes

In order to enable access to rich services and applications, modern vehicles are equipped with reasonably powerful computational capabilities. Cloud computing extends these capabilities by featuring limitless resources and enhancing the provision of services. Also, the vehicles' built-in resources are likely to be underutilized most of the time, such as when they are in a parking lot or traffic jam. There is a great potential for employing each vehicle's unused computing resources to build clouds autonomously. Enabling vehicles to connect and participate in a vehicular cloud is an extremely valuable strategy for solving complex issues in real-time and in loco, as it is considered a paradigm shift in transportation systems [78].

The issues faced in the dynamic interconnection of vehicles to assemble a vehicular cloud is closely related to the challenges faced in vehicular networks [53]. Both the vehicular cloud and vehicular networks provide a means for the design of solutions in Intelligent Transportation Systems. Vehicular networks can be seen as an expansion of Mobile Ad-hoc Networks, which have shown a steady increase in popularity with advancements in solutions, technologies, and an extensive range of applications it can support. Vehicular networks basically present two major architectures: Vehicle to Infrastructure communication (V2I) and Vehicle to Vehicle communication (V2V) [82]. Initially, considerable work has been applied to vehicular networks, focusing on avoiding traffic hazards or unpleasant driving experiences [94]; these types of issues in transportation require overcoming challenges in efficiently gathering and disseminating real-time data [101]. Vehicular networks have now expanded this scope to include concerns regarding safety, entertainment, privacy, and security.

2.4.1 Taxonomy of Literature on VCC

Based on an extensive study of VC-related literature, Figure 2.4 presents a taxonomy of vehicular cloud computing, the majority of articles focus on the applications and services of different vehicular cloudlets.

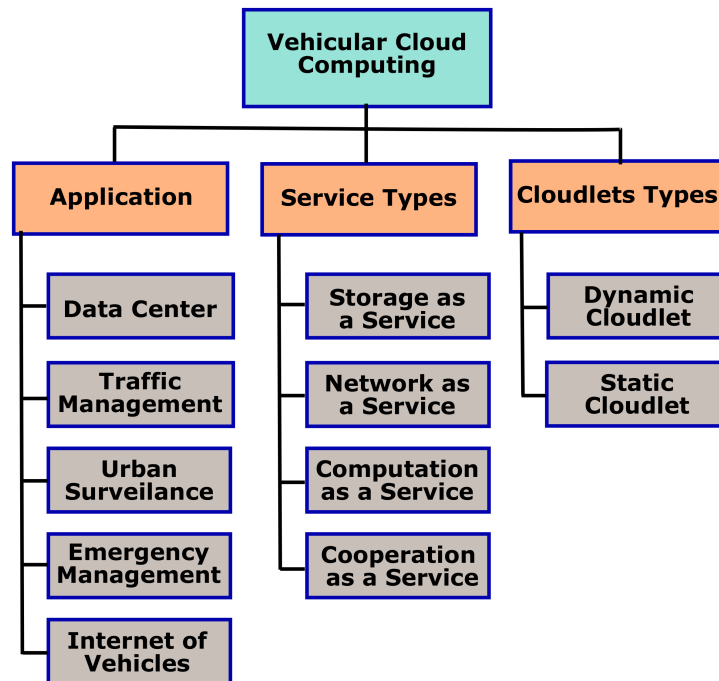


Figure 2.4: Taxonomy of the Literature on Vehicular Cloud Computing

There are many possible applications for the vehicular cloud computing [78]. One of them is the composition and assembly of a data center in the parking lot. Since a great number of cars are resting in the garage of a company or a shopping mall for a certain amount of time, the on-board storage of these cars can be used as a fundamental resource for forming a data center. Another promising application is the dynamic traffic light management system [79]. Traffic jams represent a serious growing issue in metropolitan areas due to the increasing number of vehicles on the road. The drivers who are stuck in congested traffic might be willing to give out their vehicular computing resources so

that the traffic management department can perform calculations and run simulations designed to mitigate the traffic congestion by dynamically adjusting the traffic lights. In [78], many other potential vehicular cloud applications such as dynamic assignment of HOV lanes, planned evacuation management, and dynamic traffic signal optimization are presented.

Applications are built on top of the novel services of VCC, namely NaaS, STaaS, Com-paaS, and CaaS. Many models and infrastructure are proposed to make those services available on VC [11] [13].

Those VCs can be divided into two major categories [48]. The first group can be classified as a static vehicular cloudlet, which is formed by aggregating the computing capabilities of all the still vehicles resting inside a parking lot, for instance. This kind of VC behaves like a traditional cloud. The other type of cloudlet relies on the highly dynamic traffic flow. Traffic-related applications that are highly dynamic in nature can get benefit from dynamic vehicular cloudlet and may be used to assist the municipal department of transportation to deal with the traffic congestions or the emergency conditions, such as evacuation plans built in run-time.

For the static vehicular cloud, a research work [9] took an initial step towards implementing a VC and investigated the number of cars that are expected to be present in a long-term parking lot of a typical international airport. The stochastic process with time-varying arrival and departure rates are used to model the number of compute nodes at the datacenter which is formed by the extra computing capabilities of those vehicles. In this particular work, it was deduced a closed form for the expected number of vehicles and its variance in an international airport parking garage. The time-dependent probability distribution function of the parking lot occupancy and the limiting behavior of these parameters as the initial conditions fade away. With those parameters, we could

have a clear picture of the number of vehicles in the parking lot at any given moment.

For the dynamic vehicular cloud, a work [110] analyzed the average amount of computing resources we can harness in a roadway segment by utilizing the stochastic traffic models.

2.4.2 Architecture of Vehicular Cloud

The vehicular cloud computing architecture consists of three primary layers of communication. As illustrated in Figure 2.5, these layers are the on-board layer, communication layers, and cloud computing layer. And the cloud computing layer can be divided into several sub-layers based on its internal structural dependencies. In the on-board layer, a vehicle could detect the environment condition, road condition and even driver's mood and behavior by using various on-board sensors such as environment sensors, smartphone sensors, vehicle's internal sensors and driver behavior recognition [32] [42]. The information collected by sensors needs to be stored in the distributed storage and used as input for various real-time applications. Besides those sophisticated sensors, each vehicle is equipped with computer and storage unit, which are the building blocks of cloud computing resources.

The second layer enables the vehicle to vehicle communication as well as vehicle to infrastructure communication. As vehicles are equipped with IEEE 802.11p transceivers, vehicles and VC can exchange information either V2V or V2I by using various protocols such as 3G or 4G cellular communications, Wireless Access in Vehicular Environment (WAVE) [55], or Dedicated Short Range Communication (DSRC) [105] [59]. In V2V architecture, vehicles communicate with each other as long as they are in each other's valid range of communication for the sake of improving traffic safety and enhancing the driving experience. VCC can be formed autonomously by vehicles via V2V communica-

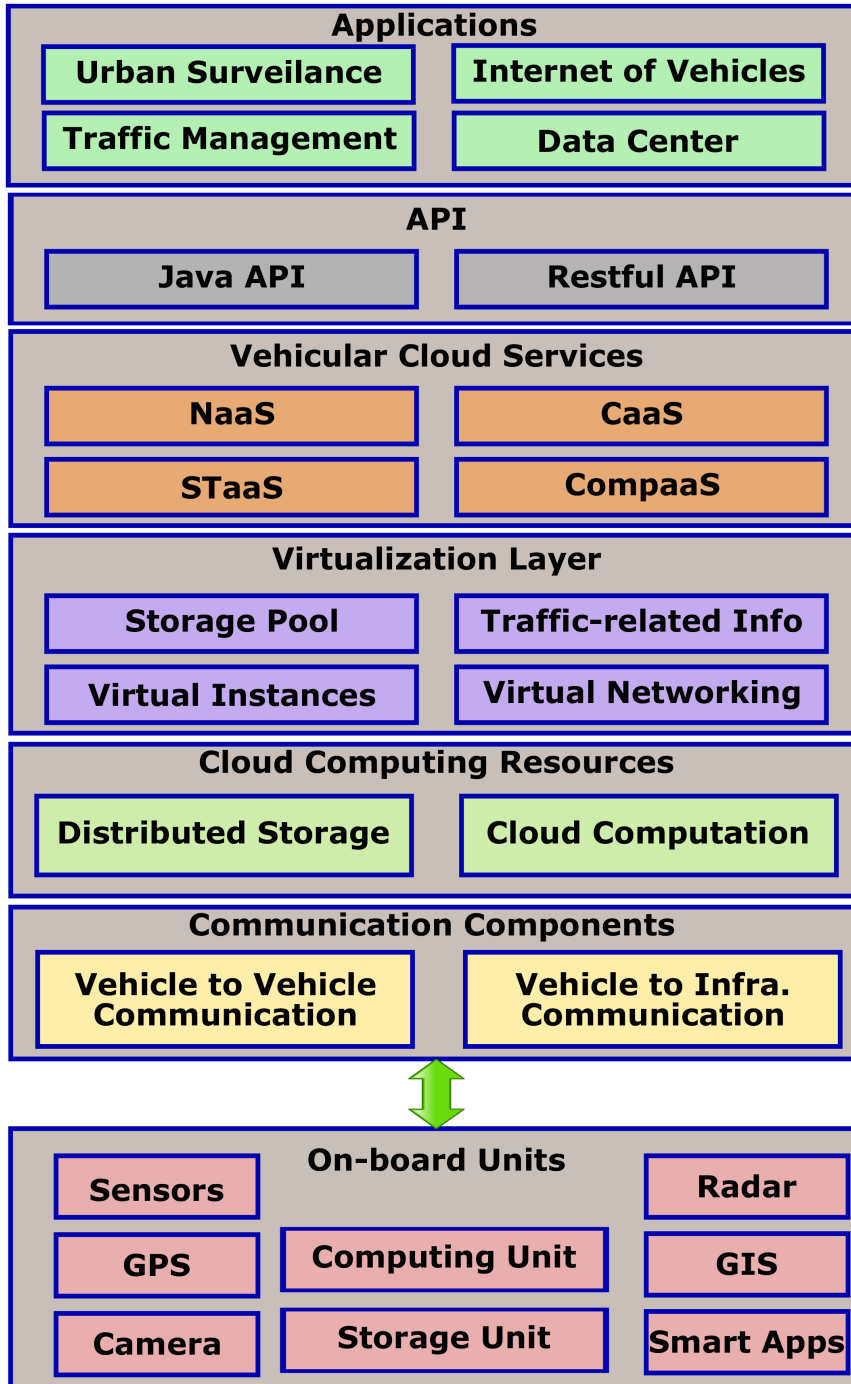


Figure 2.5: Vehicular Cloud Computing Architecture

tion scenarios. If the road condition or a driver's behavior is abnormal, an emergency warning message will be generated by the vehicle that observed this traffic abnormality and sent to VC storage pool, hence, all vehicles that are registered in this VC will receive the emergency message, which contains the geographical location where abnormal situation occurs [57]. The second component of the communication layer is V2I, which is complementary to V2V architecture and account for exchanging the operational information among vehicles, infrastructures and clouds. In addition, since RSU can be used as a gateway to the external network such as Internet, multiple autonomous vehicular clouds can share data through a common platform on the Internet. As a result, a driver can have a much larger overview of the traffic condition, which can raise driver safety level and reduce the number of traffic accidents.

The cloud computing layer relies on five internal sub-layers: cloud computing resources, virtualization layer, vehicular cloud services, API and application layer. The cloud computing resources are aggregated computation and storage capacity of vehicles that involved in VC. By using the virtualization technology, all pooled storage, computing power and traffic-rated information can be assigned to authorized tenants according to their quota of resources. Several services are deployed in the VC services layer, such as Network as a Service (NaaS), Storage as a Service (STaaS), Cooperation as a Service (CaaS) and Computation as a Service (CompaaS), which are discussed in the next section. API is provided by the cloud primary services for the development of various applications. The top layer of VCC architecture is the application layer where all the software applications reside. Those applications are accessible remotely by valid end users such as drivers and municipal traffic management departments.

2.4.3 Vehicular Cloud Services

The primary services that vehicular cloud can provide are categorized as Storage as a Service (STaaS), Network as a Service (NaaS), Computation as a Service, and Cooperation as a Service (CaaS) [103].

Storage as a Service

Due to the portable size and cheap price of storage media, it is assumed that vehicles are now equipped with large storage capacity. In this sense, a study [9] investigated the feasibility of building a data center in the international airport parking lot by exploiting the under-utilized storage resources in the vehicles. The vehicles need to be plugged into a standard power outlet so as to connect to the vehicular cloud. By giving the air travelers the proper incentives, like free parking or free car-washing, it is anticipated that the vehicle owners are most likely willing to let their vehicles participate in the airport data center. In [49], a two-tier data center architecture is proposed for the sake of harnessing the excessive storage in a parking lot with a finite capacity. In reality, unlike the static storage resources in a traditional real data center, the number of incoming and outgoing vehicles in a parking lot is a random variable. One of the most popular techniques to deal with this issue is the replication-based fault-tolerant storage [33]. The principle behind this storage demonstrates that the client stores N copies of the original file at each of the N storage servers. As a result, the original file can be retrieved as long as at least one of the N intact replicas is available.

Network as a Service

The vehicular network is composed by a set of fixed roadside access points (APs) and the mobile vehicular users. The recent works in NaaS area are mainly focusing on

utilizing the V2V and V2I connections to transfer data. A study [71] investigated the performance of downloading content by formulating and solving a linear programming problem, given the availability of different data transfer paradigms, which are the direct transfer, connected forwarding, and carry-and-forward. Specifically, if a downloader can directly get data from an AP, it is considered a direct-transfer paradigm; if a data packet needs one or more vehicles to create a multi-hop path to reach the downloader, it is defined as connected-forwarding paradigm; if data packets require one or more vehicles to store, carry them, and eventually deliver them to the downloader, it is characterized as carry-and-forward paradigm.

