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FUZZY TRAFFIC SIGNAL CONTROL IN VEHICULAR AD HOC NETWORKS

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We have read the thesis entitled **"Fuzzy Traffic Signal Control in Vehicular Ad Hoc Networks"** completed by **Muntaser Abdulwahed Salman** under the supervision of **Prof. Dr. Fatih V. ÇELEBİ** and **Assoc. Prof. Dr. Suat ÖZDEMİR** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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FUZZY TRAFFIC SIGNAL CONTROL IN VEHICULAR AD-HOC NETWORKS

ABSTRACT

Traffic signal control (TSC) is a major concern for big cities in the world. Inefficient and ineffective intersection control arise economic, environmental and social problems. It relies mostly on sensors, such as loop detectors and cameras which are costly and limited to sensor capability. Vehicular ad hoc networks (VANET) enables the TSC to acquire real information for vehicles. This requires road side unit (RSU) in the center of an intersection capable of communicate with vehicles.

TSC's with sensors have two major drawbacks, installation/maintenance costs and rate of failure. On the other hand, recently TSC's with VANETs have also two major drawbacks, sophisticated traffic surveillance and ineffective control solution. The main reason for that is the low number of vehicles that use this technology, so called penetration rate (PR).

This thesis focuses on recently TSC algorithms for signalized intersections under VANET environment under low PR. This is done through VANET communications, simple traffic surveillance and intelligent control solution.

In VANET communications, vehicle-to-everything (V2X) communications are particularly well-suited for traffic surveillance. This is due to their low latency and their ability to communicate instantly between vehicles via vehicle-to-vehicle (V2V) communication and between vehicles and infrastructure via vehicle-to-infrastructure (V2I) communications.

Simple traffic surveillance requires base information for vehicles (such as position and speed). Because of vehicles dynamic behavior, these information changes continuously and becomes fuzzy under low PR. In this context, this thesis proposed an accumulative information approach based on fuzzy logic. Two approaches investigated in this field, vehicles approaching and leaving pattern and traffic delay model. The results encourage us to use traffic delay model for intelligent control.

Recent TSC solutions focus on self-organizing algorithms (e.g. platoon, phase, marching and congestion based). The main idea of each algorithm considered traffic as an adaptive rather than an optimizing problem. Based on local information, this problem can be solved. The major drawback for each one, it is suitable for specific traffic condition and not for others. In order to solve this issue two approaches have been proposed to select one suitable algorithm based on traffic condition criteria: simple logic and fuzzy logic. The two proposed approaches have been simulated and evaluated with behaviors of recently developed algorithms in this field. The results indicate good performance of our TSCs (more specifically fuzzy logic) using VANET environment even under low PR.

Keywords: Traffic signal control, VANET, V2X communications, Self-organizing algorithm, Penetration rate.

TASARSIZ ARAÇ AĞLARINDA BULANIK TRAFİK SİNYAL KONTROLÜ

ÖZET

Trafik sinyal kontrolu (TSK), dünyanın büyük kentleri için büyük bir endişe kaynağıdır. Verimsiz ve etkisiz kesişim kontrolu, ekonomik, çevresel ve sosyal problemleri ortaya çıkarmaktadır. Çoğu zaman, döngü dedektörleri ve sensör yeteneği ile sınırlı olan kameralar gibi algılayıcılara dayanmaktadır. Tasarsız araç ağları (TAA) TSK'nin araçlar için gerçek bilgi edinmesini sağlar. Bu, araçlarla iletişim kurabilen kavşağın ortasında yol kenar birimi (YKB) gerektirir.

Sensörlü TSK'lerin iki önemli dezavantajı vardır: kurulum / bakım maliyetleri ve arıza oranı. Bunun yanı sıra, günümüzde TAA'lı TSK'lerin de karmaşık trafik gözetimi ve etkisiz kontrol çözüme olmak üzere iki önemli dezavantajı vardır. Bunun temel nedeni, penetrasyon oranı (PO) olarak adlandırılan, bu teknolojiyi kullanan araçların sayısının az olmasıdır.

Bu tez, TAA ortamında bulunan TSK sinyal kesişme algoritmalarının düşük PO'larına odaklanmaktadır. Bu işlem TAA iletişimleri, basit trafik gözetimi ve akıllı kontrol çözümü aracılığıyla yapılmaktadır.

TAA haberleşmede, Araç-Herşey (AH) iletişimleri özellikle trafik gözetleme işlemi için uygundur. Bunun nedeni, düşük gecikme süreleri ve Araç-Araç (AA) ve Araç-Altyapı (AAltyapı) iletişimi yoluyla araç arasında anında iletişim kurabilme yeteneklerinden kaynaklanmaktadır.

Son dönemdeki TSK çözümleri, kendi kendini düzenleyen algoritmalara (örn. Müfreze, aşamalı, yürüyen ve tıkanıklık temelli) odaklanmaktadır. Her algoritmanın ana fikri, bir optimizasyon sorunu yerine bir adaptif trafik çözümlerine çalışılmıştır. Yerel bilgilere dayanarak, bu problem çözülebilir. Her birinin en büyük dezavantajı, belirli trafik koşulları için değil diğerleri için uygun olmasıdır. Bu sorunu çözmek için, trafik koşul kriterlerine dayanan uygun bir algoritmayı seçmek için basit mantık ve bulanık mantık olmak üzere iki yaklaşım önerilmiştir. Önerilen iki yaklaşım, bu alanda yakın zamanda geliştirilen algoritmaların davranışlarıyla simüle edilmiş ve değerlendirilmiştir. Sonuçlar, düşük PO'da bile TAA ortamını kullanarak TSK'lerimizin (özellikle bulanık mantık) iyi bir performans gösterdiği görülmüştür.

Anahtar Kelimeler: Trafik sinyal kontrolü, TAA, AH iletişimleri, Kendini düzenleyen algoritma, Penetrasyon oranı.

CONTENTS

NOMENCLATURE

Acronyms

BSM	Basic Safety Message
CAM	Cooperative Awareness Message
COLOMBO	Cooperative self-organizing system for low carbon mobility at low penetration rate
DSRC	Dedicated short range communications
DTF	Delay times fuzzy
FPR	Full penetration rate
FTSC	Fuzzy traffic signal control
GPS	Global Positioning System
H	High
I2V	Infrastructure to vehicle
iTETRIS	Integrated wireless and traffic platform for real time road traffic management solutions
ITS	Intelligent transportation system
L	Low
LDM	Local Dynamic Map
LTE	Long term evolution
M	Medium
NS	Network simulator
OFDM	Orthogonal frequency division multiplexing
PPR	Partial penetration rate
PR	Penetration rate
RSU	Road side unit
SCAT	Sydney Coordinated Adaptive Traffic

SCOOT	Split Cycle and Offset Optimization Technique
SPOT	System for Priority and Optimization of Traffic
SUMO	Simulator of urban mobility
TraNS	Traffic network simulator
TSC	Traffic signal control
UTOPIA	Urban Traffic Optimization by Integrated Automation
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
V2X	Vehicle to everything
VANET	Vehicular ad hoc network
Veins	Vehicles in network simulation
VTL	Virtual traffic light
VTT	Vehicle total time
WiFi	Wireless-Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
Z	Zero

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CHAPTER 1

INTRODUCTION

Intersection traffic congestion is a big problem in urban areas. Several solutions have been proposed over the years to address traffic congestion. These solutions require the deployment of newer traffic management systems to monitor traffic conditions. These management systems are parts of the Intelligent Transportation System (ITS) paradigm, in which information and communication technologies are added to vehicles and transportation infrastructures to better manage the system. One important research area of ITS is Traffic Signal Control (TSC) under Vehicular Ad hoc NETworks (VANET) environment. It is a new promising application for road safety and traffic efficiency. Due to the inherently self-organizing and mobility features of VANETs, there is a growing research interest in utilizing this technique. Consequently, there is a need for TSC performance evaluation in such modern environments.

A lot of people move through traffic networks every day. If this traffic is not controlled efficiently and effectively, a wide range of economic, environmental and social problems may arise. TSC is an important research area which can help alleviate traffic congestion. Many solutions have been proposed in this field. Mostly, proposed TSC systems assume that specific information, such as traffic densities and average vehicle speeds are available. Using current road based sensor technology (i.e. induction loop sensors or cameras) does not allow for most of this information to be accurately observed in real-time. Sharing information through the use of VANET with TSC infrastructure enables effective intelligent control to become a reality.

Combining these VANET-based systems with TSC infrastructure can lead to safer and more efficient traffic networks resulting in decreased emissions, lower travel times, and less traffic-related incidents. Also, since VANETs largely rely on communication and sensor devices located within vehicles, a VANET-based control system may lead to increased savings for big cities, which may no longer have to maintain sensor and communication devices (i.e. induction loop sensors and intersection communication devices). Currently, spectra have been allocated in the Europe, United States and Japan for vehicle-specific communication, indicating that governmental authorities are beginning to acknowledge the possible power VANETs may hold. The main drawback of VANET technology is its low PR. With the required technology available, research now needs to focus on designing scalable, self-organizing, intelligent control solutions that take low PR into consideration. In this thesis, deployment of VANET technologies is surveyed under urban scenarios. In general, VANET technologies in urban scenarios are deployed and used for traffic conditions monitoring. With low PR, these traffic conditions should be estimated. Then, based on TSC algorithm requirements, estimation models should be proposed. Self-organizing TSC algorithm performs under specific traffic condition play the major rule for solving more realistic traffic conditions even under low PR. In this context, simple logic and fuzzy logic TSC approach are proposed based on traffic conditions with standard level of service (LOS) criteria.

1.1 Motivation

VANET technology is expected to support the implementation of various cooperative applications aimed at improving traffic safety and efficiency. Cooperative safety applications (like intersection monitoring and TSC) generally collect information from vehicles in the close surroundings area. For such applications, some communication requirements have to be respected. The requirements imposed by this class of applications are generally addressed by cooperate messages immediately through wireless communications. For example, an intersection monitoring application may require messages of vehicles belonging to a given destination area (i.e. edge or lane of an intersection) to be disseminated and their information about traffic conditions is collected without RSU infrastructure. In this case, the disseminated messages do not required RSU infrastructure, and hence V2V communication can be tolerated. On the other hand, TSC applications may also require the collected information of vehicles to be disseminated to RSU infrastructure from all edges of the intersection. In this case, the disseminated messages inform TSC infrastructure about the collected information, and hence V2I communication can be tolerated.

As a result, the implementation of TSC algorithms under VANET environment is not limited to the use of V2V or V2I communications alone. It is possible to exploit V2X communications capabilities provided by radio access technologies. Having multiple communication solutions at TSC provides more information reliability, a better understanding of traffic conditions, real time evaluation capability and may increase the robustness of TSC algorithm.

In order to analyze the adoption of V2X communications as an effective solution for TSC, an evaluation of the performance and adequateness of such TSC while vehicles flooded into an urban environment context is needed. When operating under a low PR, the assumption that TSC can operate with a sufficient quality needs to be studied and investigated in detail. Albeit there are different tools and models to assess the behavior of vehicles, such evaluations often lack V2X communications integration with the traffic dynamics of vehicles.

This thesis presents a self-organizing TSC algorithm for an intersection simulation within a realistic urban mobility context. Such a platform is important for analyzing how traffic flow and its dynamics affect the performance of TSC under VANET environment with different PR and traffic conditions.

1.2 Scope

This thesis deals with the research areas of TSC within VANET environments. The focus of this research is on the investigation and development of TSC systems under VANET environment within realistic traffic simulations. Furthermore, this work largely deals with the algorithmic aspects of TSC systems, and only briefly touches on software specifications. From an algorithmic point of view, this thesis focuses on approaches of TSC which are self-organizing and realistic under different PR. Several other approaches (i.e., virtual TSCs or TSC with full PR) are not included within this work due to the unrealistic assumptions required by these approaches.

1.3 Thesis Contributions

This thesis presents several traffic monitoring and TSC algorithms that are based on V2X communications. The main contributions of this thesis are as follows:

- Investigating the capability of V2X communications in traffic surveillance of an intersection under different PR. An approaching and leaving patterns had been modelled for nearby vehicles. Fuzzy logic proposed to model these patterns through time measurements. Simulation results reveal the capability of V2X communications for traffic surveillance till 20% of PR with good accuracy.
- Developing the previous model to monitor traffic conditions based on V2X communications. This model is developed based on traffic delay estimation with low PR consideration (i.e. less than 10%). Simulation results show good traffic delay estimation even under low PR (i.e. till 1%).
- Proposing efficient self-organizing TSC algorithm based on traffic conditions with standard LOS criteria. Both of them are analyzed and compared with recently known algorithms. The results show that the average traffic delay of vehicles going through an intersection with Fuzzy TSC is less than others. Therefore, it is much easier and logical than the classical TSC. On the other hand, it showed a good performance than others even without any optimization requirements.
- The improved TSC algorithms are analyzed and compared between simple logic and fuzzy logic principle as well as previous work in this field. Simulation results show that the proposed FTSC algorithm, beside its good performance, is more logical and simpler than others.
- A new parameter for evaluation TSC algorithms, called the total vehicles time interval, had been considered in performance evaluation. The simulation results proved that the operation of TSC is able to be evaluated with standard LOS considered in this field under different traffic conditions.