Computation as a Service

Similar to STaaS, the vision of computation-as-a-service is aggregating the excessive computing capabilities of vehicles and presenting it as a new service to authorized customers. Due to the fact that vehicular cloud computing is a recent technological concept, and it is at its very initial stage, there is not much related work that directly investigates the harvesting of the computing resources on the vehicles. However, the work done by [9] can also be used as the estimation of computing capabilities inside an airport parking lot. One of the technical challenges of using those on-board computing resources is to find an effective way of migrating the tasks from the outgoing vehicles to the vehicles that are still residing in the parking lot [108] [87]. From the perspective of distributed system, the task migration includes suspending the task, saving the status of computation, finding the target host and migrating jobs.

Cooperation as a Service

A work [63] proposed a Navigator Assisted Vehicular route Optimizer (NAVOPT), which is composed of an on-board navigator and the navigation server based on the cooperation of the vehicular cloud and the traditional cloud. The on-board navigator detects its own geographical coordinates using the internal area map along with GPS and reports it to the server via wireless communication. After collecting enough information from a large number of vehicles in the area, the server is able to construct the traffic load map, calculate the optimal route to the destination for each specific car, and then return the optimized routing strategy to the vehicles.

2.4.4 Applications of Vehicular Cloud

Table 2.2 2.3 2.4 2.5 2.6 summarize some representative vehicular services and applications prototypes or proposals from year 2012 to year 2016. We can see a clear trend that those diverse vehicular services and applications are more likely to be independent on the traditional cloud computing, in other words, they are able to be running on the autonomous vehicular cloud without relying on extra stationary computing resources. In addition, the researchers have tried to exploit any available on-board physical resources such as various sensing devices, on-board computer, storage, GPS, GIS, rear collision radar device, camera and electronic transceivers. It is a clear trend that along with the revolutionary change in the automotive industry, more and more smart and intelligent devices will be installed in a modern vehicle. As a result, more novel services and applications are expected to be provided by the vehicular cloud.

Table 2.2: Representative Works on Vehicular Cloud Applications–Part1

Works	Classification	Description	Traditional Cloud Dependency
<i>Datacenter at the Airport [9]</i> [Year: 2012]	Data Center	Aggregate vehicular computing resources in long-term parking lot of a typical international airport. <ul style="list-style-type: none"> • Model the number of vehicles in the parking lot of an airport using stochastic process. • Provide analytical results concerning the availability of computational resources in a rather stable environment. 	No
<i>Smart Traffic Cloud [100]</i> [Year: 2012]	Urban Surveillance	A real-time traffic condition map is developed using data collected from commuters' mobile phones. <ul style="list-style-type: none"> • Propose a software infrastructure to enable traffic data collection, and manage, analyze and present the results in a flexible manner. • Use Map-Reduce framework and ontology database to handle distributed data and parallel analysis. 	No
<i>User-Driven Cloud Transportation System [67]</i> [Year: 2012]	Traffic Management	A cloud transportation system is proposed to predict traffic congestion and construct traffic map for the purpose of smart driving. <ul style="list-style-type: none"> • Employs a scheme of user-driven crowd-sourcing to acquire user data for predicting traffic jam and building a real-time traffic model. • Propose a Map-Reduce computing model and algorithm for traffic data processing and develop an Android-based prototype application. 	Yes

Table 2.3: Representative Works on Vehicular Cloud Applications–Part2

Works	Classification	Description	Traditional Cloud Dependency
<i>Pics-on-wheels [44]</i> <i>[Year: 2013]</i>	Internet of Vehicles	<p>The surveillance application exploits the mobile service nodes (vehicles) to extend the coverage beyond the reach of stationary video cameras.</p> <ul style="list-style-type: none"> • Vehicular cloud server estimates the number of qualified candidates in Zone of Interest (ZoI) and accepts/rejects the request after receiving the picture request from a customer. • Vehicular cloud server invites authorized vehicles in ZoI to provide the pictures. 	No
<i>Two-tier Data Center [49]</i> <i>[Year: 2013]</i>	Data Center	<p>By leveraging excessive storage resources in parking lots, auxiliary vehicular data center (VDC) can effectively mitigate the pressure on conventional data center.</p> <ul style="list-style-type: none"> • Characterize the dynamic behavior of a garage with a limited number of parking spaces. • Analyze the communication cost in a two-tier data center for each resource management policy. 	Yes
<i>Intellectual Road Infrastructure [50]</i> <i>[Year: 2013]</i>	Traffic Management	<p>An Intellectual Road Infrastructure is proposed to control and monitor traffic in real-time manner in order to improve the safety and minimize the costs.</p> <ul style="list-style-type: none"> • Use the on-board radio frequency identification (RFID), GPS and sensors to gather the information of the traffic situation. • Process the information on the cloud and present valuable results via an on-line service. 	No

Table 2.4: Representative Works on Vehicular Cloud Applications–Part3

Works	Classification	Description	Traditional Cloud Dependency
<i>Parked Vehicles</i> [38] [Year: 2014]	Data Center	<p>Parked vehicles can be used as a spatio-temporal network and storage infrastructure. And the role of RSU can be replaced by the vehicles that on the roadside.</p> <ul style="list-style-type: none"> • Use Virtual Cord Protocol to enable vehicular cloud and demonstrate the feasibility by simulation. • Test the performance of storing and retrieving data on the vehicular clouds formed by parking vehicles. 	No
<i>Context-Aware Dynamic Parking Service</i> [99] [Year: 2014]	Traffic Management	<p>Besides the traditional parking garages, dynamic parking service such as parking a vehicle along the road can be supported by the vehicular cloud.</p> <ul style="list-style-type: none"> • By the method of probability analysis, the traffic authorities dynamically arrange whether the road can be authorized to provide context-aware parking services. • The context information also includes expected duration of parking for a vehicle. 	No
<i>Autonomous Driving</i> [43] [Year: 2014]	Internet of Vehicles	<p>Vehicular cloud is able to be established by the aggregate resources from neighboring vehicles and RSUs and their potential interconnections.</p> <ul style="list-style-type: none"> • Autonomous driving application requires images of next three road segments through the autonomous vehicular cloud for evaluating the traffic situation. • The images are provided by cloud members and the content is published to the entire network for different purposes. 	No

Table 2.5: Representative Works on Vehicular Cloud Applications–Part4

Works	Classification	Description	Traditional Cloud Dependency
<i>RFID-enabled Authentication Scheme</i> [64] [Year: 2015]	Healthcare	<p>An intelligent RFID-enabled authentication scheme is proposed for healthcare applications in VCC environment.</p> <ul style="list-style-type: none"> • Patients traveling on the road wear an RFID-enabled wristband while vehicles and RSUs are equipped with low-frequency and high-frequency RFID readers, respectively. • A PetriNets-based authentication model is used to secure the communication between RSUs and the central cloud. 	No
<i>Virtual Machine Migration</i> [106] [Year: 2015]	Data Center	<p>Linear programming is used to minimize the overall network cost both VM migration and normal data traffic.</p> <ul style="list-style-type: none"> • Formulate VM migration problem for minimizing network cost in VCC as a mixed-integer quadratic programming problem. • A polynomial time two-phase heuristic algorithm is proposed to tackle the computation complexity due to the large number of vehicles. 	No
<i>Multimedia Services</i> [56] [Year: 2015]	Internet of Vehicles	<p>The on-board advanced and embedded devices increase the capabilities of vehicles to provide computation and collection of multimedia content in VC.</p> <ul style="list-style-type: none"> • An improved adaptive probabilistic rebroadcasting method is proposed to deal with network saturation with large (multimedia) packet sizes in the high-density network. • Linear programming is used to determine the target bit rate for all driving recorders' videos. 	No

Table 2.6: Representative Works on Vehicular Cloud Applications–Part5

Works	Classification	Description	Traditional Cloud Dependency
<i>Prefetching-Based Data Dissemination [61]</i> [Year: 2016]	Data Center	<p>A vehicle route-based data prefetching scheme is devised to maximizes data dissemination success probability in VDC, where the size of local storage is limited and wireless connectivity is stochastically unknown.</p> <ul style="list-style-type: none"> • Deterministic greedy data dissemination algorithm is used when the stochastic features of the network connectivity success rate are predefined. • Apply Stochastic MAB-based online learning framework to learn stochastic characteristics of network connectivity success rate when its distribution is unknown. 	No
<i>Cloud-Assisted Video Reporting Service [39]</i> [Year: 2016]	Urban Surveillance	<p>Cloud-assisted video reporting service is designed for the participating vehicles to instantly report the videos of traffic accidents to official or ambulance vehicles to guarantee a timely response from them.</p> <ul style="list-style-type: none"> • The senders should transmit the reported videos to the cloud via 5G network when a communication route to the recipient may not be available. • The authentication process is achieved by using a digital signature that associates an encrypted accident video with a pseudonym. 	Yes
<i>InCloud [90]</i> [Year: 2016]	Infotainment	<p>A cloud-based middleware framework is proposed for vehicular infotainment application development.</p> <ul style="list-style-type: none"> • The application design principles include data fusion, context-awareness, re-usability and loose-coupling. Three infotainment applications are developed for vehicles using this framework. 	Yes

2.5 Mathematical Modeling of Vehicular Cloud

Model is a simplification and simulation of reality, which has almost infinite factors and, therefore, is extremely complex. Model simplifies the reality by making proper predefined assumptions. For the traffic flow, there are so many influential factors such as weather, traffic signs, road geometry, road conditions, driver's behavior and a large number of random events that make it impossible to precisely model the traffic by mathematical tools, so traffic flow model also needs assumptions. Many VANETs, as well as VC related studies, need to incorporate various traffic models that emulate the realistic vehicular traffic behavior in order to evaluate the performance of their proposals such as a new routing protocol, data dissemination in VANET, available on-board resources prediction. Those traffic models can be categorized into three 3 types: car-following models, traffic stream models, and stochastic traffic models.

2.5.1 Car-Following Models

Car-following model [107] is the category of microscopic models, which describe the individual behavior of each vehicle in the traffic flow. There are several basic assumptions in the car-following model [113]:

1. Drivers only respond to the status of the vehicles ahead and do not respond to any of the following vehicles.
2. The vehicle follows behind the preceding vehicles in the same lane and does not overtake.
3. The road conditions are ideal and each vehicle has the same performance, and drivers behave normally and have the same level of driving skills.

Car-following model is now most commonly used to analytically describe the dynamics of vehicular traffic flow since it has less restrictive assumptions and accounts for a large number of such parameters that close to reality as finite driver's reaction time, weather conditions, road conditions and vehicle technical details, resulting in an impressive degree of accuracy. In the majority of car-following models, a vehicle's speed is expressed as one of the following four modes [81]:

- Free-driving mode, when the vehicles are sparsely distributed and they are no obstacles for the vehicle. A driver can drive any speed they want as long as the speed is within the speed limit of the road.
- Approaching mode, where the vehicle's speed is faster than the preceding vehicle while maintaining the safe headway.
- Following mode, where the headway between two consecutive vehicles allows the follower vehicle to be able to accelerate or decelerate in accordance with the vehicle ahead.
- Braking mode, when the driver realizes the headway between vehicles is below the desired safety distance.

In general, microscopic models like car-following models are more conformity with real traffic. However, they are highly computationally expensive, especially when the number of vehicles becomes large in an area. In addition, it is extremely complex to get closed-form results within the analytical framework.

2.5.2 Traffic Stream Models

Unlike car-following model, traffic stream model does not focus on individual vehicle's behavior. Instead, it delineates the collective features of vehicular streams. It is cate-

gorized as a macroscopic model since the vehicular traffic is treated as a hydrodynamic flow. There are three macroscopic parameters for the vehicular traffic flow: vehicular density, the vehicles' speed and the traffic flow rate. The less amount of variables in traffic stream models makes them less difficult to implement than the microscopic models, which is the reason why they are popular in the design of data dissemination schemes for VANET. However, the assumptions of macroscopic traffic models in the open research works are not consistent and most of the time, case-specific.

In [46] and [34] the authors have conducted experiments over highways in Madrid of Spain and Beijing of China, respectively. They obtained a large amount of realistic data by putting the sensors along the highway. Then they use some well-known data processing methods such as expectation-maximization based algorithm and principal component analysis (PCA) to get the general distribution of the traffic. However, it is unrealistic for researchers to get those realistic data in every traffic scenario.

The traffic model in [1] considers the vehicles moving in one direction on the straight road segment. The movement of a vehicle is characterized by two random variables, V , and T . V is the vehicle speed level, which has only two possible values, high speed V_H and low speed V_L . The switch of those two speeds is controlled by the second parameter T , which is exponentially distributed random variable with parameter λ . To be more specific, it is assumed that a vehicle may maintain a speed level V_H (V_L) for an amount of time T before switching to V_L (V_H).

Another macroscopic free-flow traffic model in [60] has the following assumptions:

- The vehicular density on a roadway segment tend to be low or medium.
- Incoming vehicle arrivals follow an independent and identically distributed Poisson process.
- Vehicles navigate over an uninterrupted road segment (no stop signs, no traffic

lights, etc.)

- Speed is normally distributed within $[V_{min}V_{max}]$ and keep the same speed during the whole segment.