1.4 Thesis Organization

The rest of this thesis organized as follows:

Chapter one presents an introduction to TSC algorithms and their concepts. Chapter two presents a background of vehicular communications and TSC algorithms under VANET environment. It discusses the related vehicular communications and TSC algorithms followed by listing the software developed to simulate such algorithms in the literature.

Chapter three presents an algorithm for estimating traffic conditions of an intersection. An approaching and leaving model is proposed for estimating approaching and leaving time under different PR. It presents experimental results and comparisons with known algorithms.

Chapter four presents a developed algorithm based on previous algorithm results (i.e. given in chapter three) for estimating traffic delay of an intersection. A delay model is proposed for estimating average delay time and investigated under low PR. It also presents experimental results and comparisons with known algorithms.

Chapter five presents two logical solutions for TSC of an intersection. First, it proposes an algorithm called the simple logic TSC, followed by a similar solution with fuzzy logic algorithm. The experimental results of the proposed solutions are presented afterwards.

All the above chapters (i.e. three, four and five) highlight PR issue in the TSC under VANET environment and analyze the impact of this issue on its proposed algorithm performance. Thereafter, it shows the simulation results in comparisons with previous known ones.

Finally, chapter six presents thesis conclusions and future works.

CHAPTER 2

BACKGROUND

A TSC system under a VANET environment is a self-organized information system composed of vehicles and additional infrastructure capable of short-range communication. There are three possible steps to implement a TSC system under a VANET environment, including VANET communications selecting, intersection monitoring system, and TSC algorithm designing. This chapter begins by introducing VANET communications and identifying important differences between them (Section 2.1). Section 2.2 explains the basic TSC systems, including traffic monitoring systems (2.2.1) and traffic control algorithm (subsection 2.2.2) to augment the TSC functionality. Then, in section 2.3 open source VANET simulators developed in this field is abstracted. Before the chapter ends with conclusions in section 2.5, section 2.4 summarize chapter contents.

2.1 Vehicular communications

In its simplest form, a VANET environment requires a set of vehicles equipped with some form of communication device. Wireless ad hoc networks enable communications over VANETs. The use of radio interface technologies (e.g. IEEE 802.11p with ITS Technical Committee of the European Telecommunications Standards Institute ETSI ITS G5 standard [1]) on vehicles driving throughout the road network enables communications within VANET environments. However, other communication technologies (e.g. cellular networks, broadcasting systems, and floating car data) for the same purpose could be exploited. But most of these technologies are not suitable for real time applications like TSC systems discussed in this thesis.

Many vehicles need to transfer information from other nodes or geographical areas where they can have a practical utility for drivers and TSC system manager. Transferring information to other nodes or areas with vehicular short range ad hoc radio technology implies the use of specific communications protocols. In this context, protocols are necessary to determine reliable communication of vehicles connecting source to destination nodes. In addition, strategies are needed to optimally distribute the transmitted messages to possibly interested vehicles or infrastructure. The design of vehicular communications through standards, protocols and strategies is not an easy task, as it has to face the challenging vehicular communication characteristics. As a result, international (especially European countries) efforts led to development of the IEEE 802.11p/ETSI ITS G5 standards for vehicular communications applications [2].

Vehicular communications based on the exclusive use of IEEE 802.11p/ETSI ITS G5 standards had been proposed by many studies. Therefore, various reviews only focus on this type of communications (e.g. [3] and [4]). The proposed vehicular communications are based on operational characteristics. In this thesis, a different classification of vehicular communications is proposed. This classification takes into account the communications characteristics and actors involved in the TSC design. Three main types of vehicular communications are considered. First, communications that only use ad-hoc V2V are described. Then, communications exploiting the presence of fix RSUs are outlined. These communications combine V2I with I2V. In TSC system design, fixed infrastructure should be considered as a base for communication characteristics. Finally, hybrid V2X communications are combine all the previous ones.

In what follows, an overview of the state of the art on vehicular communications are outlined. This analysis permits understanding the motivations behind using the latest novel approaches presented in this thesis.

2.1.1 Ad hoc based communications

One of the simplest ad hoc based communications is referred to as V2V communication, though dedicated short range communication (DSRC) has been considered as the primary communication option for wireless data communication. V2V communication comprises a wireless network where vehicles send messages to each other with information about what they're doing. This data would include speed, location, direction, braking, and loss of stability. It uses dedicated short-range communications. Sometimes it's described as being a WiFi network because one of the possible frequencies is 5.9GHz, which is used by WiFi. The range is up to 300 meters. The use of other wireless technologies (e.g., Wi-Fi, Long Term Evolution LTE, and Worldwide Interoperability for Microwave Access WiMAX) allows longer range communications and throughput requirements that could not be supported by DSRC alone. Although all the previous methods are effective with V2V for dense traffic scenarios, they are limited when vehicles are driving in low density neighborhoods. Road-side infrastructure should represent a viable solution to extend connectivity support in those scenarios where vehicles are not able to communicate via V2V. However, the use of other wireless technologies potentially reduces the need for costly DSRC infrastructure but they are not appropriate for real time traffic data collection application in TSC systems.

2.1.2 Infrastructure based communications

The simple form of V2V communication technology, however, would not offer many benefits to users of TSC systems, other than the ability to communicate with nearby drivers. This section discusses an augmentation to this basic technology which could enable much more useful TSC systems.

1) ***V2I communication:*** Similar to V2V communication, V2I uses DSRC frequencies to transfer data. However, the main V2I limitations are due to particular vehicular applications required (i.e., popular data such as traffic and weather alerts, and also unpopular/user-specific data such as e-mail and Internet browsing), and performance is strictly dependent on the specific wireless technology for the RSUs considered (i.e., WiMax, High Speed Downlink Packet Access, LTE, etc.) [5]. V2I communications are typically wireless and bi-directional; i.e. data from infrastructure components can be delivered to the vehicle over an ad hoc network and vice versa. In January 2017, the U.S. Department of Transportation announced Federal Highway Administration (FHA) V2I guidance aimed at improving safety and mobility by accelerating the

deployment of V2I communication systems [6]. The guidance is aimed at helping state and local governments prepare to accommodate vehicle to infrastructure initiatives and manage the data that supports it.

2) ***I2V communication:*** I2V communication is a communication model that allows vehicles to capture information from the components that support ITS system. Such components may include overhead radio frequency identification readers and cameras, traffic lights, lane markers, streetlights, signage and parking meters. In an ITS, I2V communication can capture infrastructure data and provide travelers with real-time advisories about such things as road conditions, traffic congestion, accidents, construction zones and parking availability. Likewise, traffic management supervision systems can use infrastructure and vehicle data to set variable speed limits and adjust traffic signal phase and timing to increase fuel economy and traffic flow.

2.1.3 Hybrid based communications

Due to the main limitations of V2V and V2I, seamless vehicular connectivity management represents a new challenge for VANETs. To achieve the advantages of both two protocols, authors of [5] propose a novel hybrid vehicular communication paradigm, named vehicle-to-everything (V2X). V2X technique is a hybrid approach to link both between vehicles (i.e., V2V) and from vehicles to the infrastructure (i.e., V2I) communications. The cooperation and coexistence of these two different methods can assure a good connectivity in VANET scenarios, especially in sparsely connected neighborhoods where V2V communications are not always available [5].

2.2 TSC systems

TSC systems have undergone a continuous evolution. Today, due to advanced sensing, computation and communication technologies, real-time traffic measurements are commonly available. In addition to sensing, computation and communication abilities, these TSC systems have the ability to control physical dynamics of vehicles and/or road infrastructures. Such complex systems are considered as ITS. In this section, an abstract of TSC systems in ITS is presented.

The theoretical research work on TSC systems dates back to the mid-20th century [7]. Since then, TSC systems have gone through three methodologies: fixed time, actuated, and adaptive control. These methods are discussed in greater detail in several hand books, textbooks, and surveys before (e.g. [8] and [9]). The simplest one, fixed time TSC method, uses a predetermined cycle (the time required for one complete sequence of signal intervals) and split (green duration as a portion of the cycle time) time plan. Such kind of TSC method does not required any monitoring system to implement their algorithm (i.e. timing is decided by statistical methods based on research and observation of traffic flows which occur at the intersection). It does not provide an automatic capability for signal timing adjustments in response to changes in traffic conditions. Although, it still used commonly in the world, there has been a growing interest in adaptive TSC systems.

In what follows, we briefly describe the rest TSC methods (i.e. actuated and adaptive) according to their monitoring and control algorithm requirements.

2.2.1 Traffic monitoring systems

In order to have the capability to alter the signal timings in response to detected changes in traffic conditions, TSC systems need to monitor intersection traffic conditions. This is done to reduce the potential of negative traffic impacts on the general traffic that arise from going through such intersections. Traditional traffic monitoring systems used inductive loops, cameras, radar …etc. to detect traffic conditions. The main drawbacks are their cost, scalability and sophisticated algorithms required to provide real time traffic information. Recently, VANET technology offer promising solution to overcome these drawbacks. With the capability of providing a lot of information using VANET environment, traffic conditions should be specified according to the TSC requirements. In its simplest architecture, VANET environment with an infrastructure in the middle of an intersection called roadside unit (RSU), as shown in **Figure 2.1** is sufficient to monitor different measurements of the traffic conditions.

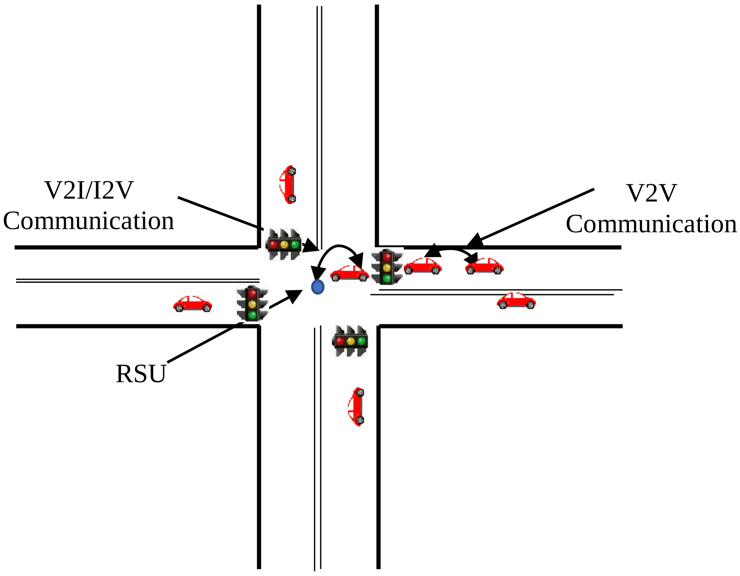

Figure 2.1 An intersection under VANET environemnt.

As described previously, i.e. Section 2.1, and shown in **Figure 2.1**; VANET environment have different types of vehicular communications. The potential of vehicular communications encouraged the design of innovative vehicular communications based traffic monitoring solutions. A lot of researches documented in this context. For instance, in [10] Fukumoto et. al. presents Contents Oriented Communications protocol where vehicles estimate road traffic density from received beacon messages, and periodically transmit this information to other vehicles. Vehicles can then detect traffic congestion conditions by comparing the exchanged traffic density estimates with average density values for the road segments under evaluation. This capability is obtained at the expense of over-loading the communication channel through the continuous exchange of traffic density estimates.

Bauza et.al, in [11] present a novel V2V based traffic congestion detection technique that efficiently uses the communication channel. To limit communication load, Nadeem et. al. in [12] employs an aggregation method that combines data from different vehicles located close to each other. Other techniques also propose to efficiently combine the information generated by multiple vehicles using digital road-maps. For example, in [13] Wischhof et. al. proposes vehicles to generate and exchange traffic information about the road segment they are currently located in, and other road segments for which they have traffic information. This information can be generated by the vehicles themselves or received from other vehicles. To reduce the overhead due to these messages, Dornbush and Joshi in [14] limits the exchange of traffic information to situations of unexpected or abnormal traffic conditions, e.g. traffic jams. The mechanism reported in [15] by Vaqar and Basir reduces the risk of communication overhead by only estimating traffic congestion locally at each vehicle using pattern recognition techniques on the beacon messages received from nearby vehicles. However, the lack of any mechanism to validate or correlate the traffic congestion estimates among various vehicles may lead to unreliable detection's. This problem is partially solved in [16], where Lin and Osafune propose a voting procedure so that neighboring vehicles exchange their traffic estimates and try to reach a consensus decision. The work introduced in [17] by Fahmy and Ranasinghe also proposes a cooperative detection process that calculates the number of vehicles in a traffic jam using a tree-based counting algorithm. However, the formation and management of the tree requires the exchange of a large number of packets, with the consequent risk of over loading the communications channel.

Also, there are several monitoring systems that utilize V2I communication in the literature. However, most of these systems are just as complex as detector-based monitoring systems, utilizing mixed-integer linear programming and platoon recognition algorithms [66] or queue length estimation techniques and variable search horizons [67]. Due to such complexity, these systems face deployment issues.