2.5.3 Stochastic Traffic Models

Stochastic traffic models are rarely used by researchers now since it has highly restrictive assumptions and often deviate from reality. Two most common stochastic mobility models include Random Walk and Random Direction Mobility Model [93] [5], where the mobile nodes are free to move in any random directions based on the road map. The following features that are commonly seen in this type of model.

- The roadway topology is often represented by a grid. The movement of vehicles on the grid is random.
- Vehicles select a random point as their destination and move toward this destination at constant speed [84] [5]. The navigation directions are either vertical or horizontal.
- The interactive behavior among vehicles are not considered and the three inter-correlated macroscopic parameters in the traffic stream model (e.g. vehicular density, speed, flow rate) are simply neglected.

A brief summary of the aforementioned traffic models are presented in Table 2.7.

2.6 Summary

In this chapter, we primarily presented the technical revolution of vehicular cloud computing based on an extensive review of the literature. Plenty of research works have contributed to this paradigm shift from vehicular networks to vehicular clouds. Various

Table 2.7: Strengths and Weaknesses of Existing Traffic Models

Traffic Model	Strengths	Weaknesses
<i>Car-Following Model</i> [107] [113]	<ul style="list-style-type: none"> • Consider a large number of realistic parameters and the interactive behavior among individual vehicles. • Have relatively high degree of accuracy 	<ul style="list-style-type: none"> • Highly computationally expensive and extremely complex. • Very hard, most likely impracticable to get the analytical results.
<i>Traffic Stream Model</i> [1] [60]	<ul style="list-style-type: none"> • Focus on the collective behavior of vehicle flows. • Easy to get the analytical results and useful for high-level traffic behavior studies. 	<ul style="list-style-type: none"> • Some of these models have unrealistic assumptions [1].
<i>Stochastic Traffic Model</i> [93] [5]	<ul style="list-style-type: none"> • Based on stochastic theory and very simplistic 	<ul style="list-style-type: none"> • Have highly restrictive assumptions and often deviate from reality. • Overlook the fundamental characteristics of vehicular traffic flow.

services and applications that can possibly be implemented on the vehicular cloud have been classified and discussed here. At the end, since our work is based on the traffic modeling, we also did a survey on the existing traffic models. This chapter provides a broad insight into the vehicular cloud applications and their implementation.

At this stage, as far as we know, most works in the literature about vehicular cloud are about taxonomy definition and concept proposal. Some works focus on the implementation of vehicular clouds in a rather stable environment, such as the parking lot of an international airport or the garage of a large shopping mall. There are no works

on the implementation of vehicular cloud on the road. While a static VC may provide the same services as the traditional cloud facilities, the majority of vehicles spends a substantial amount of time on the road. Furthermore, the infrastructure of the vehicular cloud is the combination of the static vehicular cloudlet in the parking lot and dynamic vehicular cloudlet on the road. In order to provide a more dynamic and broader model, our thesis presents an initial step towards implementing vehicular cloud in a roadway segment.

Chapter 3

Stochastic Modeling

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 molded by different conditions are observed: free flow traffic and queueing-up traffic. The two scenarios analyzed in this work represent the most common situations found in the traffic and are used for enabling a comprehensive modeling.

3.1 Free-flow Model

In the free-flow traffic model, the traffic is not blocked by any obstacles such as traffic light, stop sign, bifurcations or traffic congestion, and a driver can drive at any speed, provided they remain within road constraints. Therefore, the traffic density in this case is more likely to be low or medium, as high density slows down the traffic due to the road capacity. In other words, vehicles are vastly isolated on the road and the arrivals at the entry point of the road segment are independently and identically distributed. The Poisson process is a common random process for depicting vehicles' arrival. We use the

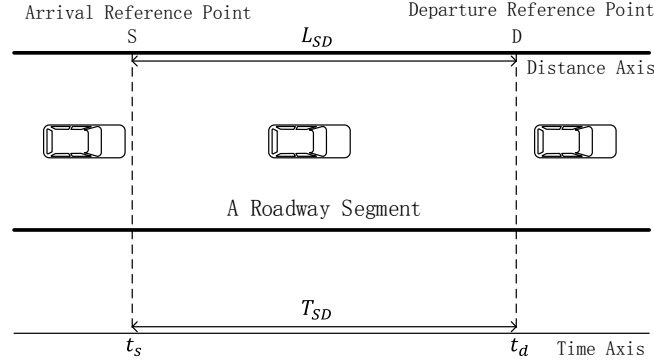


Figure 3.1: Free-flow Traffic in Roadway Segment [SD]

free-flow model [60] as a base to carry out our analysis.

Figure 3.1 shows a typical roadway segment [SD]. The traffic theory in [89] represents the average speed observed over a road segment, and is given by:

$$\bar{V} = V_{max} \left(1 - \frac{\rho_v}{\rho_{max}}\right) \quad (3.1)$$

where \bar{V} is the average speed, V_{max} is the upper speed limit, ρ_v is traffic density (Unit: *veh/meter*) and ρ_{max} is the maximum traffic density. In general, each road segment has a speed range $[V_{min}, V_{max}]$ and the traffic model in [60] assumes that vehicles' speeds are a Gaussian distribution between V_{min} and V_{max} with mean \bar{V} and standard deviation σ_V . Another assumption is that vehicles maintain the same speeds over the length of the road segment L_{SD} . Therefore, the navigation time from arrival reference point S to departure reference point D for a arbitrary car i with speed v_i is $T_i = \frac{L_{SD}}{v_i}$, which is commonly called residence time for a vehicle. It is also a random variable due to the arbitrary value of v_i . Let $F_T(\tau)$ denote the cumulative distribution function (CDF) of the residence time.

$$F_T(\tau) = P[t \leq \tau] = P\left[\frac{L_{SD}}{\nu} \leq \tau\right] = P\left[\nu \geq \frac{L_{SD}}{\tau}\right] = 1 - F_V\left(\frac{L_{SD}}{\tau}\right) \quad (3.2)$$

where $F_V(\nu)$ is the CDF of vehicular speed. Accordingly, the probability density function (PDF) of the residence time is shown as

$$f_T(t) = \frac{dF_T(\tau)}{d\tau} = \frac{M \cdot L_{SD}}{t^2 \sigma_V \sqrt{2\pi}} e^{-\left(\frac{L_{SD} - \bar{v}}{\sigma_V \sqrt{2}}\right)^2} \quad (3.3)$$

where M is a normalization factor, as defined in [60].

The real free-flow vehicular traffic was investigated in [46], where the real-time traffic measurements collected from several highways in the City of Madrid are analyzed. A Gaussian-exponential mixture model was proposed in order to characterize the time intervals between vehicles on the highway. The results also reveal that when the traffic density is a small or medium number, the vehicles are somehow isolated, and the time intervals between two consecutive vehicle arrivals, i.e. inter-arrival times, feature the exponential distribution. As a result, the PDF for the inter-arrival time is expressed as

$$f_A(t) = \mu e^{-\mu t} \quad (3.4)$$

in which the mean value of inter-arrival time $1/\mu$ is inversely proportional to arrival rate μ (Unit: *veh/s*). Consequently, the CDF of the inter-arrival time is

$$F_A(\tau) = P[t \leq \tau] = \int_{-\infty}^{\tau} f_A(t) d\tau = 1 - e^{-\mu t} \quad (3.5)$$

Figure 3.2 and 3.3 demonstrate the stochastic features of a Poisson arrival process. Figure 3.2 presents the probability of vehicular occurrences in a 15-minute interval. Specifically, if the traffic arrival rate $\mu = 0.2$ *vehicles/minute*, 2 or 3 vehicles are expected to show up at the arrival reference point during the period of 15 minutes, with a probability rate of 23%. On the other hand, when $\mu = 0.5$ *vehicles/minute*, it is expected that more vehicles will enter the road segment. For instance, in contrast to 10%

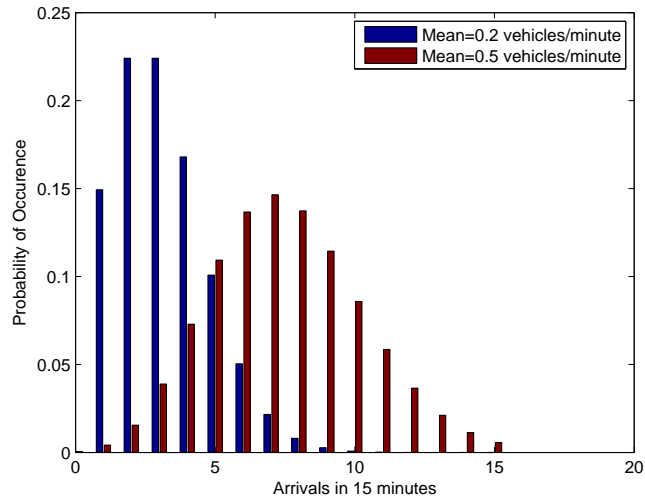


Figure 3.2: Occurrence

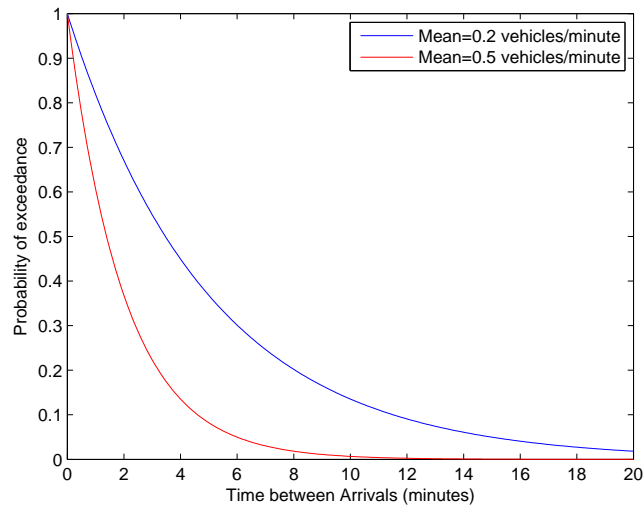


Figure 3.3: Exceedance

probability for the event that 10 vehicular arrivals within 15 minutes when $\mu = 0.5$, that probability is negligible when $\mu = 0.2$. Figure 3.3 depicts the exponentially distributed inter-arrival time of a Poisson process. For example, the probability of the inter-arrival time that exceeds 4 minutes is 45% when $\mu = 0.2$ vehicles/minute; this value plummets to 12% as μ increases to 0.5 vehicles per minute. In addition, the chance of an

inter-arrival time that is longer than 12 minutes is zero when $\mu = 0.5$ vehicles/minute, which means the next arrival will occur within 12 minutes, with approximately 100% probability.

The vehicular arrival in free-flow traffic is commonly modeled as a Poisson process; therefore, Little's Formula [65] can be applied here to estimate the average number of vehicles inside the segment [SD].

$$E(N) = \mu E(T) = \mu \int_0^{\infty} t f_T(t) dt = \mu \int_0^{\infty} \frac{M \cdot L_{SD}}{t \sigma_V \sqrt{2\pi}} e^{-\left(\frac{L_{SD} - \bar{v}}{\sigma_V \sqrt{2}}\right)^2} dt \quad (3.6)$$

Normally, the first moment (i.e. mean value) of a random variable offers very limited information about the actual distribution of this variable. Higher moments are required to obtain a full picture. Likewise, to have a detailed and precise description of the available computing capabilities inside the road segment, it is necessary to characterize the dynamics of the vehicles. A counting process $\{N(t)|t \geq 0\}$ with time parameter t can be used to model the number of vehicles. The event $\{N(t) = i\}$ represents segment [SD] holding i vehicles at time t . The probability of this event is denoted as $P_i(t) = P\{N(t) = i|t \geq 0\}$. Assume the total number of vehicular arrivals during time interval $(0, t)$ is s , and $p(t)$ is the probability that a vehicle remains in [SD] at time t ; the distribution of vehicles within segment [SD] can be derived by the theorem of total probability.

$$\begin{aligned} P_n(t) &= \sum_{s=0}^{\infty} P_{n|s}(t) \cdot M_s(t) \\ &= \sum_{s=n}^{\infty} \binom{s}{n} [p(t)]^n [1 - p(t)]^{s-n} \cdot \frac{(\mu t)^s e^{-\mu t}}{s!} \\ &= \frac{[\mu t \cdot p(t)]^n e^{-\mu t \cdot p(t)}}{n!} \end{aligned} \quad (3.7)$$

where $P_{n|s}(t)$ denotes the probability of n vehicles remaining in [SD] at time t given

s vehicular arrivals during $(0, t)$, while $M_s(t)$ represents the probability of an event that s vehicular arrivals in time interval $(0, t)$.

Additionally, an arbitrary vehicle might arrive at segment $[SD]$ at time τ ($0 < \tau \leq t$). The equivalent event of observing this vehicle in $[SD]$ at time t is that the residence time of the vehicle is greater than $t - \tau$. Formula 3.8 shows the probability of the equivalent event.

$$P(u > t - \tau) = 1 - P(u \leq t - \tau) = 1 - F_T(t - \tau) \quad (3.8)$$

where u denotes the residence time of a random vehicle. Therefore, we can obtain the limiting behavior of $t \cdot p(t)$ by assuming $t \rightarrow \infty$, as described in Formula 3.9.

$$\begin{aligned} t \cdot p(t) &= t \cdot \int_0^t [1 - F_T(t - \tau)] \cdot \frac{1}{t} d\tau = \int_0^\infty [1 - F_T(\tau)] d\tau \\ &= \int_0^\infty \int_\tau^\infty f_T(t) dt d\tau = \int_0^\infty \int_0^t f_T(t) d\tau dt = E(T) \end{aligned} \quad (3.9)$$

Since we assume that vehicular arrival is a Poisson process, given a specific time interval, the arrival times are independently and uniformly distributed during this time period. In our case, the PDF of arrivals during $(0, t)$ is $1/t$, which has been employed in Formula 3.9. The closed-form expression of P_n , which represents the probability mass function (PMF) of the number of vehicles within $[SD]$, can be obtained by substituting Formula 3.9 into Formula 3.7; the result is shown in Formula 3.10.

$$P_n = \frac{[\mu E(T)]^n e^{-\mu E(T)}}{n!} \quad (3.10)$$

where $E(T)$ is the mean value of residence time within segment $[SD]$.

It is evident that the number of vehicles in roadway segment $[SD]$ over the long term is

a Poisson-distributed random variable with mean value $\mu E(T)$ according to Formula 3.10. Moreover, this distribution is independent of the vehicular velocities; in other words, the number of vehicles remains as a Poisson-distributed random variable, regardless of which velocity distribution is chosen to represent the traffic mobility within segment $[SD]$. The distribution in Formula 3.10 matches the results in [110], where the expected number of vehicles in segment $[SD]$ is discussed. Moreover, the limiting behavior of the variance of the counting process $\{N(t)|t \geq 0\}$ is expressed in Formula 3.11.

$$VAR(N) = \mu E(T) \quad (3.11)$$

It is noteworthy that variance $VAR(N)$ has the same form as mean value $E(N)$ in [110], which implies the percent variance is as high as 100%. However, in order to prove the feasibility of the vehicular cloud and utilize vehicles' excessive computing power, it is critical to demonstrate that a scenario very few vehicles exist in $[SD]$ is unlikely to occur, despite the high percent variance.

3.2 Queueing-up Model

Urban roads are more likely to be congested, due to a rapidly increasing number of vehicles and the traffic capacities of city roads. Figure 3.4 illuminates a normal traffic queue scenario. The bottleneck of the traffic could be an intersection, construction site or location of an accident. In general, the queue is bound to emerge when the departure rate is less than the arrival rate.

A few assumptions are made before we conduct our analysis. The roadway segment has only one lane, and the vehicular arrival follows a Poisson process with parameter λ , which means the inter-arrival time is an exponential distributed random variable

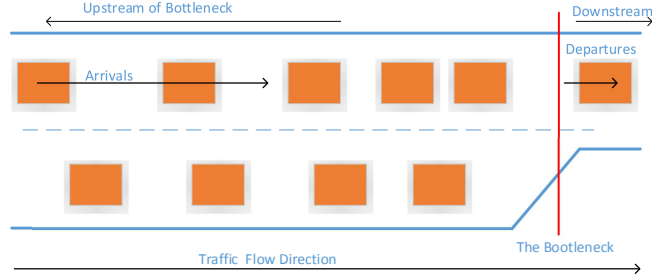


Figure 3.4: A illustration of a queue in a road segment

with parameter $1/\lambda$ [65]. In addition, we define the time it takes a vehicle to pass the bottleneck as the leaving time (τ). The total delay time D_i of an arbitrary vehicle i in a roadway segment is the summation of its waiting time W_i in the queue and the leaving time τ_i , as described in 3.12.

$$D_i = W_i + \tau_i \quad (3.12)$$

We consider the queue with some level of equilibrium, which means the initial conditions of this queue have faded out and the state probabilities are independent of the preconditions. Therefore, the expected length of the queue maintains a constant value. We defined traffic density ρ as the expected number of vehicular arrivals $E(V)$ within the time period of $E(\tau)$, which represents the expected value of the leaving time. Moreover, as the arrival process is Poissonian with rate λ , the vehicular arrival is a Poisson distributed random variable, with a mean value of $\lambda\tau$ for a given time range τ .

$$\rho = E(V) = \lambda E(\tau) \quad (3.13)$$

Since the expected value and the variance have the same form for a Poisson distribution, the second moment of the arrival process V is

$$E(V^2) = \text{VAR}(V) + E^2(V) = \lambda\tau + (\lambda\tau)^2 \quad (3.14)$$

According to Little's law, Formulas 3.13 and 3.14 as well as the mathematical deduction in [35] [51], the expected number of vehicles in the queueing system is

$$E(N) = \lambda E(W + \tau) = \rho + \frac{\lambda^2 \sigma_\tau^2 + \rho^2}{2(1 - \rho)} \quad (3.15)$$

in which σ_τ^2 represents the standard deviation of vehicular leaving time. We can easily derive the mean value of leaving time $E(\tau) = \rho/\lambda$ by utilizing Formula 3.13, then substitute $E(\tau)$ in 3.15 with ρ/λ . Eventually, we have the expected waiting time for a vehicle

$$E(W) = \frac{1}{\lambda}(E(N) - \lambda E(\tau)) = \frac{\lambda^2 \sigma_\tau^2 + \rho^2}{2\lambda(1 - \rho)} \quad (3.16)$$

Consequently, the expected traffic queue length is

$$E(Q) = \lambda E(W) = \frac{\lambda^2 \sigma_\tau^2 + \rho^2}{2(1 - \rho)} \quad (3.17)$$

Two specific scenarios are considered here.

- The leaving time is fixed. The standard variance for the leaving time is $\sigma_\tau^2 = 0$ in this case, so the Formula 3.17 becomes

$$E(Q) = \frac{\rho^2}{2(1 - \rho)} \quad (3.18)$$

- The leaving time is an exponentially distributed random variable. As a result, we have $\sigma_\tau^2 = E^2(\tau) = \rho^2/\lambda^2$, substituting in Formula 3.17 thus gives

$$E(Q) = \frac{\rho^2}{1 - \rho} \quad (3.19)$$

Utilizing the computing resources of vehicles in the queue requires more detailed information about the distribution of the queue length and waiting time, which represents the amount of resources and their time availability, respectively. The Pollackzek-Khinchin transform formula is used to derive the closed-form of the distribution; however, the numerical methods are employed when the closed-form is not available.

$$G_N(z) = \frac{(1 - \rho)(z - 1)b^*(\lambda(1 - z))}{z - b^*(\lambda(1 - z))} \quad (3.20)$$

where $G_N(z) = \sum_{k=0}^{\infty} Pr[N = k]z^k$ represents the generating function for N and $b^*(s)$ denotes Laplace transform of the PDF of leaving time. When the vehicular leaving time is an exponentially distributed random variable with mean value $1/\mu$, then the PDF of leaving time is $f_\tau(t) = \mu e^{-\mu t}$. Consequently, the Laplace transform of $f_\tau(t)$ is

$$b^*(s) = \int_0^{\infty} e^{-st} f_\tau(t) dt = \frac{\mu}{s + \mu} \quad (3.21)$$

Substituting $b^*(s)$ in Formula 3.20 with Formula 3.21, we can get the expression of $G_N(z)$ when the leaving time is exponentially distributed.

$$\begin{aligned} G_N(z) &= \frac{(1 - \rho)(z - 1) \frac{\mu}{\lambda(1-z) + \mu}}{z - \frac{\mu}{\lambda(1-z) + \mu}} = \frac{1 - \rho}{1 - \rho z} \\ &= \sum_{n=0}^{\infty} (1 - \rho) \rho^n \cdot z^n \end{aligned} \quad (3.22)$$

where we used the steady state condition ($\rho < 1$ and $|z| < 1$). Formula 3.22 implies the PMF of the number of vehicles $N(t)$ in the queue is

$$p_n = (1 - \rho)\rho^n \quad (n \geq 0) \quad (3.23)$$

Similarly, the PDF of the waiting time can be derived by using the Pollackzek-Khinchin transform formula 3.24

$$c^*(s) = \frac{(1 - \rho)s}{s - \lambda + \lambda b^*(s)} \quad (3.24)$$

where $c^*(s)$ represents the Laplace transform of the waiting time PDF $f_W(w)$. Replacing $b^*(s)$ with Formula 3.21 in Formula 3.24, we have

$$c^*(s) = (1 - \rho) \frac{s + \mu}{s + \mu - \lambda} = (1 - \rho) \left(1 + \frac{\lambda}{s + \mu - \lambda} \right) \quad (3.25)$$

Then we obtain the PDF of the waiting time by implementing the reverse Laplace transform of Formula 3.25

$$f_W(w) = (1 - \rho)\delta(w) + \rho(\mu - \lambda)e^{-(\mu - \lambda)w} \quad w > 0 \quad (3.26)$$

It is noteworthy that the delta function at $w = 0$ corresponds to the fact that an arbitrary vehicle has zero waiting time in the queue with probability $1 - \rho$.

In addition, we focus on the second scenario, in which a vehicles leaving time is deterministic, and assume the leaving rate has a fixed value of 1 vehicle/second. Therefore, the traffic intensity $\rho = \frac{\lambda}{\mu} = \lambda$. By Formula 3.20, we have

$$G_N(z) = \frac{(1 - \lambda)(z - 1)\exp(\lambda(z - 1))}{z - \exp(\lambda(z - 1))} \quad (3.27)$$

in which we used the mathematical fact that the PDF of a constant random variable (i.e. degenerate distribution) is a delta function at $t = 1s$ (first vehicle always leaves at 1s).

The explicit expression of PMF of $N(t)$ is obtained by the Taylor expansion of Formula 3.27, according to the deduction process in [47].

$$\begin{aligned}
 Pr[N = 0] &= 1 - \lambda \\
 Pr[N = 1] &= (1 - \lambda)(e^\lambda - 1) \\
 Pr[N = 2] &= (1 - \lambda) \left(e^{n\lambda} + \sum_{j=1}^{n-1} e^{j\lambda} (-1)^{n-j} \cdot \left[\frac{(j\lambda)^{n-j}}{(n-j)!} + \frac{(j\lambda)^{n-j-1}}{(n-j-1)!} \right] \right), \quad n \geq 2
 \end{aligned} \tag{3.28}$$

Similarly, the waiting time distribution can also be determined by using Formula 3.24 when the leaving time is a constant value.

$$c^*(s) = \frac{(1 - \lambda)s}{s - \lambda + \lambda e^{-s}} \tag{3.29}$$

where we assume the leaving rate $\mu = 1 \text{ vehicle/second}$ and consequently, the Laplace transform of leaving time becomes $b^*(s) = e^{-s}$ for the reason that the PDF of the leaving time is a delta function $\delta(t - 1)$ in this scenario. It might be hard to obtain the explicit form of the PDF of the waiting time from Formula 3.29. However, the numerical analysis can be achieved by implementing the fast Fourier transform methods on Formula 3.29.

Chapter 4

Analytical Results

From the models described in Chapter 3, we present a comprehensive discussion of the results obtained from our analysis on the two traffic scenarios: free-flow and queueing-up traffic. The analysis of the models consider different metrics and factors that might condition or restrict vehicle traffic flows. In order to observe the models conditioned under different situations, the models' parameters have been configured according to the value ranges described in Table 4.1.

In this study, traffic load and vehicles' residence times are the major factors we observe in our scenarios since the scope of this work concentrates on the utilization of excessive, under-utilized resources of vehicles in a road segment. Traffic load consists of the quantity of resources that can be harvested from vehicles, while residence time

Table 4.1: Summary of Experimental Parameters

<i>Name</i>	<i>Symbol & Units</i>	<i>Default Values</i>
Traffic Density	ρ (veh/meter)	0.07
Max Traffic Density	ρ_{max} (veh/meter)	0.25
Road Segment Length	L_{SD} (meter)	200
Maximum Speed	V_{max} (m/s)	50

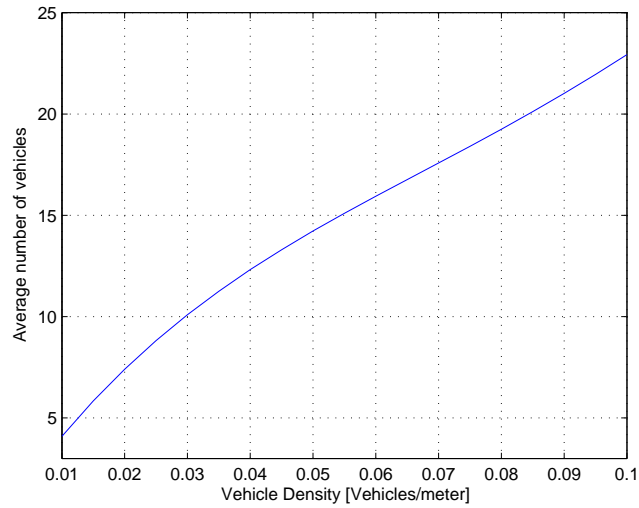


Figure 4.1: Average Number of Vehicles versus Vehicular Density over [SD]

determines the length of time resources are available.

4.1 Free-flow Model

By essence, the free-flow traffic model deals with low traffic density, with relatively high average speeds and low residence time. Even though this model represents a scenario in which it is impractical to employ computational resources because of the rapidly changing topology and sparsity of the vehicular network, it can provide beneficial solutions for intermittently-connected vehicular networks. An integration of this model with delay-tolerant mechanisms might serve and fit requirements to increase the packet delivery ratio.

4.1.1 Traffic Load

The relation between the analysis parameters and average number of vehicles within a road segment [SD] has been investigated as described in Formula 3.6 to provide a study on traffic load.