Although the literature review clearly indicate the capability of vehicular communications (especially V2V communications) as a promising solution for traffic conditions monitoring. But Most of these studies have been proposed for highway scenarios. Also, traffic conditions of an intersection may rely on sampling aggregation areas of vehicular communications. One drawback of these approaches comes from defining the area in static or dynamic approach. In order to overcome the above issues, suitable intersection control algorithm should be considered.

2.2.2 Traffic control algorithms

Recent research has led to the development of several traffic responsive methods which allow the basic control elements, cycle time, phase splits and offset to vary according to prevailing traffic conditions. The most two famous methods in this field are the Sydney Coordinated Adaptive Traffic (SCAT) method developed in Australia and the Split Cycle and Offset Optimization Technique (SCOOT) developed in the UK. The field evaluations of SCOOT and SCAT show that both methods are capable of performing better than the simpler fixed time control method in reducing journey time and stops [18]. Other methods like, INSYNC adaptive traffic control system which was developed in 2005. It is an ITS that enables traffic signals to adapt to the actual traffic demand. Also UTOPIA (Urban Traffic Optimization by Integrated Automation) - SPOT (System for Priority and Optimization of Traffic) in Italy. One of the major problems of almost all the above adaptive traffic control systems is the dependency on the detectors to collect the data and send them to the controllers for processing procedure. A detector failure can paralyze the system. On the other hand, the main idea of these system is to solve the traffic as an optimization problem. These traditional systems try to optimize traffic lights for particular traffic conditions. The disadvantage of this lies in the fact that traffic conditions change constantly. Thus, traffic seems to be an adaptation problem rather than an optimization problem. In this context, self-organizing TSC algorithms proposed recently in [19] where each TSC senses local traffic conditions and react with proper action.

2.3 VANET simulators

Simulation is considered as an effective tool for TSC system verification as practical TSC systems implementation and deployment require high cost and intensive labor. In this section, we briefly review VANET simulators that are open access and couple traffic mobility simulators and networks simulators, respectively.

VANET simulation architecture is required which combines the well-developed traffic simulator and network simulator through general traffic control interfaces, as illustrated in **Figure 2.2** [20].

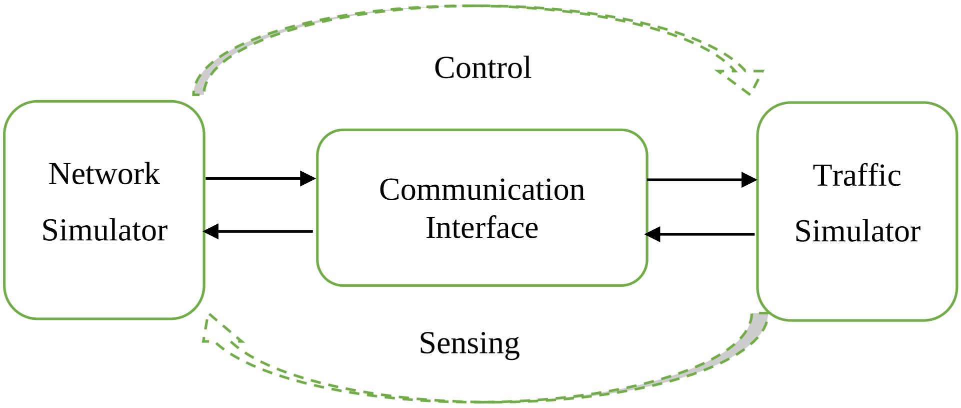

Figure 2.2 VANET architecture of the integrated simulators.

Veins [21], TraNS [22] and iTETRIS [23] are some typical integrated simulators. Veins federates a traffic simulator SUMO and a networking simulator OMNET++, and TraNS integrates SUMO and NS-2, while iTETRIS couples SUMO with NS-3. All the three integrated simulators utilize the Traffic Control Interface (TraCI) as the communication interface which adopts a very similar command response approach and a transmission control protocol connection.

Vehicles in network simulation (Veins) is an open source inter-vehicular communication simulation framework which is composed of network simulator OMNeT++/MiXiM and the road traffic simulator SUMO. To perform TSC system evaluations, both simulators run in parallel and connect to each other via TraCI, with client/server principle. This implementation allows bidirectional-coupled simulation of road traffic and network behavior. Aside from modules to model and to influence road traffic, Veins offers a comprehensive suite of inter-vehicular communication specific models that can serve as a modular framework for developing user own applications. Although the graphical user interface (GUI) of OMNeT++ and SUMO can be used for quickly setting up and interactively running simulations but simulation is time consuming especially for large scale scenarios.

Traffic and network simulation environment (TraNS) is a GUI tool that integrates traffic and network simulators (SUMO and NS-2) to generate realistic simulations of VANETs. TraNS allows the information exchanged in a VANET to influence the vehicle behavior in the mobility model. For example, when a vehicle broadcasts information reporting an accident, some of the neighboring vehicles may slow down.

The development of TraNS is suspended. Hence, TraNS does not support the latest version of both SUMO and NS-2.

Integrated wireless and traffic platform for real time road traffic management solutions (iTETRIS) is a European-funded simulation platform that combines SUMO and NS-3. The central block of this open source platform is referred to as iTETRIS Control System (iCS). The modular architecture of iCS allows the platform to interface with modules written in different programing languages through sockets; such modular design is also beneficial for future upgrades. Additionally, iTETRIS is designed to support large scale simulation, and is compliant with ETSI Technical Committee on ITS Communication Architecture.

Cooperative self-organizing system for low carbon mobility at low penetration rates, referred to COLOMBO project [24], is an extension to iTETRIS. Within the project a set of modern cooperative traffic surveillance and control applications delivered. The traffic control applications are of self-organizing type using swarm intelligence methods. They are optimized based on simulations-in-the-loop.

2.4 Summary

This chapter summarizes the background of TSC systems under VANET environment. The objective was to deliver the multi discipline approach required in this topic. Involving or requiring expertise in a number of fields, first, the vehicular communications were categorized based on the communications characteristics and actors involved in the TSC systems. Then, TSC systems were explained briefly with two main subtopics: Traffic monitoring systems and traffic control algorithms. Vehicular communications with hybrid V2X protocol should be used in traffic monitoring system design taking into consideration the low penetration rate of this technology. In the same time, a traffic control algorithm should be self-organizing one since optimization one required more time to be assigned. Due to our focus on designing and evaluating traffic light algorithms under a VANET environment, we have concentrated on modeling the above two subtopics at an intersection with suitable VANET simulator. In this context, recently developed open access simulator had been chosen, i.e. COLOMBO framework.

2.5 Conclusions

To develop an algorithm for TSC systems under a VANET environment, the last hybrid vehicular communications, i.e. V2X, should be considered and investigated under varying penetration rates. The core of V2X communications is V2V communication that is capable of road traffic monitoring. Besides the real time traffic monitoring systems capability, it will provide a lot of information for traffic control algorithms through an infrastructure via V2I. By that, the fact that TSC is an adaptive problem rather than an optimization problem can be solved with self-organizing principle. COLOMBO framework, the last open source project in this field, can be develop with new approach.

CHAPTER 3

TRAFFIC SURVEILLANCE SYSTEM WITH V2X COMMUNICATIONS

The need for wide area traffic surveillance to capture traffic dynamics has led to the growing interest in VANET communications. Such emerging cooperative techniques, like V2X communications, open new channels for delivering information. In real world applications, it is necessary that such information have a good accuracy with limited V2X communications capable vehicle PR. This chapter proposes a traffic surveillance technique capable of estimating traffic conditions of an intersection with low V2X communications capable vehicle that can be directly used for signal control design.

Traffic surveillance using V2X communications is merged very recently [25]. For instance, the FP7 COLOMBO project [24] used V2X protocols for smart traffic lights in order to determine traffic surveillance information about local queue length, with the goal to use such traffic indicators to dynamically adapt traffic light control. COLOMBO project deals with two traffic management topics: traffic surveillance and advanced traffic light control algorithms using cooperative data. In this chapter the first topic is analyzed for the purpose of replacing traditional detection V2X protocols using the more detailed information that cooperative detection can offer. Traditionally, the main function of this detection for adaptive control is the estimation of queue length and vehicles approaching patterns. Ideally, a bird's eye view of the traffic network with speed, position and route information about each vehicle approach should be available. Using this information, the TSC knows exactly how many vehicles are waiting or approaching in each signal group. Both traditional detection V2X protocols and standard cooperative systems cannot deliver this [26] even with full PR. This means that TSC algorithms rely on estimation of traffic conditions to divide the vehicles approaching flow between signal groups. COLOMBO uses swarm intelligence algorithm to estimate the abstract of this traffic condition (called it pheromone) based on average speed. Swarm intelligence, as an optimization algorithm taking inspiration from the collective behavior of social insects such as ants, is time consuming and requires a lot of traffic data to be aggregated in offline (i.e. static) or online (i.e. dynamic) approach. One drawback of these approaches that rely on traffic condition estimation comes from defining the sample aggregation areas. In offline approaches [27], [28] and [29], the challenge is to determine the area length that is neither large nor small. Online approaches [12] and [30] adjust to true traffic conditions, the challenge is to dynamically build and maintain clusters and cluster leaders. Another issue, to avoid same vehicles impacting different traffic conditions in space or time, traffic conditions need to be mutually exclusive.

In this chapter, an online strategy is followed. The physical relation between the data dissemination time of each vehicle and the underlying traffic speed/density observed by COLOMBO project is used for estimating the traffic conditions. Fuzzy logic with data fusion technique is used to avoid same vehicles impacting different traffic conditions in space or time. This is done by differentiating between approaching and leaving flow condition for each cluster (or group) based on average speed and their derivative (i.e. acceleration, zero, and deceleration) through online time updating with respect to their traffic density.

The simulation results show that the proposed technique is superior to the Swarm optimization technique used in COLOMBO project. Compared to COLOMBO project, in the proposed technique determining the traffic conditions does not require any optimization and therefore it is a simpler task.

3.1 Introduction

Cooperative V2X technology can monitor an intersection approach continuously and thus provide extensive information of approaching vehicles. V2X capable vehicles frequently transmit a Cooperative Awareness Message (CAM) containing all required relevant information (e.g. speed, position, etc.). A convenient method to acquire data from cooperative vehicles is to receive CAM messages with RSU. After receiving the message, the RSU extract the most important information that is suitable for a TSC.

3.1.1 Related works

In most countries, especially in the United States and Europe, several researches have been worked on traffic surveillance of an intersection using V2X protocols. Generally speaking, two different approaches for traffic surveillance can be observed: either topology based or dissemination based. This observation based on whether knowledge of the traffic conditions related with messages dissemination time of V2X protocol or not. Topology-based approach is based upon clustering vehicles for a compress description of the traffic condition. This is capable for determining traffic efficiency performance indicators without involving a RSU. Therefore, it may be applied for monitoring parts of the road network with a sparse RSU coverage for computing average speed and number of vehicles. In this context, by elected leaders, authors of [31] explored the benefits from local preprocessing of GPS probe data. While [27] and [28] divide roads into fixed sections, to consolidate traffic volumes in vehicles, either directly or through a zone leader. Another example, [25], [32], [33] and [34] let a sampler (or group leader) to estimate traffic density by broadcast a message and count the returned messages. Similar approaches, [12], [29] and [30] showed to be more adapted to dynamic traffic by clustering vehicles according to similar properties rather than static road. Researches [35] and [36] use the V2X Local Dynamic Map (LDM), populated by periodic CAM/Basic Safety Message (BSM) to estimate local traffic conditions.

On the contrary, in dissemination based approach counting is not needed, vehicles send messages and the density/speed can be estimated using message propagation speed (e.g. [37]), which may be implemented on top of n-hop communication protocols. Researches [38], [39], [40] and [41] characterized the relationship between traffic density and information dissemination delay under the assumption of an exponential inter-distance, and prove the existence of a density threshold below which dissemination is linear, and above which dissemination becomes exponential. The exponential inter-distance with any general distribution is relaxed by [42]. Further investigation on this relationship done by [40], [43] and [44] through which the impact of a low PR of the V2X technology on the dissemination speed had been modeled.

3.1.2 Our work

In this thesis, we propose to follow a new strategy by using message dissemination time as well as average speed and number of vehicles to estimate the traffic conditions. Unlike [45], we propose to use RSU to evaluate traffic conditions rather than vehicles. Unlike [36], we propose to use fuzzy logic to evaluate traffic conditions for each direction in an intersection rather than traffic congestion for each vehicle in highway scenario. Finally, unlike COLOMBO traffic surveillance algorithms [24] that uses swarm optimization algorithm to abstract adapted traffic condition, we do not use any optimization algorithm and get adaptable results in comparison with them. Our approach uses the V2X protocol that is also used in COLOMBO project, mainly for average speed estimation purposes, to monitor the road traffic conditions. These conditions are monitored locally by the RSU of an intersection. However, in contrast to COLOMBO, we employ fuzzy logic to locally detect a potential direction traffic condition. When a different direction situation is detected, we sum the individual estimations made locally by different directions to collaboratively and accurately detect and characterize the whole intersection traffic conditions.

1) Traffic conditions local estimation: From an abstract perspective, our protocol operate as in [32]. Protocol in [32] can be summarized in two protocol sets: group formation and group life-cycle management. Group formation protocol set consists of two main phases: the first one adopts a simple flooding protocol to discover and activate all nearby vehicles that can be grouped together (i.e., that are traveling along the same path), while the second phase takes over the group leader election. In group life-cycle management protocol set the leader is responsible for determining when the group can be safely disposed as well as harvesting and processing the available vehicle information from all the group members. Since positions of vehicles are neither lane level accurate nor accurate enough to determine the exact amount of vehicles at a certain distance to the stop line. We used their detected number of vehicle per direction to estimate the approaching time and leaving time for whole approaching and leaving directions respectively. Also, [32] protocol keeps the times at which a vehicle approached and left the communication range for *group life cycle management*, in our protocol the vehicle total time (VTT) can be computed (as done in COLOMBO framework but not used), albeit only for the roads that are within the communication range. One further issue, VTT can be only directly computed if a vehicle passes the communication range or direction within it completely. In order to overcome this issue fuzzy logic with data fusion technique have been introduced to differentiate between “approaching time” and “leaving time”. This will be done in the RSU so that the estimation of them (i.e. approaching and leaving time) can be evaluated with VTT extracted from NS-3 benchmark continually. Thus, VTT can be defined as the duration that a vehicle remains associated with RSU directly or through group leader. Approaching time can be defined as the time required for each vehicle to approach to the RSU. And finally leaving time can be defined as the time required for each vehicle to leave the RSU. For each second the information of vehicle or group of vehicle is sent to the RSU that joins the intersection directly or through group leader respectively. The RSU use the incoming information including VTT as an indicator for estimating the traffic conditions by estimating approaching and leaving time continuously. As the vehicle travels along an intersection encounters different degrees of delay (i.e. different traffic conditions), so the value of VTT varies accordingly. Intuitively, the higher value of VTT indicates the worse degree of traffic condition. When introducing a fuzzy logic, it is possible to detect the halts of equipped vehicles based on their average speed and its derivative. As previously explained, each RSU implementing our solution to estimates its local approaching and leaving time based on its average vehicles speed and their derivative. The average vehicles speed can be easily obtained from the [32] protocol. We used a discrete derivative, since our system is discrete, computed as the difference between the average speed at two subsequent time instants divided by the interval between them (since our solution follow the COLOMBO’s one for the sake of comparison we also use time steps of a fixes length of one second, i.e. the division is always by 1). Therefore, in each road (i.e. direction) we can estimate its approaching and leaving time in terms of its average vehicles speed and their derivative, and then feeds these values into the fuzzy system. The input variables, as in any fuzzy system, are first classified into different categories or fuzzy sets. Possible fuzzy sets for speed are L for low, M for medium, and H for high. For speed derivative, the defined fuzzy sets are N for negative, Z for zero, and P for positive. In addition, output fuzzy sets corresponding to approaching and leaving estimated time have also been defined for one second time span, with L for low, M for medium and H for high. One of the main particularities of fuzzy logic is that a fuzzy set can contain elements with partial degree of membership, and consequently, an input value can belong to several fuzzy sets at the same time. For example, a speed value of 6.9445m/s (i.e. with maximum speed equal to 13.889m/s) could be member of both medium and low/high speed fuzzy sets. Membership functions are employed, in order to determine the degree of membership of the input values to each of the fuzzy sets. The membership functions used in our solution have been implemented based on simple rating system, illustrated in **Figure 3.1** (a), (b) (with average acceleration a=2.8 and deceleration d=4.8 determined from [25] based on simple rating) and (c). Finally, fuzzy rules that relate input (speed and its derivative) and output fuzzy sets (approaching and leaving time per second) have been established and are displayed in **Table 3-1**. The fuzzy rules have been designed based on the speed, its derivative and approaching/leaving time physical relationship.

For example:

If Speed is *H(igh)* and it's Derivative is *P(ositive)* then Approaching time is *L(ow)* and Leaving time is *L(ow)*

As **Figure 3.1**(c) illustrates, the output of the fuzzy system is a continuous value within one second interval [0,1] indicating the approaching and leaving time per second.

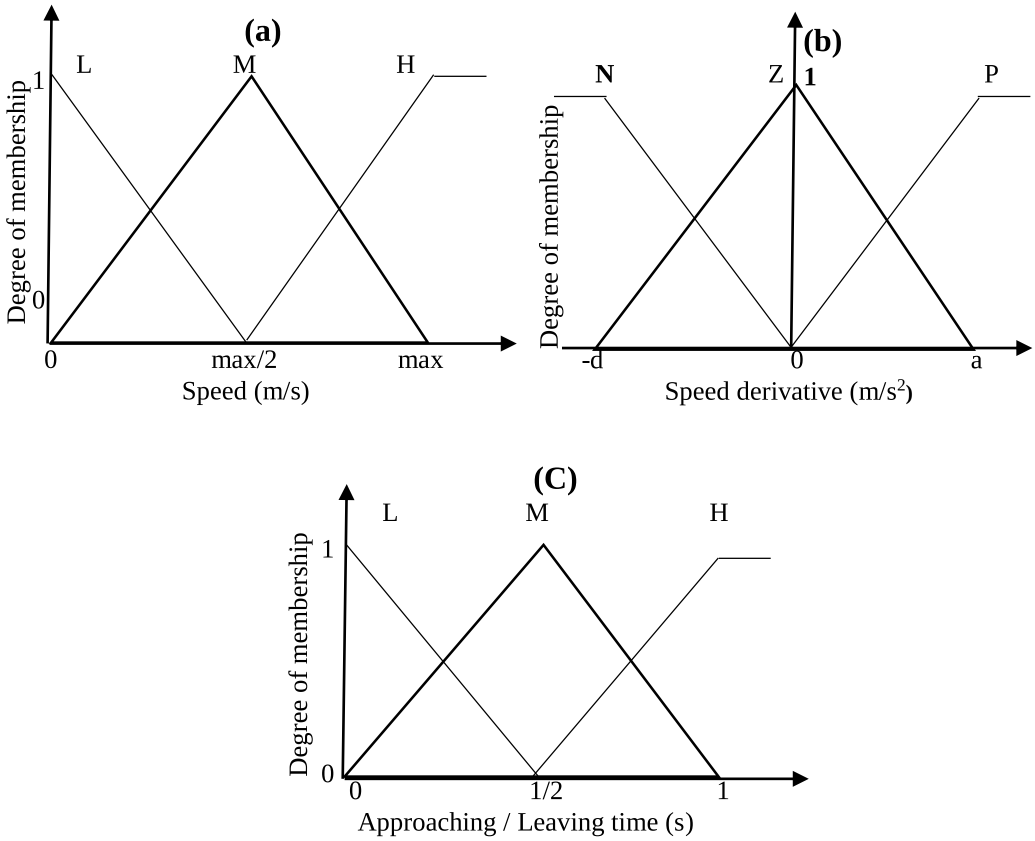

Figure 3.1 Fuzzy-based estimation system (a) Speed sets, (b) Speed derivative sets, and (c) Output sets

Table 3-1 Fuzzy rules relating input (speed and its derivative) sets with output (approaching and leaving time) sets

Approaching time/ Leaving time		**Speed Derivative**		
		N	**Z**	**P**
Speed	**L**	H/L	H/L	M/M
	M	H/L	M/M	L/H
	H	M/M	L/H	L/L

2) *Online adaptation with data fusion technique:* The proposed approach allows online evaluating the individual estimations that different participating directions make locally. As described in the previous section, every RSU in an intersection continuously monitors the individual traffic conditions for each direction, and estimates through the fuzzy-based system the current estimation of approaching and leaving time. Only when the sum of the traffic estimation exceeds a predefined VTT, RSU activate the cooperative traffic information update with data fusion mechanism. VTT corresponds to the sum of approaching and leaving time, to be monitored for each direction, varied depending on traffic management policies. Our solution does

not generate any additional communications overhead when traffic conditions are normal or not, since the data fusion procedure is launched without any additional information. The data fusion mechanism is based on messages which are exchanged when the leader updates the group fused data and sends it to the corresponding RSU. These messages are employed to send local number of vehicles estimated made by different directions (i.e. direction in [32] protocol), and VTT for each vehicle left the corresponding direction. In addition, and as novelty with respect to other proposals, the positions of last updating is also exchanged to quantify the level of approaching and leaving time estimation and its value. To this aim, message updates the traffic information included in the packet based on its own approaching and leaving time estimation. Finally, RSU situated in the center of an intersection will get a global and complete vision of the level of approaching and leaving time for whole the intersection. In order to determine the value of all the incoming and outgoing direction of the intersection, estimated approaching and leaving time averaged respectively. A key aspect in our solution is to identify the approaching and leaving time close to the RSU of the intersection that will change the data fusion procedure. Data fusion technique defines a procedure that is open for further optimization. For example, which vehicles that have recently passed the stop line or stay in the traffic jam direction, will be responsible for increasing (or decreasing) the VTT values of the next vehicles. To this aim, local traffic estimation for every road direction will be evaluated for a certain period of time. The road direction is considered to have increase value of approaching and leaving time if its previous local estimations sustainable reported some stayed vehicle from previous cycle. Thus, such intersection controller is not operated well to clear all the vehicles. The vehicles at the stop line of the corresponding direction will periodically generate VTT messages at a configurable frequency rate which allows selecting the periodicity of the traffic information updates. Since our solution has to be robust to low PRs, instead of using the number of cars only, the updating of approaching and leaving time is also computed with suitable traffic measurement for each direction. For measuring traffic associated to each direction, the current approach based on counter called CTF (Cars-Times-Fuzzy). Every direction has a counter that is either increased by approaching time when the direction has red light or decrease by the leaving time after the related direction is executed in green light. Updating the value of this counter is done according to the following equation:

$$CTF_e(k) = CTF_e(k-1) + Cars_e(k) * F_e(v(k), k); \qquad (3.1)$$

$$with\ CTF_e(0) = 0$$

where $CTF_e(k)$ is the new value of the CTF counter for direction e , $CTF_e(k-1)$ is the value of the counter at the previous time-step and $Cars_e(k)$ is the number of cars on the target direction e, and finally $F_e(v(k), k)$ is the estimated approaching and leaving time respectively.

3.2 Simulation results

For evaluating our approach, a simple scenario consisting of one intersection was taken from COLOMBO framework system (called RiLSA intersection [46], as shown in **Figure 3.2**). This is done for two reason, comparability and traffic realistic (although it is synthetic but traffic is configured to be realistically reflect urban intersection traffic, and has been used as a baseline traffic scenario in COLOMBO). The quality of the performed surveillance is not effected by neither infrastructure nor TSC settings. Number of vehicles on the regarded direction and their speed (i.e. time-space patterns) are quite complex yielding in strong fluctuations of the approaching and leaving time, due to being limited by the TSC operation.

All communications, at the network level, are performed by the NS-3 standard ***yans*** WiFi model using IEEE 802.11p with ETSI ITS G5 standards. A 6 Mbps bandwidth rate with OFDM is used. To compute signal loss, default log-distance propagation model is used. The main parameters and configurations used in our simulations reported in **Table 3-2** concisely.

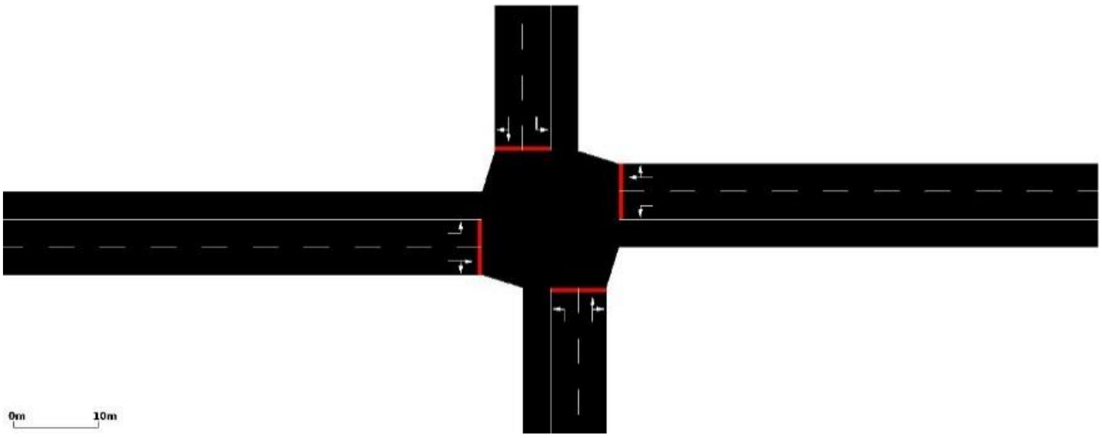

Figure 3.2 RiLSA Intersection from [46].

Table 3-2 Communication parameters and configuration used.