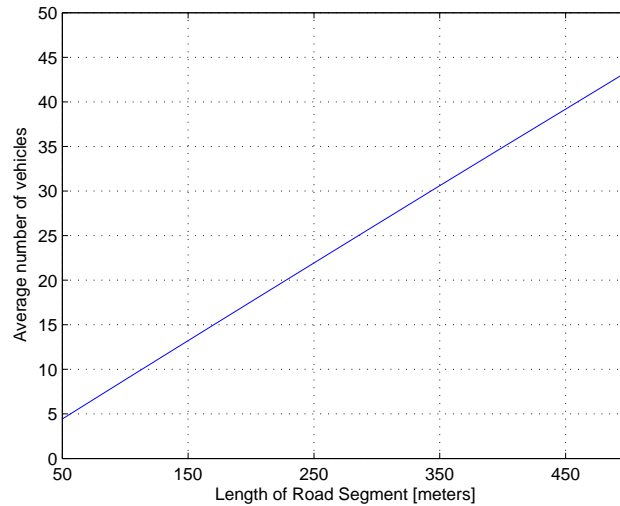


Figure 4.2: Average Number of Vehicles versus Road Length of [SD]

As depicted in Figure 3.6, the average number of vehicles within a road segment [SD] increases with the vehicular density growth. This behavior is conditioned through the average vehicle speed (\bar{V}), which decreases as ρ_v increases; consequently, the flow of vehicles also increases proportionally. Therefore, the arrival of vehicles in a road segment develops with growing frequency under such conditions.

Figure 4.2 provides analytical values that compare the average number of vehicles in a given road segment with its length. The chances of finding more vehicles in a road segment are directly proportional to the dimension of the segment. The figure shows that there is a linear association in the model that connects the quantity of vehicles and the segment length. From the analysis, the average vehicle residence time is longer in a longer road, when the speed distribution is the same. With the longer time required to traverse the road segment, the average number of vehicles within the segment increases proportionally, according to Little's law.

Figure 4.3 presents an analysis of the free-flow model on vehicle speed. Results show that the average number of vehicles in a road segment grows as the maximum vehicle

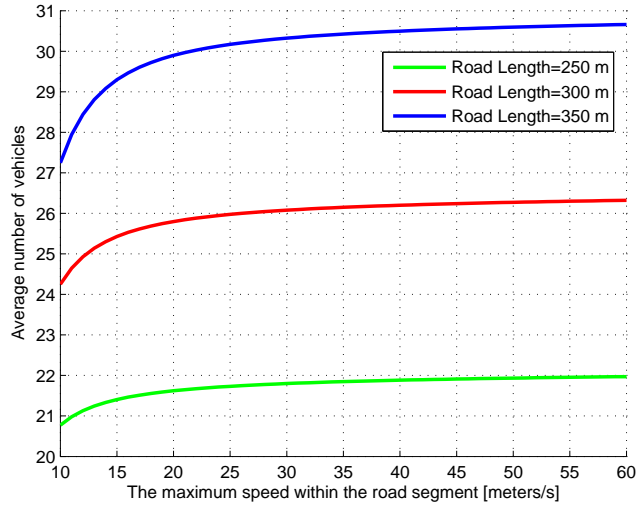
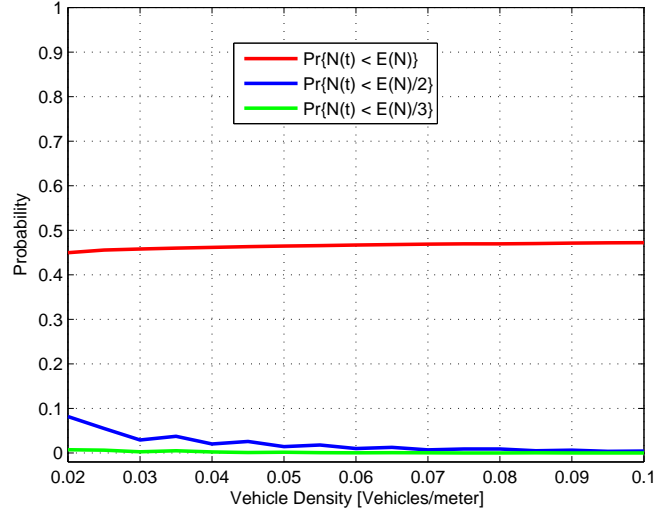


Figure 4.3: Average Number of Vehicles versus Max Speed Limit within [SD]

speed in the segment increases from 10 meters per second (36 km/h) to 60 meters per second (216 km/h); however, this behavior occurs at initial maximum speeds, and the number of vehicles asymptotically converges as the maximum surpasses a threshold. As described in Formula 3.1, the maximum speed directly influences the average vehicle speed, and a higher maximum speed consequently allows for an increase in the vehicle arrival rate μ . The average number of vehicles $E(N)$ also increases, as defined in Formula 3.6. Nevertheless, high vehicle speeds cause the average resident time $E(T)$ to decrease due to the limited, fixed road length. Finally, the decrease of average resident time neutralizes the increase of the vehicle arrival rate.

When the vehicle density in the road segment increases, the probability $Pr[N(t) < E(N)]$ converges to 0.5, based on Formula 3.10. This behavior is shown in Figure 4.4, which depicts that this probability tendency is expected, since both $VAR(N)$ and $E(N)$ equal $\mu E(T)$ for the defined Poisson process. Let vehicle density in a road segment of $\rho = 0.02$ (*vehicles/meter*); the probability of containing a number of vehicles within [SD] less than half of the expected value is 0.08. Assuming an increase in vehicle density (ρ), the

Figure 4.4: The Probability $P[N(t)]$

expected value quickly tends to 0. For example, the probability $Pr[N(t) < 6]$ is equal to 0.02 if the expected value of $N(t)$ is defined as 12 with a vehicle density of $\rho = 0.04$. These conditions ensure that there are more than 5 vehicles in the road segment $[SD]$ with a probability of 0.98. The value of probability $Pr[N(t) < E(N)/3]$ stands near zero for any vehicle density in the road segment, indicating that the probability of occurring at least $E(N)/3$ vehicles in the segment is 100%. This assures us that there are at least $E(N)/3$ vehicles within $[SD]$ at any time for utilization of any application.

The analysis of the number of vehicles in a road segment $[SD]$ is depicted in Figure 4.5. For instance, there is a probability of $Pr[N(t) > 7] > 0.99$ in encountering at least 7 vehicles in the segment, as the vehicle density equals $\rho = 0.06$. Furthermore, increasing the probability to 0.80, it is possible to find at least 12 vehicles in the segment. With a probability of 0.5 on the events, more than 15 vehicles are in road segment $[SD]$.

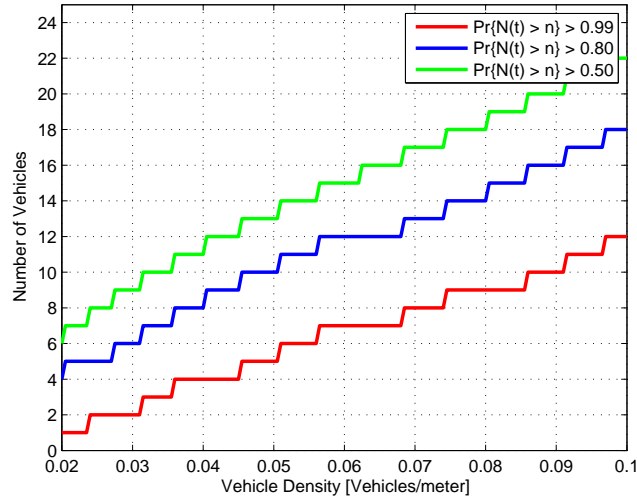


Figure 4.5: Number of Vehicles Distribution versus Vehicular Density

4.1.2 Residence Time

The residence time contains valuable information for vehicular clouds, since it estimates the time availability of a vehicle, as well as its computational resources, in a road segment. Estimating the availability of resources is essential for properly scheduling cloud tasks. In the context of free-flow traffic, the fixed road length and an increasing maximum speed causes the average residence time $E(T)$ to decrease, as described in Figure 4.6. As the average residence time decreases, the average number of vehicles in the road segment decreases; this behavior is depicted in Figure 4.3.

4.2 Queuing-up Model

Vehicles queuing-up in a road segment facilitates many promising applications, due to longer residence times and higher vehicle density in a road segment. For instance, vehicles under these circumstances can autonomously self-organize and dynamically build a vehicular cloud, which can help to solve traffic-related problems in real-time. Such

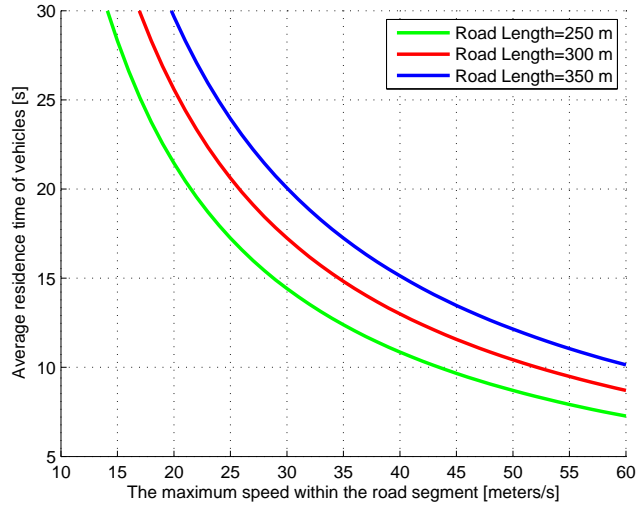


Figure 4.6: Average Residence Time versus Max Speed Limit within [SD]

a cloud can execute traffic management applications and dynamically and accordingly extend green lights in a given direction, for the sake of alleviating traffic congestion.

4.2.1 Traffic Load

The average number of vehicles in a road segment increases in accordance with the intensity of the traffic. This behavior follows the queueing-up model described in Formulas 3.18 and 3.19, and is shown in Figure 4.7. The average number of vehicles increases to a large value in the event that the traffic intensity is close to 1, representing an intense traffic jam in the segment. For instance, the average number of vehicles in the queue is $E(Q) = 0.8^2 / (1 - 0.8) = 3.2$ when the leaving time is exponentially distributed and with $\rho = 0.8$. Following this relation, $\rho = 0.88$ leads to an average number of vehicles of $E(Q) = 6.4$. Consequently, an increase of $0.08 / 0.8 = 10\%$ in the arrival rate leads to a 100% increase in the mean number of queueing vehicles.

Formula 3.23 provides PMF of the number of vehicles in the queue, considering that the leaving time is exponentially distributed, and including the departing time vehicle

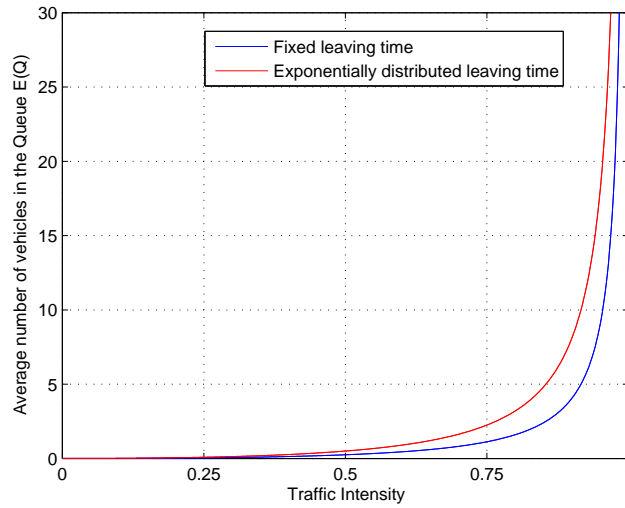


Figure 4.7: Mean Number of Vehicles in a Roadway Segment versus Traffic Intensity

in the segment. Figure 4.8 depicts the behavior of the PMF in the queueing-up model, in which we focus on achieving an equilibrium scenario that satisfies the condition $\rho = \frac{\lambda}{\mu} < 1$. As described in the figure, the traffic queue shows a lower chance to occur, close to 0, as the departure rate of vehicles is twice the size of the arrival rate, represented by $\rho = 0.5$. The PMF also shows a uniform distribution, as the arrival rate is close to the departure rate ($\rho = 0.99$). This demonstrates that the number of vehicles can become very large in the presence of probability such as a situation with a low number of queued vehicles. Figure 4.9 indicates that the probability of the number of queueing vehicles is conditioned by a given number. This demonstrates that it is very unlikely that more than 5 vehicles will be queued with $\rho = 0.5$. The same close-to-zero chance is observed with 13 vehicles, $P[N(t) > 13]$, with $\rho = 0.75$. However, encountering more than 20 vehicles in the queue occurs with a probability of 0.82 with $\rho = 0.99$. This shows a high chance of forming a queue in the road segment, increasing the chances that resources might be utilized.