Parameter	Value
Wi-Fi mode	802.11p
Transmission mode	6 Mbps (OFDM)
Node radius	170 m
Propagation loss	Logarithmic
Propagation speed	Constant ($3*10^8$ m/s)

We use COLOMBO framework to supply our simulation environment, considering that it provide a realistic model to simulate vehicular behavior (i.e. mobility and communications) in urban scenario. All simulations were performed in the same one hour time span. Vehicle densities change during time. This is because of wave trend that follows the green and red timings controlled by the TSC. In a first step, we compare the VTT from COLOMBO's NS-3 framework with the estimated one (i.e. approaching and leaving time from our solution) with real number of cars (i.e. 100% PR with precise position data) in order to test fuzzy system ability to reflect traffic conditions. In a second phase, in order to evaluate the capability of our solution to follow and emulate realistic conditions (i.e. localization affected by errors), we make PR vary (from 100% to 10%) with position sampling error using COLOMBO framework.

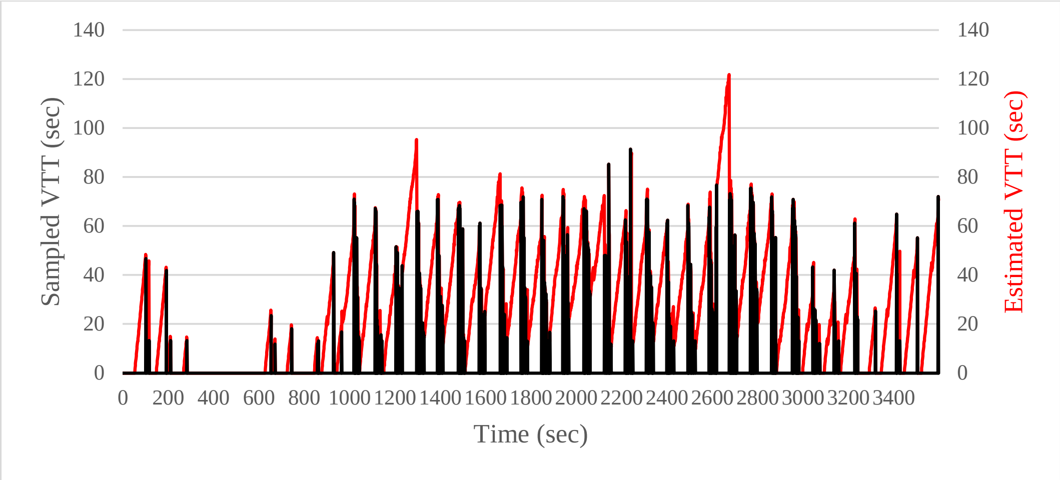

Figure 3.3 Estimated VTT with Sampled VTT for one direction (i.e. 180^o outgoing).

Relates to the first step, **Figure 3.3** depicts the VTT raw samples received by the RSU (black line) with the estimated one from our solution (red line). We can observe that our fuzzy system estimate the VTT accurately and continuously. Another important notice, our estimated solution does not drop to zero as the sample VTT in cases where the vehicles need more than one cycle to leave the intersection (e.g. between 1000 and 3400 sec in **Figure 3.3**). Although at some situation (e.g. between 2400 and 2600 sec), it seems does not react to large varying states but having a look at the real number of cars in **Figure 3.4**, we can see that this comes from the fast increase in traffic density (i.e. real number of cars with time).

For the second phase, **Figure 3.4** depicts the real number of cars approached and estimated by COLOMBO framework (black line) with the approaching time estimated from our solution (red line), with a 170 meters range from the inspected RSU. This value of 170 meters is chosen to match the maximum communication range of a mobile node used in COLOMBO framework.

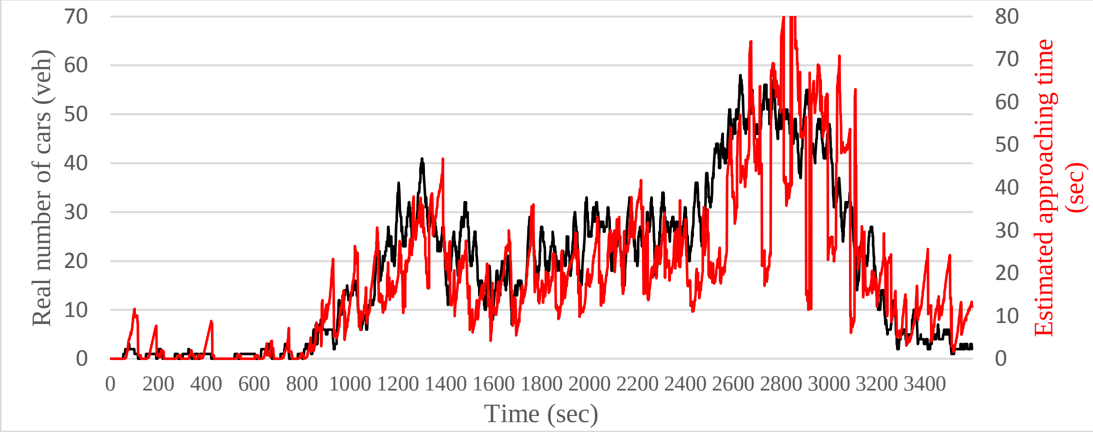

Figure 3.4 Approaching time estimated with real number of cars.

The same thing can be done for the whole leaving directions for RiLSA intersection as shown in **Figure 3.5**.

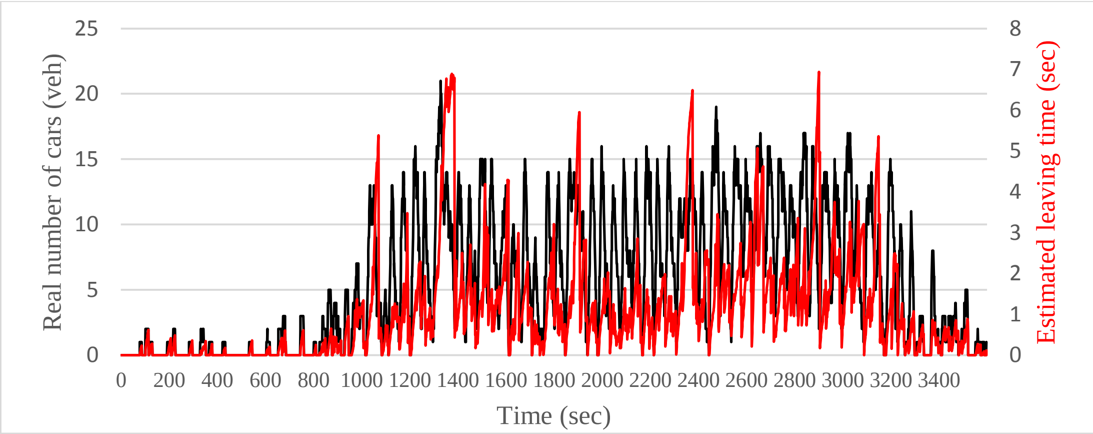

Figure 3.5 Leaving time estimated with real number of cars.

In addition, **Figure 3.6** shows our solution behaviors with different PRs.

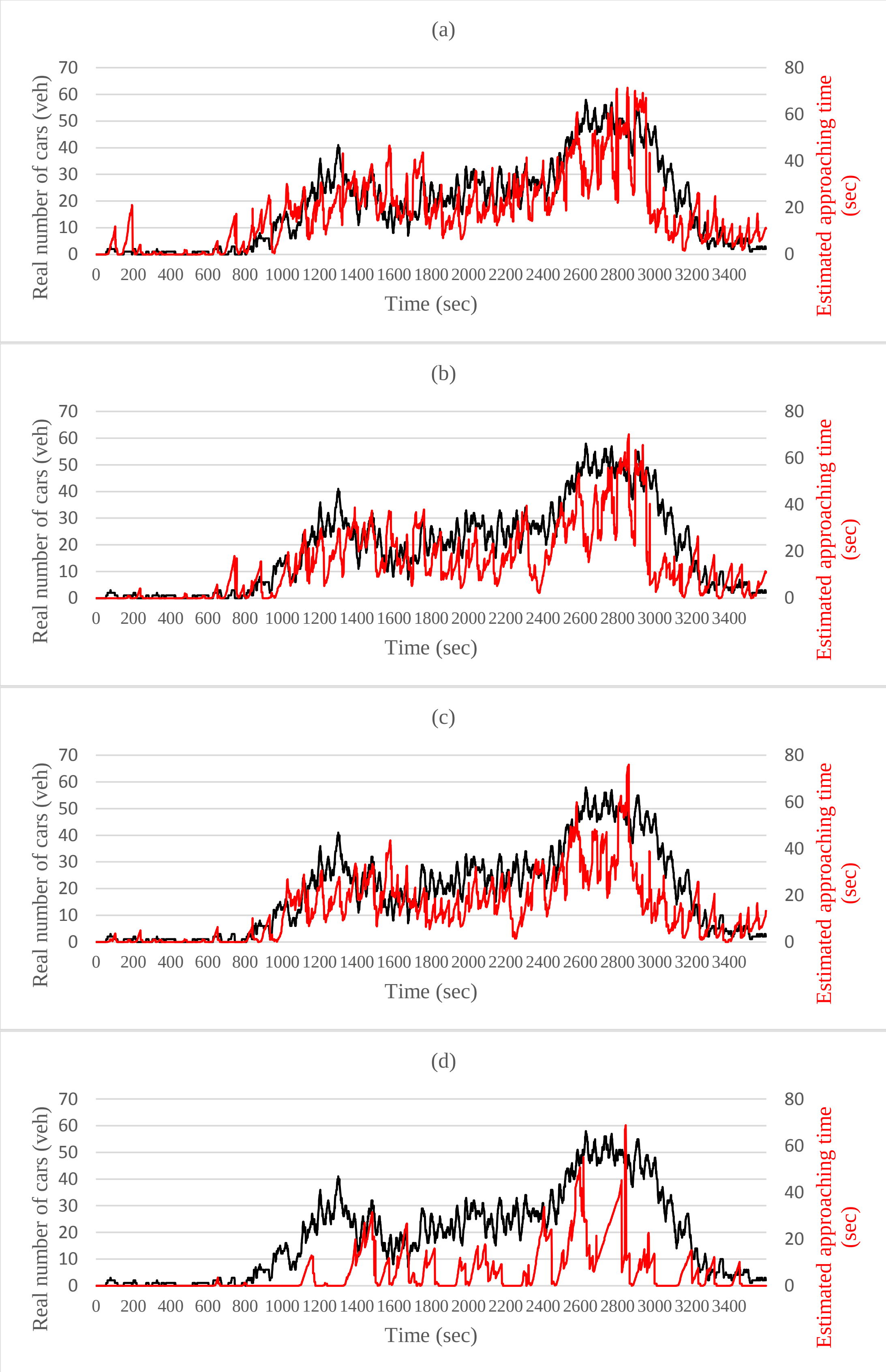

Figure 3.6 Approaching time estimated with (a)100%, (b)50%, (c)20%, and (d)10% PRs.

3.3 Comparison

In order to have a simple comparison with COLOMBO results, **Figure 3.7** depict the pheromone that was computed with COLOMBO project by the following equations:

$$f_l(k+1) = \beta f(k) + \gamma v(l,k) \tag{3.2}$$

$$with\ f_l(0) = 0\ and\ v(l,k) = \frac{MaxSpeed(l) - MeanVehicleSpeed(l,k)}{\frac{dMeanVehicleSpeed}{dk}}$$

Where $f_l(k)$ is the pheromone defined in COLOMBO project for edge (or lane) l at time step k. β and γ are constants. $MaxSpeed(l)$ is the maximum speed allowed for edge l and $MeanVehicleSpeed(l,k)$ is the average speed of vehicles measured based on V2X communications.

From our simulation results, a simple comparison can be made between our traffic surveillance solution and COLOMBO's. In **Table 3-3** the main differences between them are summarized.

Table 3-3 Main differences between our solution and COLOMBO

Characteristics	**COLOMBO's surveillance**	**Ours**
Approaches followed	Topology-based or Dissemination-based	Topology-based and Dissemination-based
Data required	Speed and/or Number of Vehicles	Speed, Number of Vehicles As well as vehicle total time
Surveillance data type	Pheromone	Approaching and leaving time
Algorithm used	Swarm intelligence	Fuzzy logic
Disadvantage	Time consuming with optimization	Without optimization
Advantage	Dynamically adapted with traffic flow	Dynamically adapted with traffic flow
Penetration rate	Effected without optimization	Not effected a lot (till 20%)
Data quality	Close to benchmark (SUMO)	Close to benchmark (COLOMBO, more specifically NS-3)

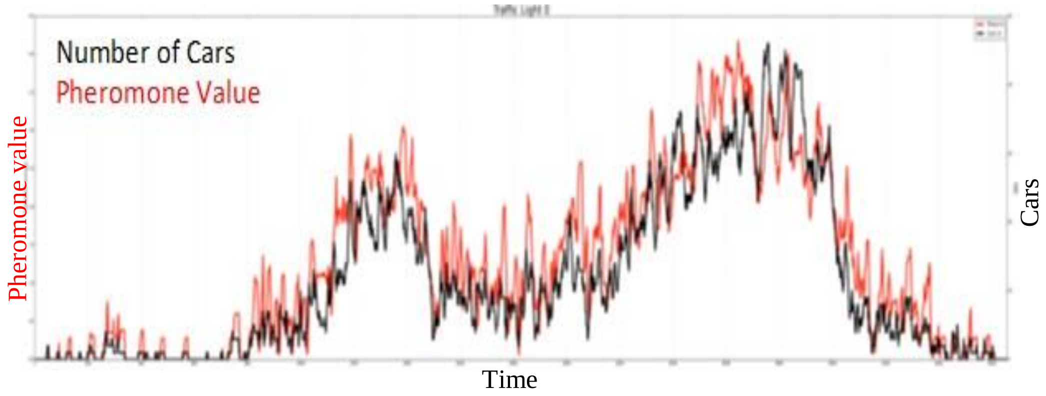

Figure 3.7 Depicts the pheromone value with real number of cars in COLOMBO project [24].