In the scenario in which the leaving time of vehicles is constant, different distributions are obtained, as depicted in Figures 4.10 and 4.11. Compared with a scenario that shows

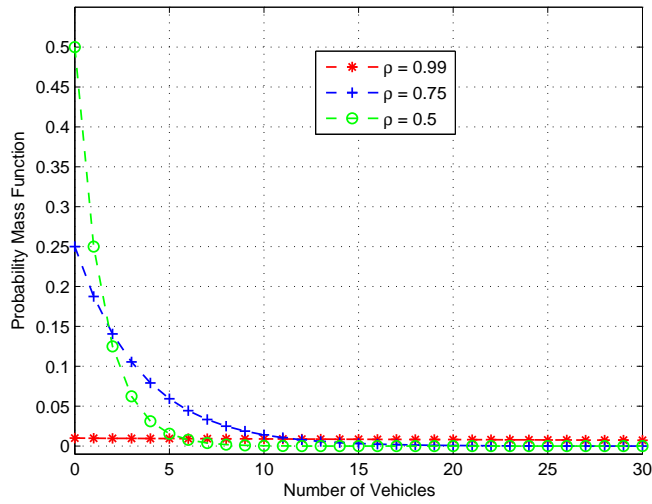


Figure 4.8: Probability Mass Function

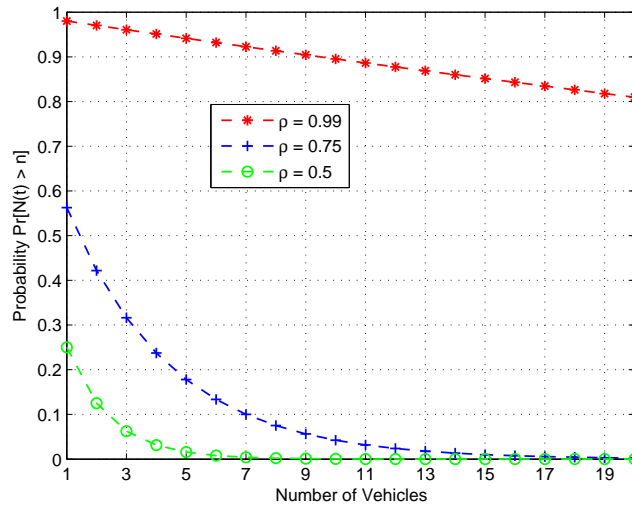


Figure 4.9: Number of Vehicles with Exponential Leaving Time

the exponentially distributed leaving time of vehicles, the fixed leaving time matches some aspects; for instance, with low ρ , the PMF and probability curves follow the same pattern, showing similar values. The difference resides on $\rho = 0.99$; in this case, the probability of encountering more than 20 vehicles in the road segment is 68% for a fixed leaving time. This presents a lower value when compared with the exponentially distributed leaving time scenario, which shows a chance of 82% under the same conditions. This difference

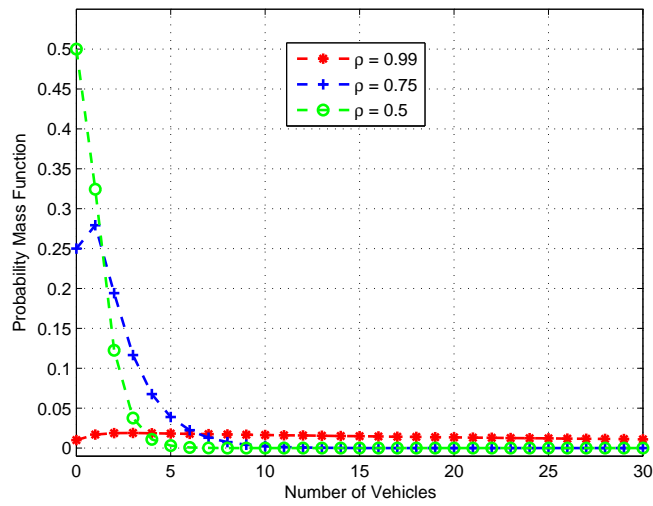


Figure 4.10: Probability Mass Function

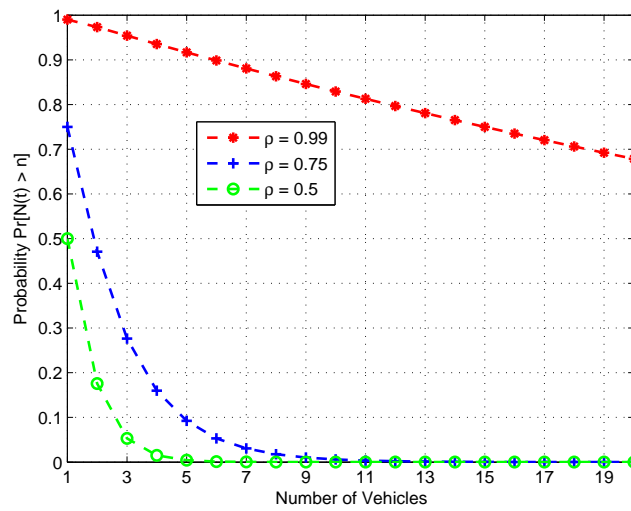


Figure 4.11: Number of Vehicles with Fixed Leaving Time

is justified in Figure 4.7, which shows that an exponentially distributed leaving time scenario presents a larger number of vehicles in the segment than a fixed leaving time scenario does.

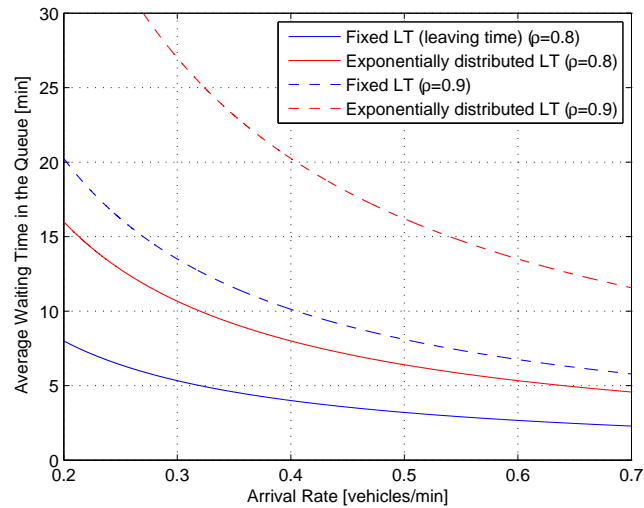


Figure 4.12: Mean Waiting Time in the Queue Arrival Rate

4.2.2 Residence Time

The residence time is a significant metric that provides a means of determining the amount of time computing resources are available in the road segment, in order to schedule and migrate applications and tasks. Figure 4.12 presents the average waiting times of vehicles in a traffic queue of our exponentially distributed and fixed leaving time scenarios with $\rho = 0.8, 0.9$.

Figure 4.13 depicts the PDF of the waiting times of vehicles in a queue with an arrival rate of $\mu = 1$, and the leaving time of vehicles follows a random variable with exponential distribution. The analytical results totally match the behavior of the PMF shown in Figure 4.8 with $\rho = 0.5$, which means that 50% of the vehicles traverse the road segment without waiting in the queue. With $\rho = 0.99$, it is observed that the waiting time of vehicles is uniformly distributed over a long time frame. Larger wait times occur due to arrival rates close proximity to departure rates.. The times are better described in Figure 4.14, which contains probabilities of waiting times according to different arrival rates. For a $\rho = 0.5$, it is very unlikely that any vehicle will wait in the queue for longer

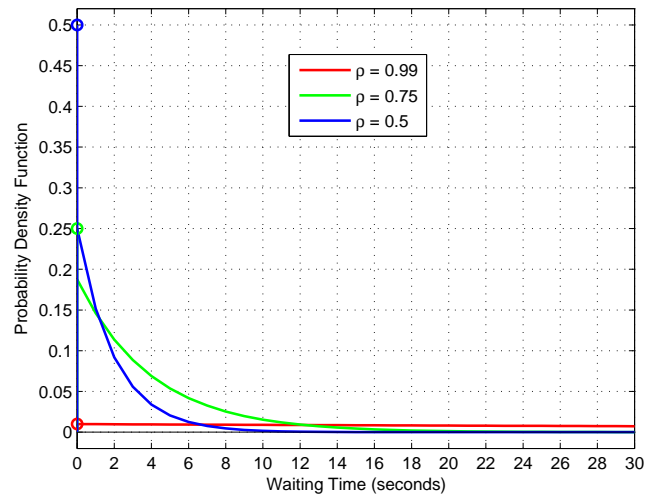


Figure 4.13: PDF of Waiting Time in the Queue with Exponential Leaving Time

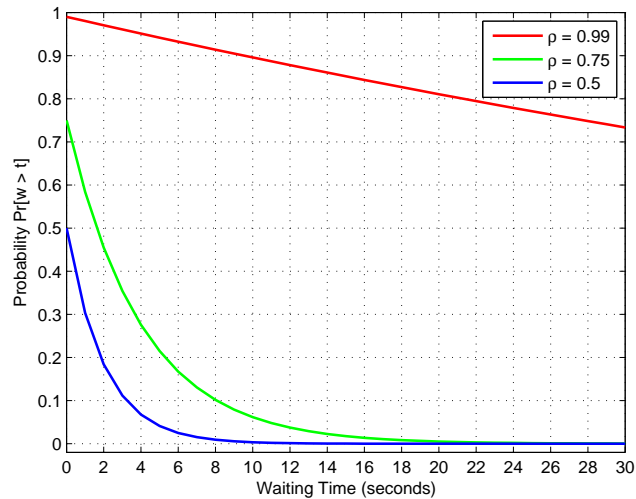


Figure 4.14: $\Pr[W(w) > t]$ with Exponential Leaving Time

than 8 seconds. On the other hand, with $\rho = 0.99$, there is a probability of 0.75 that it will take longer than 30 seconds for vehicles to traverse the road segment.

Finally, waiting times in the queue according to the fixed leaving time scenario are depicted by Figures 4.15 and 4.16. Consistent with the results presented in Figure 4.12, the fixed leaving time scenario describes shorter leaving times when compared with the

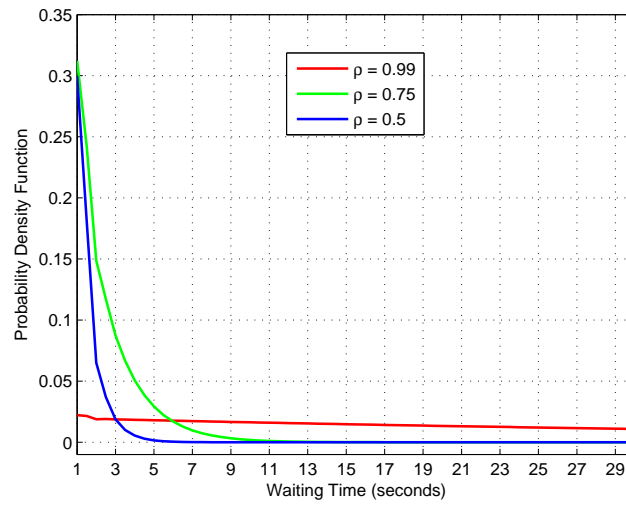


Figure 4.15: PDF of Waiting Time in the Queue with Fixed Leaving Time

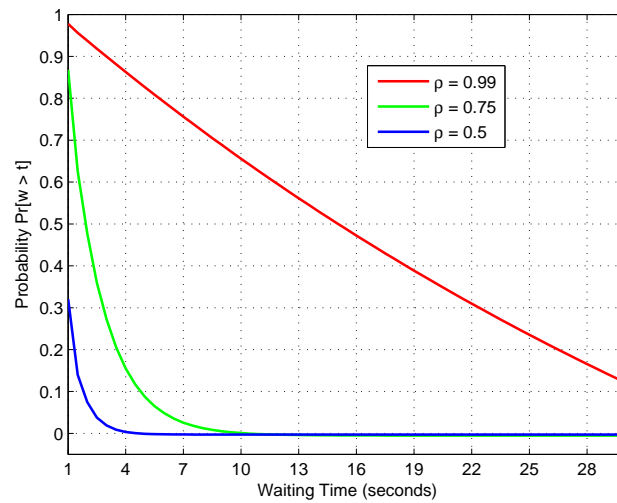


Figure 4.16: $\Pr[W(w)>t]$ with Fixed Leaving Time

exponentially distributed leaving time scenario.

Chapter 5

Conclusion and Future Work

In this study, we took a very first step towards implementation of a vehicular cloud, namely collecting the computing resources of moving vehicles in a rather dynamic environment, a roadway segment.

5.1 Conclusion

We have described two traffic flow models to represent the behavior of vehicles in a road segment. The models provide the analytical means for dynamically estimating the availability of computational resources in the traffic network, and can integrate a vehicular cloud. The proposed models reflect two common scenarios: free-flow and queueing-up traffic. Different from the previous works that explore such resources in a static environment, like the long-term resting of vehicles in an airport parking lot, this work observes a rather dynamic environment, with a limited residence time of vehicles in a road segment, lasting for a matter of seconds or minutes. The estimates allow the design of models to determine the feasibility and possible scenarios for assigning computational tasks to vehicles, as well as migrating tasks from departing vehicles to those arriving in a road

segment. Cluster computing with mobile nodes and message passing interface [69] are approaches for resolving assignment issues.

5.2 Future Work

Our future work consists of implementing our free-flow traffic model and evaluating it through simulators, such as NS2 [73] or OMNeT++ [97], to observe the distribution of computational tasks on vehicles in a road segment and the effect of load migrations among vehicles. The work in [83] could be our step stone to explore this direction. In a less dynamic scenario, the queueing-up traffic situation, we intend to couple our model with scheduling techniques to determine the best task assignment for benefiting applications. In the context of unexpected critical traffic issues, it is ideal that processing deadlines are matched with the time span of an on-demand assembled vehicular cloud. Thus, critical applications spawned for solving critical issues are able to conclude their execution, resulting in a valuable answer. Moreover, our work explored the traffic flow in single-lane road segments in which an equilibrium is achieved. This scenario is expected to be extended into multi-lane road segments, involving non-equilibrium queues.