3.4 Conclusions

Our traffic surveillance solution includes several simplifications compared to the one used in COLOMBO project. Consequently also some of the COLOMBO's codes are used in ours (more specifically, traffic monitoring using V2X communications[1]).

The optimized procedure in COLOMBO however, is often not relevant to the calculation of traffic surveillance data. One central result of high relevance is the positive behavior of the performance decreasing and increasing linearly with actively cooperating vehicles up to about 20% PR. Less than this value, our solution can exchange data (even only when one vehicle is under the RSU's communication range), but the performance will decrease. This motivates that the solution can be used for low PR but further investigation should be done for rapid decrease (i.e. till 1%). At the same time, focusing on approaching and leaving time measurements are less dependent on the PR; in fact, as shown in **Figure 3.6** (d) following the closely real behavior up to 20%, and having reasonably good results. Already deployed RSU with V2X capability can be a source of information for traffic efficiency. The PR is the major factor that influences the performance of the surveillance, but the aggregation interval (for both approaching and leaving time) should be taken into account. One obvious issue where no equipped vehicle was sensed is the lack of data for that intervals.

[1] This product includes software developed by the University of Bologna and its contributors.

Depends on that, the probability to have no data for an interval will be changed. Hence, low PRs show data lacks at times where no equipped vehicle has been within the communication range. As a result, our solution can provide the TSC with a fairly good estimation of the approaching and leaving time with real traffic flow. These results were confirmed using simulations.

CHAPTER 4

TRAFFIC DELAY ESTIMATION WITH V2X COMMUNICATIONS

Traffic condition detection of a single road is much easier then crossroads (i.e. intersections). This is because speed and number of vehicles measurements are enough indicators for road traffic condition detection while they are not sufficient for an intersection. Ideally, a birds-eye view of an intersection with speed, position and route information about each vehicle should be available instantaneously. Using such information, an intersection with traffic surveillance method knows exactly how many vehicles are waiting, approaching or leaving in each direction. In other words, approaching and leaving patterns of vehicles in an intersection are known. Traditional surveillance methods (e.g. using inductive loops, cameras ...etc.) and emerged surveillance methods (e.g. using wireless sensor networks, V2V communications, V2I communications ...etc.) cannot deliver this information. The main reason for that is the non-deterministic nature of vehicles approaching and leaving the intersection as well as the limitations of technology used for such surveillance methods. This means that traffic condition detection approaches rely on estimates of vehicles approaching and leaving patterns. Without standard patterns (e.g. a mathematical model that is out of scope of this thesis), a number of measures have to be used among which traffic delay/vehicle waiting time is the most important one. This is because it directly relates to the time loss that a vehicle/driver experiences while crossing an intersection. Another reason may be it is an essential indicator of LOS for TSC operation in a signalized intersection.

In this chapter, vehicles approaching and leaving patterns proposed in previous chapter is developed under low PR. With this development, traffic delay is determined and considered as a direct indicator for traffic condition estimation.

4.1 Related works

Vehicular communication monitoring provides extensive information of approaching vehicles as they frequently transmit a specific messages containing all required relevant information (e.g. speed, position, ...etc.). A convenient method to acquire data from cooperative vehicles is to receive messages with RSU. After receiving the message, the RSU extract the most important information that is suitable for traffic condition detection. Cooperative vehicular communication based on continuous exchange of information between vehicles via V2V communications or between vehicles and infrastructure nodes via V2I communications.

In the field of detecting traffic conditions using cooperative vehicular communications, several studies have been published recently. Many of these studies rely on techniques used for periodic exchange of specific packets, in order not to overload the cooperative communications channel. For example, techniques used in [12], [47], [48] and [36] have been designed to monitor and estimate road traffic condition through V2V communications, and broadcast this information to neighboring vehicles. These studies are done for highway scenarios without the need to deploy additional infrastructure nodes. On the other hand, techniques used in [49], [50], [51] and [52] have been designed to monitor and control an intersection through V2I communications. These studies are done for urban scenarios with the need to deploy infrastructure nodes and without delay measurement. An advantage of using vehicle information (e.g. speed and position) through V2I communication is that difficulties of defining traffic condition at real-time are circumvented.

The previous techniques have clearly highlighted the potential of pure V2V communications to monitor road traffic condition or pure V2I communications to control an intersection.

However, cooperation communication between V2V and V2I, known as V2X, have been further studied. In this context, techniques used in [53], [54], [55] and [56] have been designed to investigate this cooperation. In particular, the technique used in [53] describes the benefits of the V2V2I architecture over the pure V2I or V2V architectures. In the V2V2I architecture, the transportation network is broken into zones in which a single vehicle, known as the super vehicle, is able to communicate with the central infrastructure. All other vehicles can only communicate with the super vehicle responsible for the zone in which they are currently traversing. The technique used in [54] defends the applicability of cellular network in the V2V field, and presents a novel communication paradigm for vehicles which unifies both V2V and V2I paradigms into one system. The technique used in [55] proposes a system that allows an intersection TSC to adapt to the approaching of a priority vehicle by using real-time vehicle positions collected via V2I. Finally, the technique used in [56] introduces vehicle groups to deliver their information in a comprehensive stream with wide set of properties of the traffic flow to the infrastructure node in the center of an intersection.

In V2X communications, the reviewed studies have highlighted the potential of cooperative vehicular communication to be efficiently, in distributive and locally use for intersection. However, there are still trade-offs between efficient use of the communication channel versus accurate traffic condition detection using traffic delay measurement. In particular, the difficulties of defining and estimating vehicles approaching and leaving patterns of an intersection under low PR at real-time. Hence, a valid estimating methodology is used and addressed here within this thesis. The following section describes our proposal in detail.

4.2 Proposed technique

Vehicles' approaching and leaving a RSU is investigated through a cooperative V2X communications using COLOMBO framework [57]. First, measurements that can be provided by COLOMBO framework with V2X communications are analyzed. Then, definitions for approaching and leaving time based on the less effected measured (mostly it is the average speed of group of vehicles) with low PR are introduced. Based on these definitions, the approaching and leaving time are extracted using a fuzzy logic system. In order to estimate traffic condition for each incoming edge, this thesis proposes a novel approach using the estimated approaching and leaving patterns to estimate cumulative approaching and leaving time respectively.

Cumulative approaching and leaving time should take into consideration low PR. The proposed approach is also capable to detect the traffic delay of incoming edge with respect to their number of vehicles. Finally, to detect traffic delay for the intersection as a whole, the estimated delay for all incoming edges are averaged. The proposed solution is also capable of providing LOS for the signalized intersection as a whole as well as for each incoming direction even under low PR. The details of our traffic delay estimation is going to be explained in the following subsection.

4.2.1 Traffic delay estimation

The definition of “high” versus “low” traffic and on how to measure it have some uncertainty. This comes from its dependence on the intersection topology (e.g. lanes width, lanes number, and geometry of the intersection) as well as the deterministic flow of vehicles.

In V2X communications approach, with low PR, one could coarsely assume that absolute numbers can be hardly determined, while averaging measures can be retrieved with a sufficient quality. Hence, average speed of vehicles per edge and its derivative are used to define approaching and leaving time for each direction. Here, the approaching time is defined as the time that is determined with low speed and/or decreasing acceleration for each vehicle (or group of vehicles) entered to the direction under the RSU communication coverage area per moment. Moreover, the leaving time is defined as the time that is determined with high speed and/or increasing acceleration for each vehicle (or group of vehicles) entered to the direction under the RSU communication coverage area per moment. As it is clear, the uncertainty in the definition of the approaching and leaving times (e.g. low and high as well as decreasing and increasing) can be managed using fuzzy logic system.

In order to make our traffic condition definition and estimation react rapidly to more persistent traffic changes, approaching and leaving estimation times are multiplied by their number of vehicles and accumulated to the current moment in an adaption procedure per direction. Proposing this procedure is not just as a traffic condition estimation approach but also give an indicator for the delay with respect to cumulative period time. This is determined by multiplying the estimated approaching and leaving time by number of vehicles for the corresponding direction per moment respectively. For each moment (e.g. second in our simulation), the delay of each direction is determined by dividing the difference between approaching and leaving patterns by its number of vehicles. Then, the delay to all directions of the incoming edges are averaged by RSU to determine the delay for the whole intersection. In the following subsections the proposed approach is described in detail.

4.2.2 Fuzzy logic system

As explained in pervious chapter for any fuzzy system, the input variables are first classified into different categories or fuzzy sets. The possible fuzzy sets for the average speed are L for low, M for medium, and H for high. For the average speeds' derivative, the defined fuzzy sets are N for negative, Z for zero, and P for positive. In addition, output fuzzy sets corresponding to estimated cumulative average approaching and leaving time have also been defined for one second time span, with L for low, M for medium and H for high. In order to determine the degree of membership of the input values to each of the fuzzy sets, membership functions are illustrated in **Figure 4.1**. The membership functions used in our solution are implemented based on simple rating system.

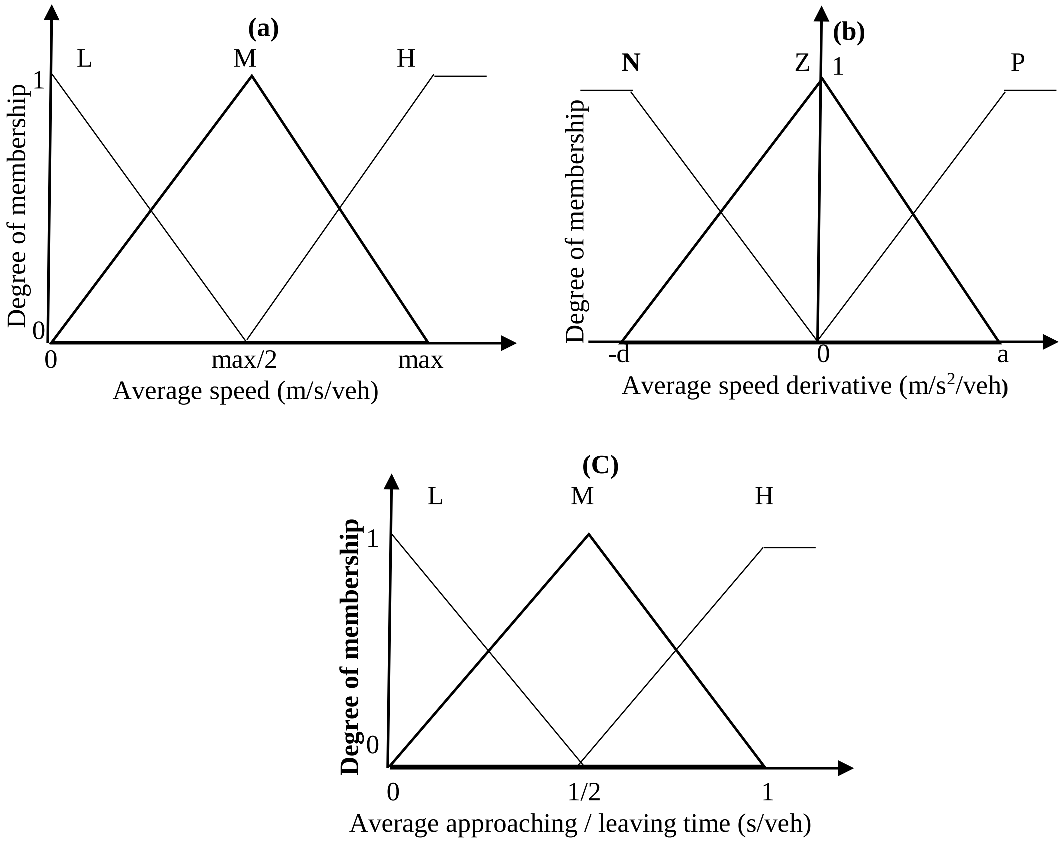

Figure 4.1 Fuzzy-based estimation system (a) Average speed sets, (b) Average speed derivative sets, and (c) Output sets

To finalize the definition of our fuzzy system, fuzzy rules that relate the input (average speed and its derivative) and the output fuzzy sets (average approaching and leaving time per second) are established as displayed in **Table 4-1**. The fuzzy rules are designed based on the average speed and its derivative with average approaching/leaving time definitions.

Table 4-1 Fuzzy rules relating inputs (average speed and its derivative) sets with outputs (average approaching and leaving time) sets.