Appendix A

Glossary of Terms

API	Application Program Interface
Caas	Cooperation as a Service
CC	Cloud Computing
CDF	Cumulative Distribution Function
CompaaS	Computation as a Service
DSRC	Dedicated Short Range Communications
EC2	Amazon Elastic Computing Cloud
GIS	Geographic Information System
GPS	Global Positioning System
IaaS	Infrastructure as a Service
MANET	Mobile Adhoc Network
MCC	Multiple Input Multiple Output

NaaS	Network as a Service
OBU	On Board Unit
PaaS	Platform as a Service
PDF	Probability Distribution Function
PMF	Probability Mass Function
QoS	Quality of Service
RFID	Radio Frequency IDentification
RSU	Road Side Unit
SaaS	Software as a Service
STaaS	Storage as a Service
V2I	Vehicle to Infrastructure Communication
V2V	Vehicle to Vehicle Communication
VANET	Vehicular Adhoc Network
VC	Vehicular Cloud
VCC	Vehicular Cloud Computing
VDC	Vehicular Data Center
WAVE	Wireless Access in Vehicular Environment
ZOI	Zone of Interest

Bibliography

- [1] A. Abdrabou and W. Zhuang. Probabilistic delay control and road side unit placement for vehicular ad hoc networks with disrupted connectivity. *IEEE Journal on Selected Areas in Communications*, 29(1):129–139, January 2011.
- [2] K. Abrougui, A. Boukerche, and R. W. N. Pazzi. Design and evaluation of context-aware and location-based service discovery protocols for vehicular networks. *IEEE Transactions on Intelligent Transportation Systems*, 12(3):717–735, Sept 2011.
- [3] Mahmoud Abuelela and Stephan Olariu. Taking vanet to the clouds. In *Proceedings of the ACM Int. Conference on Advances in Mobile Computing and Multimedia*, pages 6–13, 2010.
- [4] O. Abumansoor and A. Boukerche. A secure cooperative approach for nonline-of-sight location verification in vanet. *IEEE Transactions on Vehicular Technology*, 61(1):275–285, Jan 2012.
- [5] A. A. Agashe and S. K. Bodhe. Performance evaluation of mobility models for wireless ad hoc networks. In *Emerging Trends in Engineering and Technology, 2008. ICETET '08. First International Conference on*, pages 172–175, July 2008.
- [6] E. E. Ajaltouni, A. Boukerche, and M. Zhang. An efficient dynamic load balancing scheme for distributed simulations on a grid infrastructure. In *Distributed*

- Simulation and Real-Time Applications, 2008. DS-RT 2008. 12th IEEE/ACM International Symposium on*, pages 61–68, Oct 2008.
- [7] Saif Al-Sultan, Moath M. Al-Doori, Ali H. Al-Bayatti, and Hussien Zedan. A comprehensive survey on vehicular ad hoc network. *Journal of Network and Computer Applications*, 37:380 – 392, 2014.
- [8] EC Amazon. Amazon elastic compute cloud (amazon ec2). *Amazon Elastic Compute Cloud (Amazon EC2)*, 2010.
- [9] S. Arif, S. Olariu, Jin Wang, Gongjun Yan, Weiming Yang, and I. Khalil. Datacenter at the airport: Reasoning about time-dependent parking lot occupancy. *IEEE Transactions on Parallel and Distributed Systems*, 23(11):2067–2080, 2012.
- [10] Michael Armbrust, Armando Fox, Rean Griffith, Anthony D. Joseph, Randy Katz, Andy Konwinski, Gunho Lee, David Patterson, Ariel Rabkin, Ion Stoica, and Matei Zaharia. A view of cloud computing. *Commun. ACM*, 53(4):50–58, April 2010.
- [11] Ashwin Ashok, Peter Steenkiste, and Fan Bai. Enabling vehicular applications using cloud services through adaptive computation offloading. In *Proceedings of the 6th International Workshop on Mobile Cloud Computing and Services, MCS '15*, pages 1–7, New York, NY, USA, 2015. ACM.
- [12] Lee Badger, Tim Grance, Robert Patt-Corner, and Jeff Voas. Draft cloud computing synopsis and recommendations. *NIST special publication*, 800:146, 2011.
- [13] S. Bitam, A. Mellouk, and S. Zeadally. Vanet-cloud: a generic cloud computing model for vehicular ad hoc networks. *IEEE Wireless Communications*, 22(1):96–102, February 2015.

- [14] A. Boukerche and X. Fei. A voronoi approach for coverage protocols in wireless sensor networks. In *IEEE GLOBECOM 2007 - IEEE Global Telecommunications Conference*, pages 5190–5194, Nov 2007.
- [15] A. Boukerche and Xu Li. An agent-based trust and reputation management scheme for wireless sensor networks. In *GLOBECOM '05. IEEE Global Telecommunications Conference, 2005.*, volume 3, pages 5 pp.–, Nov 2005.
- [16] A. Boukerche, N. J. McGraw, C. Dzermajko, and Kaiyuan Lu. Grid-filtered region-based data distribution management in large-scale distributed simulation systems. In *38th Annual Simulation Symposium*, pages 259–266, April 2005.
- [17] A. Boukerche, H. A. B. F. Oliveira, E. F. Nakamura, and A. A. F. Loureiro. Secure localization algorithms for wireless sensor networks. *IEEE Communications Magazine*, 46(4):96–101, April 2008.
- [18] A. Boukerche, H. A. B. F. Oliveira, E. F. Nakamura, and A. A. F. Loureiro. Dv-loc: a scalable localization protocol using voronoi diagrams for wireless sensor networks. *IEEE Wireless Communications*, 16(2):50–55, April 2009.
- [19] A. Boukerche, R. W. N. Pazzi, and R. B. Araujo. Hpeq a hierarchical periodic, event-driven and query-based wireless sensor network protocol. In *The IEEE Conference on Local Computer Networks 30th Anniversary (LCN'05)*, pages 560–567, Nov 2005.
- [20] A. Boukerche, C. Rezende, and R. W. Pazzi. Improving neighbor localization in vehicular ad hoc networks to avoid overhead from periodic messages. In *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, pages 1–6, Nov 2009.

- [21] A. Boukerche and S. Rogers. Gps query optimization in mobile and wireless networks. In *Computers and Communications, 2001. Proceedings. Sixth IEEE Symposium on*, pages 198–203, 2001.
- [22] A. Boukerche, A. Zarrad, and R. Araujo. A cross-layer approach-based gnutella for collaborative virtual environments over mobile ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems*, 21(7):911–924, July 2010.
- [23] Azzedine Boukerche and Kaouther Abrougui. An efficient leader election protocol for mobile networks. In *Proceedings of the 2006 International Conference on Wireless Communications and Mobile Computing, IWCMC '06*, pages 1129–1134, New York, NY, USA, 2006. ACM.
- [24] Azzedine Boukerche and Luciano Bononi. *Simulation and Modeling of Wireless, Mobile, and AD HOC Networks*, pages 373–409. John Wiley & Sons, Inc., 2005.
- [25] Azzedine Boukerche, Ioannis Chatzigiannakis, and Sotiris Nikolettseas. A new energy efficient and fault-tolerant protocol for data propagation in smart dust networks using varying transmission range. *Computer Communications*, 29(4):477 – 489, 2006. Current areas of interest in wireless sensor networks designs.
- [26] Azzedine Boukerche and Amir Darehshoorzadeh. Opportunistic routing in wireless networks: Models, algorithms, and classifications. *ACM Comput. Surv.*, 47(2):22:1–22:36, November 2014.
- [27] Azzedine Boukerche and Caron Dzermajko. Performance evaluation of data distribution management strategies. *Concurrency and Computation: Practice and Experience*, 16(15):1545–1573, 2004.

- [28] Azzedine Boukerche and Xin Fei. A coverage-preserving scheme for wireless sensor network with irregular sensing range. *Ad Hoc Networks*, 5(8):1303 – 1316, 2007. Recent Research Directions in Wireless Ad Hoc Networking.
- [29] Azzedine Boukerche, Xin Fei, and Regina B. Araujo. An optimal coverage-preserving scheme for wireless sensor networks based on local information exchange. *Computer Communications*, 30(1415):2708 – 2720, 2007. Network Coverage and Routing Schemes for Wireless Sensor Networks.
- [30] Azzedine Boukerche, Anahit Martirosyan, and Richard Pazzi. An inter-cluster communication based energy aware and fault tolerant protocol for wireless sensor networks. *Mob. Netw. Appl.*, 13(6):614–626, December 2008.
- [31] Azzedine Boukerche and Sotiris Nikolettseas. *Wireless Communications Systems and Networks*, chapter Protocols for Data Propagation in Wireless Sensor Networks, pages 23–51. Springer US, Boston, MA, 2004.
- [32] G. Castignani, T. Derrmann, R. Frank, and T. Engel. Driver behavior profiling using smartphones: A low-cost platform for driver monitoring. *IEEE Intelligent Transportation Systems Magazine*, 7(1):91–102, Spring 2015.
- [33] Bo Chen, Reza Curtmola, Giuseppe Ateniese, and Randal Burns. Remote data checking for network coding-based distributed storage systems. In *Proceedings of the ACM Workshop on Cloud Computing Security Workshop*, pages 31–42, 2010.
- [34] Dewang Chen, Junping Zhang, Shuming Tang, and Jue Wang. Freeway traffic stream modeling based on principal curves and its analysis. *IEEE Transactions on Intelligent Transportation Systems*, 5(4):246–258, Dec 2004.

- [35] D. R. Cox. A use of complex probabilities in the theory of stochastic processes. *Mathematical Proceedings of the Cambridge Philosophical Society*, 51:313–319, 1955.
- [36] H. A. B. F. de Oliveira, A. Boukerche, E. F. Nakamura, and A. A. F. Loureiro. An efficient directed localization recursion protocol for wireless sensor networks. *IEEE Transactions on Computers*, 58(5):677–691, May 2009.
- [37] Hoang T. Dinh, Chonho Lee, Dusit Niyato, and Ping Wang. A survey of mobile cloud computing: architecture, applications, and approaches. *Wireless Communications and Mobile Computing*, 13(18):1587–1611, 2013.
- [38] Falko Dressler, Philipp Handle, and Christoph Sommer. Towards a vehicular cloud - using parked vehicles as a temporary network and storage infrastructure. In *Proceedings of the 2014 ACM International Workshop on Wireless and Mobile Technologies for Smart Cities, WiMobCity '14*, pages 11–18, New York, NY, USA, 2014. ACM.
- [39] M. Hashem Eiza, Q. Ni, and Q. Shi. Secure and privacy-aware cloud-assisted video reporting service in 5g enabled vehicular networks. *IEEE Transactions on Vehicular Technology*, PP(99):1–1, 2016.
- [40] G. Galante and L. C. E. d. Bona. A survey on cloud computing elasticity. In *Utility and Cloud Computing (UCC), 2012 IEEE Fifth International Conference on*, pages 263–270, Nov 2012.
- [41] Vaibhav A Gandhi and CK Kumbharana. Comparative study of amazon ec2 and microsoft azure cloud architecture. *International Journal of Advanced Networking & Applications*, 2014.

- [42] Darrin Garrett and Darren Mann. Assessment of electronic sensor data to remotely identify a motor vehicle and monitor driver behavior, December 24 2015. US Patent 20,150,371,465.
- [43] M. Gerla, Eun-Kyu Lee, G. Pau, and Uichin Lee. Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds. In *Internet of Things (WF-IoT), 2014 IEEE World Forum on*, pages 241–246, March 2014.
- [44] M. Gerla, J. T. Weng, and G. Pau. Pics-on-wheels: Photo surveillance in the vehicular cloud. In *Computing, Networking and Communications (ICNC), 2013 International Conference on*, pages 1123–1127, Jan 2013.
- [45] Rahul Ghosh, Francesco Longo, Vijay K Naik, and Kishor S Trivedi. Modeling and performance analysis of large scale iaas clouds. *Future Generation Computer Systems*, 29(5):1216–1234, 2013.
- [46] M. Gramaglia, P. Serrano, J.A. Hernandez, M. Calderon, and Carlos J. Bernardos. New insights from the analysis of free flow vehicular traffic in highways. In *Proceedings of the IEEE Int. Symposium on a World of Wireless, Mobile and Multimedia Networks*, pages 1–9, 2011.
- [47] Donald Gross, John F. Shortle, James M. Thompson, and Carl M. Harris. *Fundamentals of Queueing Theory*. Wiley-Interscience, 4th edition, 2008.
- [48] Lin Gu, Deze Zeng, and Song Guo. Vehicular cloud computing: A survey. In *Proceedings of the IEEE Globecom Workshops*, pages 403–407, Dec 2013.
- [49] Lin Gu, Deze Zeng, Song Guo, and Baoliu Ye. Leverage parking cars in a two-tier data center. In *Proceedings of the IEEE Wireless Communications and Networking Conference*, pages 4665–4670, 2013.

- [50] V. Hahanov, W. Gharibi, B. A. A. Abbas, S. Chumachenko, O. Guz, and E. Litvinova. Cloud traffic monitoring and control. In *Intelligent Data Acquisition and Advanced Computing Systems (IDAACS), 2013 IEEE 7th International Conference on*, volume 01, pages 244–248, Sept 2013.
- [51] Frank A. Haight. *Mathematical Theories of Traffic Flow*. Academic Press, 1963.
- [52] Brian Hayes. Cloud computing. *ACM Communications*, 51(7):9–11, 2008.
- [53] Rasheed Hussain, Junggab Son, Hasoo Eun, Sangjin Kim, and Heekuck Oh. Rethinking vehicular communications: Merging vanet with cloud computing. In *Proceedings of the IEEE CloudCom*, pages 606–609, 2012.
- [54] Pietro Iannucci, Manav Gupta, et al. *IBM SmartCloud: Building a Cloud Enabled Data Center*. IBM Redbooks, 2013.
- [55] Daniel Jiang and Luca Delgrossi. Ieee 802.11 p: Towards an international standard for wireless access in vehicular environments. In *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, pages 2036–2040. IEEE, 2008.
- [56] Ming-Kai Jiau, Shih-Chia Huang, Jenq-Neng Hwang, and A. V. Vasilakos. Multimedia services in cloud-based vehicular networks. *IEEE Intelligent Transportation Systems Magazine*, 7(3):62–79, Fall 2015.
- [57] Algimantas Kajackas, Antanas Vindašius, and Šarūnas Stanaitis. Inter-vehicle communication: Emergency message delay distributions. *Elektronika ir Elektrotechnika*, 96(8):55–58, 2015.
- [58] Sapna S Kaushik. Review of different approaches for privacy scheme in vanets. *Int. J. Adv. Eng. Technol*, 5:2231–1963, 2013.