Average approaching time/ Average leaving time		**Average speed derivative**		
		N	**Z**	**P**
Average speed	**L**	H/L	H/L	M/M
	M	H/L	M/M	L/H
	H	M/M	L/H	L/H

Based on the output of the fuzzy logic system, different traffic condition of the incoming edge is determined in an adaptation procedure. The details of such procedure is given in the following subsection.

4.2.3 Adaptation procedure

As described previously, every RSU in an isolated intersection monitors the individual traffic condition for each incoming edge, and estimates through the fuzzy based system the average approaching and leaving time per moment. Every direction has two counters associated to it, we called them cars times fuzzy (CTF) that represent cumulative approaching time and leaving time multiplied by its number of vehicles respectively. These counters, i.e. approaching CTF and leaving CTF, are updated only when at least one vehicle is sensed in the corresponding direction according to the following equations:

$$ArCTF_e(k) = \begin{cases} 0 \; if \; cars_e(k) = 0 \\ ArCTF_e(k-1) + cars_e(k) * Ar_e[F(v(k), dv(k)/dk)] \; else \end{cases}$$

$$LvCTF_e(k) = \begin{cases} 0 \; if \; cars_e(k) = 0 \\ LvCTF_e(k-1) + cars_e(k) * Lv_e[F(v(k), dv(k)/dk)] \; else \end{cases} \quad (4.1)$$

$$with \; ArCTF_e(0) = 0 \; and \; LvCTF_e(0) = 0$$

Where $ArCTF_e(k)$ and $LvCTF_e(k)$ are the new value of cumulative approaching and leaving CTF for edge e at time k respectively. $ArCTF_e(k-1)$ and $LvCTF_e(k-1)$ are the value of the cumulative approaching and leaving CTF at the previous time-step $(k-1)$ respectively. Ar_e and Lv_e are the estimated output of approaching and leaving time respectively based on the fuzzy inference F with speed $v(k)$ and its derivative $dv(k)/dk$ as an inputs. Finally, $cars_e(k)$ is the number of vehicles in edge e at time k.

To this point, for each incoming edge, traffic condition is estimated based on the difference between cumulative approaching and leaving CTF estimated value. In order to determine the delay value per direction the following equations are used:

$$Delay_e\,(k) = ArCTF_e(k) - LvCTF_e(k) \quad (4.2)$$

In order to determine the delay for the intersection as a whole, delay for all incoming edges (e.g. n) are averaged as given in the following equation:

$$Delay\ (k) = 1/n \sum_{e=1}^{n} Delay_e(k) \qquad (4.3)$$

4.3 Simulation results

For evaluating our proposal, the scenario shown previously in **Figure 4.2** is used here also. **Figure 4.2** shows the scenario with incoming edges directions.

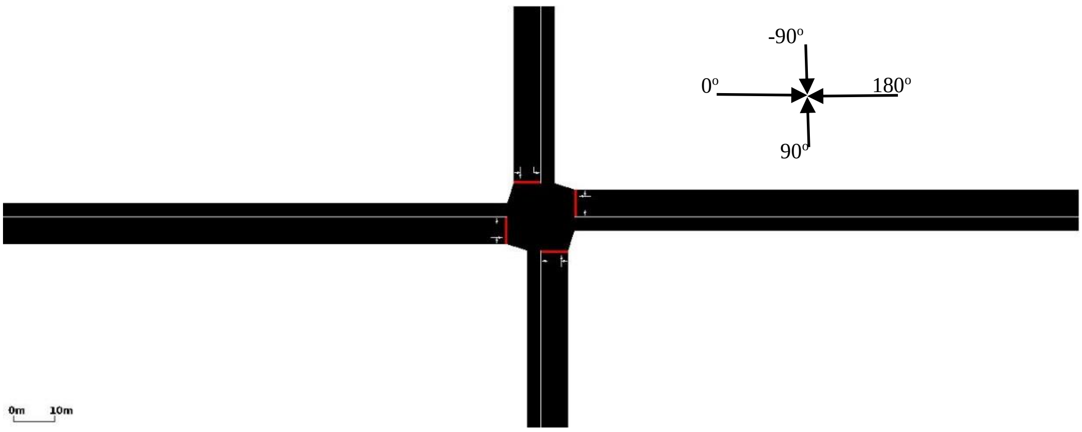

Figure 4.2 RiLSA intersection with incoming edge directions.

All communications are performed by using the same parameters of **Table 3-2**. All simulations are performed in the same one hour time span for different PR (i.e. 100, 50, 20, and 10%). Vehicle densities change during time. This is because of wave trend that follows the green and red timings controlled by the TSC. **Table 4-2** concisely reports the main simulation parameters used.

Table 4-2 Simulation parameters

Parameter	Value
Wi-Fi mode	802.11p/ETSI ITS G5
Transmission mode	6 Mbps (OFDM)
Node radius	170 m
Propagation loss	Logarithmic
Propagation speed	Constant ($3x10^8$ m/s)
Penetration rate	100, 50, 20, 10, 5, 2, 1%
Simulation time	1 hour

In a first step, we simulate the selected scenario with real data (i.e. number of vehicles) and constant traffic light control setting (i.e. fixed time).

This has been done to produce benchmark traffic condition against which to compare those estimated through our proposal with different PR.

This step is depicted in **Figure 4.3** for approaching and leaving patterns estimated versus real number of vehicles for all incoming edges. In addition, the average of all incoming edges is shown in **Figure 4.4**.

Then, delay is determined as described previously. **Figure 4.5** and **Figure 4.6** depicts this step and will be considered as the baseline to compare with.

Finally, our proposal with different PR (e.g. 100, 50, 20, 10, 5, 2, and 1%) are simulated. **Figure 4.7-Figure 4.20** depicts these steps respectively.

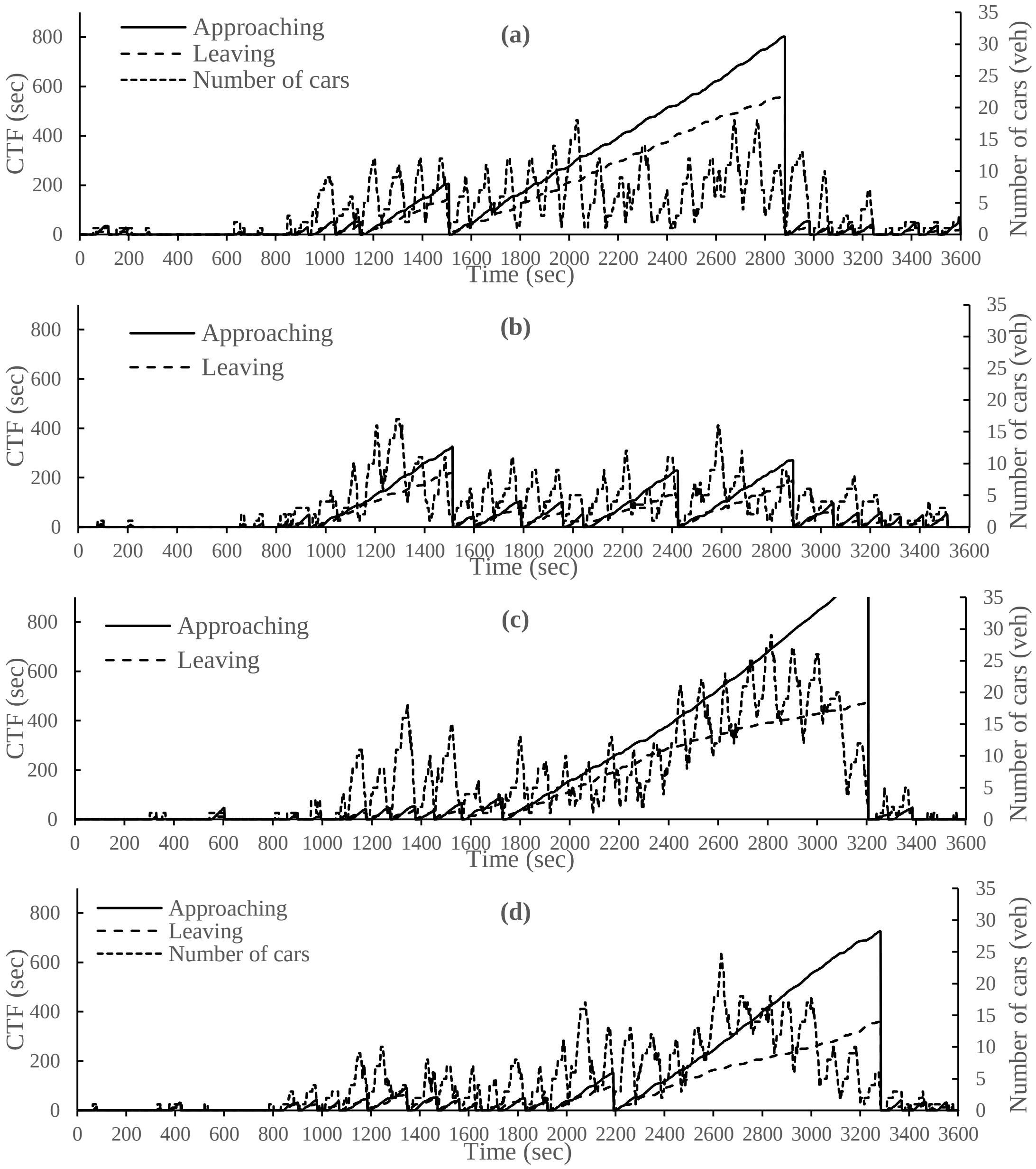

Figure 4.3 Estimated patterns versus real data for incoming edges with (a)180^o (b)0^o (c)90^o and (d) -90^o direct.

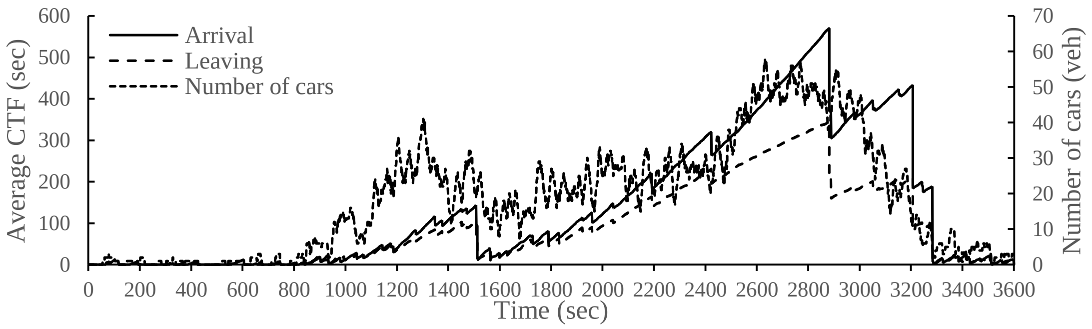

Figure 4.4 Estimated average patterns versus real data for all incoming edges.

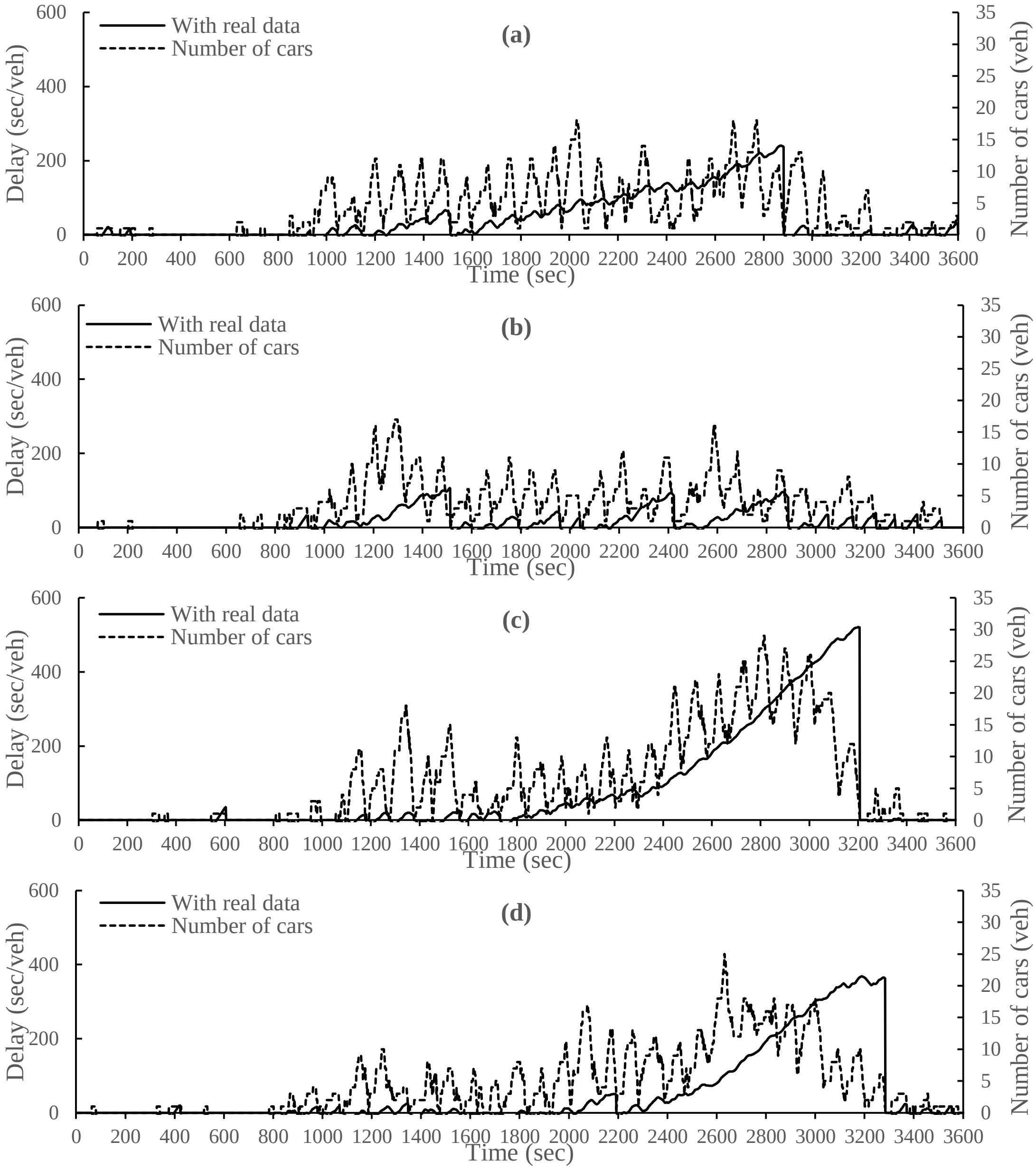

Figure 4.5 Estimated delay versus real data for incoming edges with (a)180^o (b)0^o (c)90^o and (d)-90^o direction.