- [59] John B Kenney. Dedicated short-range communications (dsrc) standards in the united states. *Proceedings of the IEEE*, 99(7):1162–1182, 2011.
- [60] M.J. Khabbaz, W.F. Fawaz, and C.M. Assi. A simple free-flow traffic model for vehicular intermittently connected networks. *IEEE Transactions on Intelligent Transportation Systems*, 13(3):1312–1326, 2012.
- [61] Ryangsoo Kim, Hyuk Lim, and B. Krishnamachari. Prefetching-based data dissemination in vehicular cloud systems. *IEEE Transactions on Vehicular Technology*, 65(1):292–306, Jan 2016.
- [62] Won Kim. Cloud computing: Today and tomorrow. *Journal of object technology*, 8(1):65–72, 2009.
- [63] Wooseong Kim and M. Gerla. Navopt: Navigator assisted vehicular route optimizer. In *Proceedings of the Int. Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, pages 450–455, 2011.
- [64] Neeraj Kumar, Kuljeet Kaur, Subhas C. Misra, and Rahat Iqbal. An intelligent rfid-enabled authentication scheme for healthcare applications in vehicular mobile cloud. *Peer-to-Peer Networking and Applications*, pages 1–17, 2015.
- [65] Alberto Leon-Garcia. *Probability, Statistics, and Random Processes for Electrical Engineering*. Prentice Hall, Englewood Cliffs, NJ, 2008.
- [66] Gang Lu and Wen Hua Zeng. Cloud computing survey. In *Applied Mechanics and Materials*, volume 530, pages 650–661. Trans Tech Publ, 2014.
- [67] M. Ma, Y. Huang, C. H. Chu, and P. Wang. User-driven cloud transportation system for smart driving. In *Cloud Computing Technology and Science (CloudCom), 2012 IEEE 4th International Conference on*, pages 658–665, Dec 2012.

- [68] Yajie Ma, Yike Guo, Xiangchuan Tian, and M. Ghanem. Distributed clustering-based aggregation algorithm for spatial correlated sensor networks. *Sensors Journal, IEEE*, 11(3):641–648, March 2011.
- [69] ElsaM. Macias, Alvaro Suarez, and Vaidy Sunderam. An approach toward mpi applications in wireless networks. In *Distributed and Parallel Systems*, volume 777 of the *Int. Series in Engineering and Computer Science*, pages 55–62. Springer US, 2005.
- [70] Tuomas Mäkilä, Antero Järvi, Mikko Rönkkö, and Jussi Nissilä. How to define software-as-a-service—an empirical study of finnish saas providers. In *Software business*, pages 115–124. Springer, 2010.
- [71] F. Malandrino, C. Casetti, C. Chiasserini, and M. Fiore. Content downloading in vehicular networks: What really matters. In *Proceedings of the IEEE INFOCOM*, pages 426–430, 2011.
- [72] MCC Forum. Discover the world of mobile cloud computing, 2011. [Online] <http://http://www.mobilecloudcomputingforum.com/>.
- [73] S. McCanne and S. Floyd. Network simulator, 1999. [Online] <http://www.isi.edu/nsnam/ns/>.
- [74] Mohamed Nidhal Mejri, Jalel Ben-Othman, and Mohamed Hamdi. Survey on {VANET} security challenges and possible cryptographic solutions. *Vehicular Communications*, 1(2):53 – 66, 2014.
- [75] Peter M. Mell and Timothy Grance. Sp 800-145. the nist definition of cloud computing. Technical report, National Institute of Standards & Technology, Gaithersburg, MD, United States, 2011.

- [76] Lusheng Miao, Karim Djouani, Barend J van Wyk, and Yskandar Hamam. Evaluation and enhancement of iee 802.11 p standard: A survey. *Mobile Computing*, 1(1):15–30, 2012.
- [77] National Institute of Standards and Technology (NIST). Draft cloud computing synopsis and recommendations definition of cloud computing, 2011. [Online] <http://csrc.nist.gov/publications/drafts/800-146/Draft-NIST-SP800-146.pdf>.
- [78] S. Olariu, T. Hristov, and G. Yan. The next paradigm shift: From vehicular networks to vehicular clouds. In S. Basagni, M. Conti, S. Giordano, and I. Stojmenovic, editors, *Mobile Ad Hoc Networking: Cutting Edge Directions*, chapter 19. John Wiley & Sons, Inc., 2nd edition, 2013.
- [79] Stephan Olariu, Ismail Khalil, and Mahmoud Abuelela. Taking vanet to the clouds. *Int. Journal of Pervasive Computing and Communications*, 7(1):7–21, 2011.
- [80] Horacio ABF Oliveira, Eduardo F Nakamura, Antonio AF Loureiro, and Azzedine Boukerche. Error analysis of localization systems for sensor networks. In *Proceedings of the 13th annual ACM international workshop on Geographic information systems*, pages 71–78. ACM, 2005.
- [81] S. Panwai and H. Dia. Comparative evaluation of microscopic car-following behavior. *IEEE Transactions on Intelligent Transportation Systems*, 6(3):314–325, Sept 2005.
- [82] P. Papadimitratos, A. La Fortelle, K. Evensen, R. Brignolo, and S. Cosenza. Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation. *IEEE Communications Magazine*, 47(11):84–95, 2009.

- [83] Mohammad Pasha, Mohd Umar Farooq, and Khaleel-Ur-Rahman Khan. *Innovations in Computer Science and Engineering: Proceedings of the Third ICICSE, 2015*, chapter A Proof-of-Concept Model for Vehicular Cloud Computing Using OMNeT++ and SUMO, pages 193–198. Springer Singapore, Singapore, 2016.
- [84] H. Ramzan and A. Iqbal. Throughput and connectivity using constraint based mobility model for mobile ad hoc networks. In *Multitopic Conference, 2008. INMIC 2008. IEEE International*, pages 249–254, Dec 2008.
- [85] Prabhakar Ranjan and Kamal Kant Ahirwar. Comparative study of vanet and manet routing protocols. In *Proceedings of the International Conference on Advanced computing and communication Technologies (ACCT 2011)*, 2011.
- [86] M. Raya, P. Papadimitratos, V.D. Gligor, and J.-P. Hubaux. On data-centric trust establishment in ephemeral ad hoc networks. In *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, April 2008.
- [87] T.K. Refaat, B. Kantarci, and H.T. Mouftah. Dynamic virtual machine migration in a vehicular cloud. In *Proceedings of the IEEE Symposium on Computers and Communication*, volume Workshops, pages 1–6, June 2014.
- [88] Y. Ren and A. Boukerche. Modeling and managing the trust for wireless and mobile ad hoc networks. In *2008 IEEE International Conference on Communications*, pages 2129–2133, May 2008.
- [89] R. P. Roess, E. S. Prassas, and W. R. McShane. *Traffic Engineering*. Prentice Hall, Englewood Cliffs, NJ, 4th edition, 2010.

- [90] Mukesh Saini, Kazi Masudul Alam, Haolin Guo, Abdulhameed Alelaiwi, and Abdulmotaleb El Saddik. Incloud: a cloud-based middleware for vehicular infotainment systems. *Multimedia Tools and Applications*, pages 1–29, 2016.
- [91] S. Samarah, M. Al-Hajri, and A. Boukerche. A predictive energy-efficient technique to support object-tracking sensor networks. *IEEE Transactions on Vehicular Technology*, 60(2):656–663, Feb 2011.
- [92] Z. Sanaei, S. Abolfazli, A. Gani, and R. Buyya. Heterogeneity in mobile cloud computing: Taxonomy and open challenges. *IEEE Communications Surveys Tutorials*, 16(1):369–392, First 2014.
- [93] Christian Schindelhauer, Tamás Lukovszki, Stefan Rührup, and Klaus Volbert. Worst case mobility in ad hoc networks. In *Proceedings of the Fifteenth Annual ACM Symposium on Parallel Algorithms and Architectures*, SPAA '03, pages 230–239, New York, NY, USA, 2003. ACM.
- [94] C.K. Toh. *Ad Hoc Wireless Networks: Protocols and Systems*. Prentice Hall PTR, 1st edition, 2001.
- [95] US Department of Transportation, Research and Innovative Technology Association. National transportation statistics, 2012. [Online] http://www.bts.gov/publications/national_transportation_statistics/.
- [96] Hamed Vahdat-Nejad, Azam Ramazani, Tahereh Mohammadi, and Wathiq Mansoor. A survey on context-aware vehicular network applications. *Vehicular Communications*, 3:43 – 57, 2016.

- [97] András Varga and Rudolf Hornig. An overview of the omnet++ simulation environment. In *Proceedings of the Int. Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops*, pages 60:1–60:10, 2008.
- [98] L. A. Villas, A. Boukerche, H. S. Ramos, H. A. B. F. de Oliveira, R. B. de Araujo, and A. A. F. Loureiro. Drina: A lightweight and reliable routing approach for in-network aggregation in wireless sensor networks. *IEEE Transactions on Computers*, 62(4):676–689, April 2013.
- [99] Jiafu Wan, Daqiang Zhang, Shengjie Zhao, L. Yang, and J. Lloret. Context-aware vehicular cyber-physical systems with cloud support: architecture, challenges, and solutions. *IEEE Communications Magazine*, 52(8):106–113, Aug 2014.
- [100] Wen Qiang Wang, Xiaoming Zhang, Jiangwei Zhang, and H. B. Lim. Smart traffic cloud: An infrastructure for traffic applications. In *Parallel and Distributed Systems (ICPADS), 2012 IEEE 18th International Conference on*, pages 822–827, Dec 2012.
- [101] Mohamed Watfa. *Advances in Vehicular Ad-Hoc Networks: Developments and Challenges*. IGI Global, University of Wollongong, UAE, 1st edition, 2010.
- [102] Xiaolong Wen, Genqiang Gu, Qingchun Li, Yun Gao, and Xuejie Zhang. Comparison of open-source cloud management platforms: Openstack and opennebula. In *Fuzzy Systems and Knowledge Discovery (FSKD), 2012 9th International Conference on*, pages 2457–2461. IEEE, 2012.
- [103] Md Whaiduzzaman, Mehdi Sookhak, Abdullah Gani, and Rajkumar Buyya. A survey on vehicular cloud computing. *Journal of Network and Computer Applications*, 40(0):325 – 344, 2014.

- [104] Bill Wilder. *Cloud architecture patterns: using microsoft azure.* ” O’Reilly Media, Inc.”, 2012.
- [105] Qing Xu, R. Segupta, D. Jiang, and D. Chrysler. Design and analysis of highway safety communication protocol in 5.9 ghz dedicated short range communication spectrum. In *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual*, volume 4, pages 2451–2455 vol.4, April 2003.
- [106] Hong Yao, Changmin Bai, Deze Zeng, Qingzhong Liang, and Yuanyuan Fan. Migrate or not? exploring virtual machine migration in roadside cloudlet-based vehicular cloud. *Concurrency and Computation: Practice and Experience*, 27(18):5780–5792, 2015. cpe.3642.
- [107] Zeng You-zhi and Zhang Ning. *Proceedings of the 6th International Asia Conference on Industrial Engineering and Management Innovation: Core Theory and Applications of Industrial Engineering (volume 1)*, chapter Review and New Insights of the Car-Following Model for Road Vehicle Traffic Flow, pages 87–96. Atlantis Press, Paris, 2016.
- [108] R. Yu, Y. Zhang, H. Wu, P. Chatzimisios, and S. Xie. Virtual machine live migration for pervasive services in cloud-assisted vehicular networks. In *Communications and Networking in China (CHINACOM), 2013 8th International ICST Conference on*, pages 540–545, Aug 2013.
- [109] Alexander Zahariev. Google app engine. *Helsinki University of Technology*, 2009.
- [110] Tao Zhang, Robson E. De Grande, and Azzedine Boukerche. Vehicular cloud: Stochastic analysis of computing resources in a road segment. In *Proceedings of*

the 12th ACM Int. Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks, 2015.

- [111] Zhenxia Zhang, Azzedine Boukerche, and Richard Pazzi. A novel multi-hop clustering scheme for vehicular ad-hoc networks. In *Proceedings of the 9th ACM International Symposium on Mobility Management and Wireless Access*, MobiWac '11, pages 19–26, New York, NY, USA, 2011. ACM.
- [112] Zhenxia Zhang, Richard W. Pazzi, and Azzedine Boukerche. A mobility management scheme for wireless mesh networks based on a hybrid routing protocol. *Computer Networks*, 54(4):558 – 572, 2010. *Advances in Wireless and Mobile Networks*.
- [113] R.X. Zhong, K.Y. Fu, A. Sumalee, D. Ngoduy, and W.H.K. Lam. A cross-entropy method and probabilistic sensitivity analysis framework for calibrating microscopic traffic models. *Transportation Research Part C: Emerging Technologies*, 63:147 – 169, 2016.
- [114] P. Zou, C. Wang, Z. Liu, and D. Bao. Phosphor: A cloud based drm scheme with sim card. In *Web Conference (APWEB), 2010 12th International Asia-Pacific*, pages 459–463, April 2010.