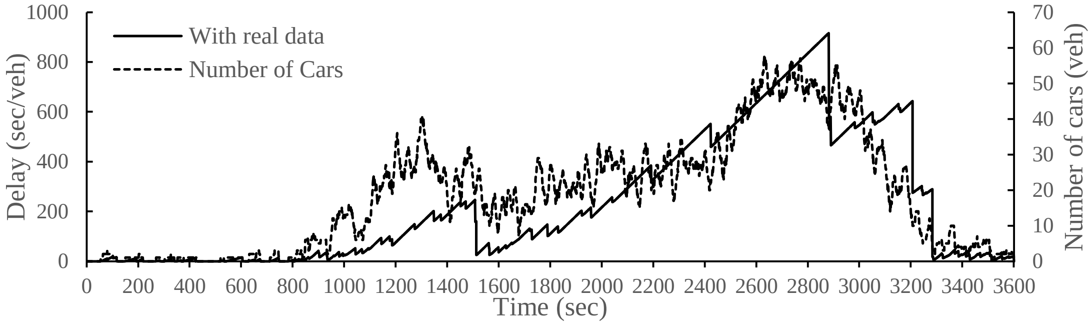

Figure 4.6 Estimated average delay versus real data for all incoming edges.

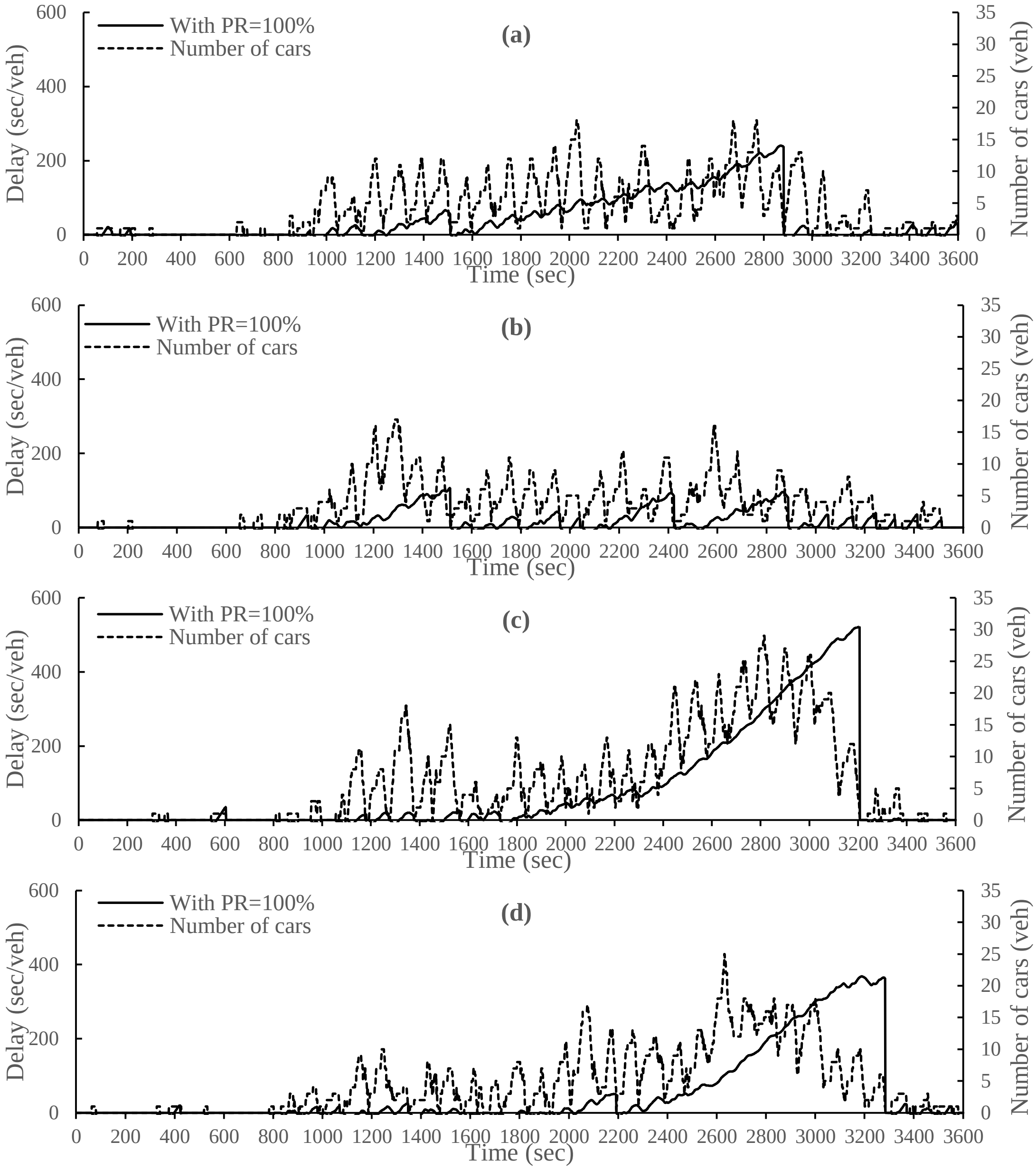

Figure 4.7 Estimated delay versus PR=100% for incoming edges with (a)180º (b)0º (c)90º and (d)-90º direction.

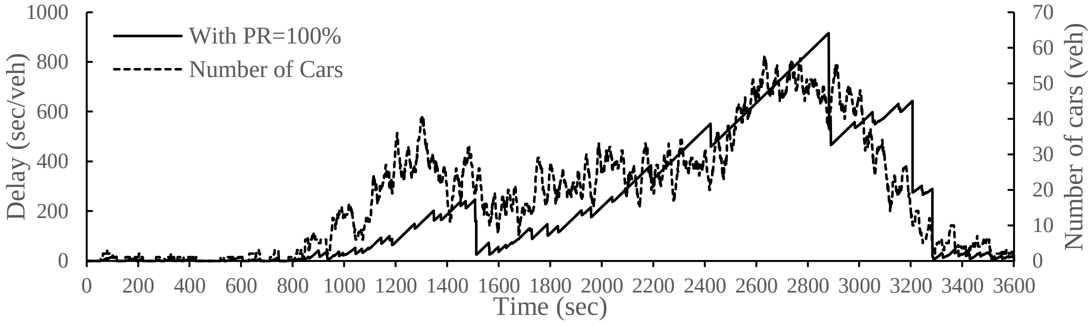

Figure 4.8 Estimated average delay versus PR=100% for all incoming edges.

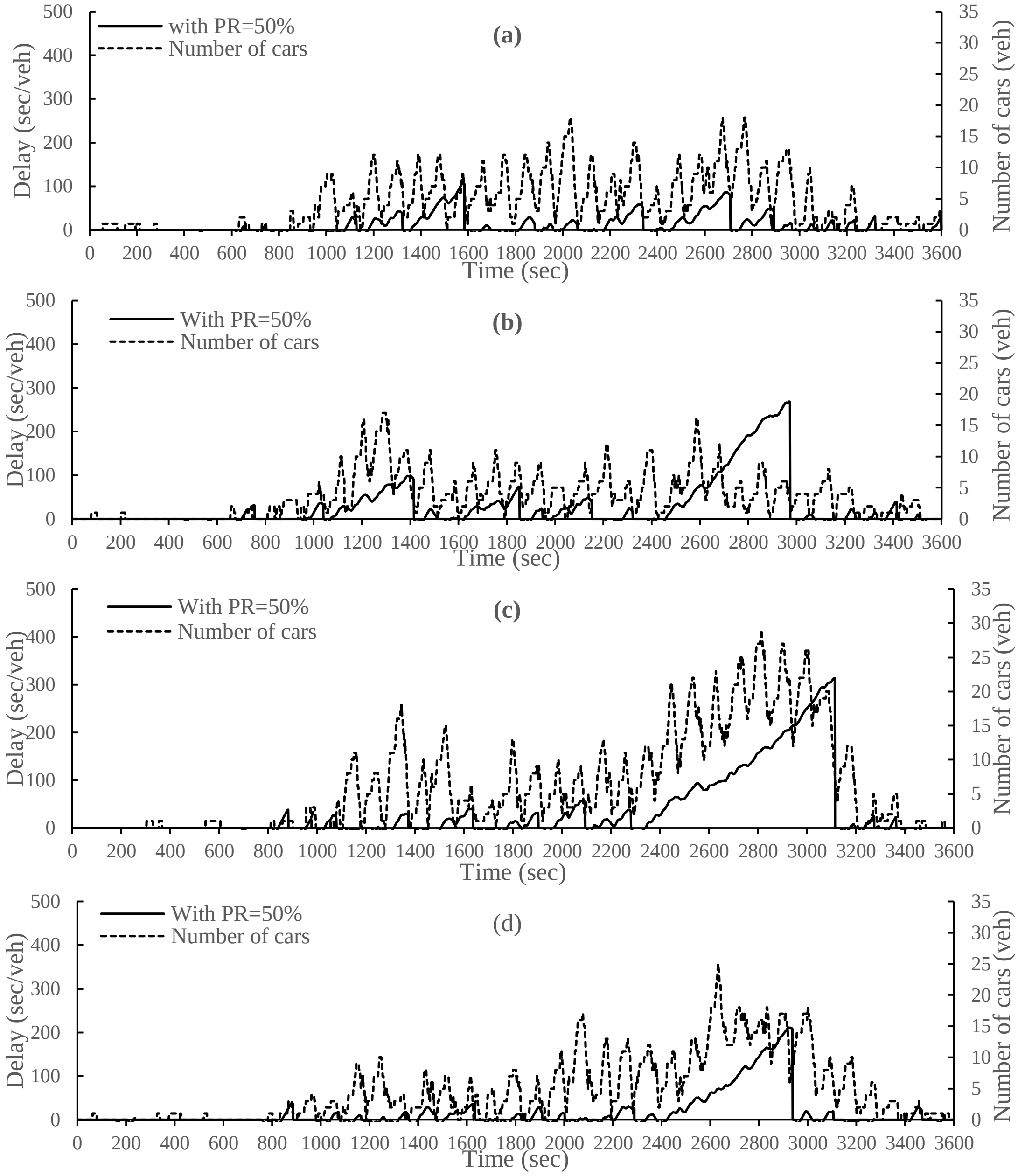

Figure 4.9 Estimated delay versus PR=50% for incoming edges with (a)180º (b)0º (c)90º and (d)-90º direction.

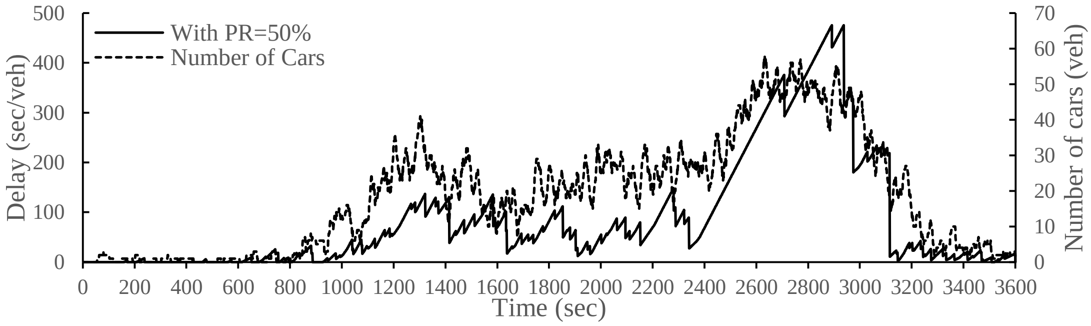

Figure 4.10 Estimated average delay with PR=50% for all incoming edges.

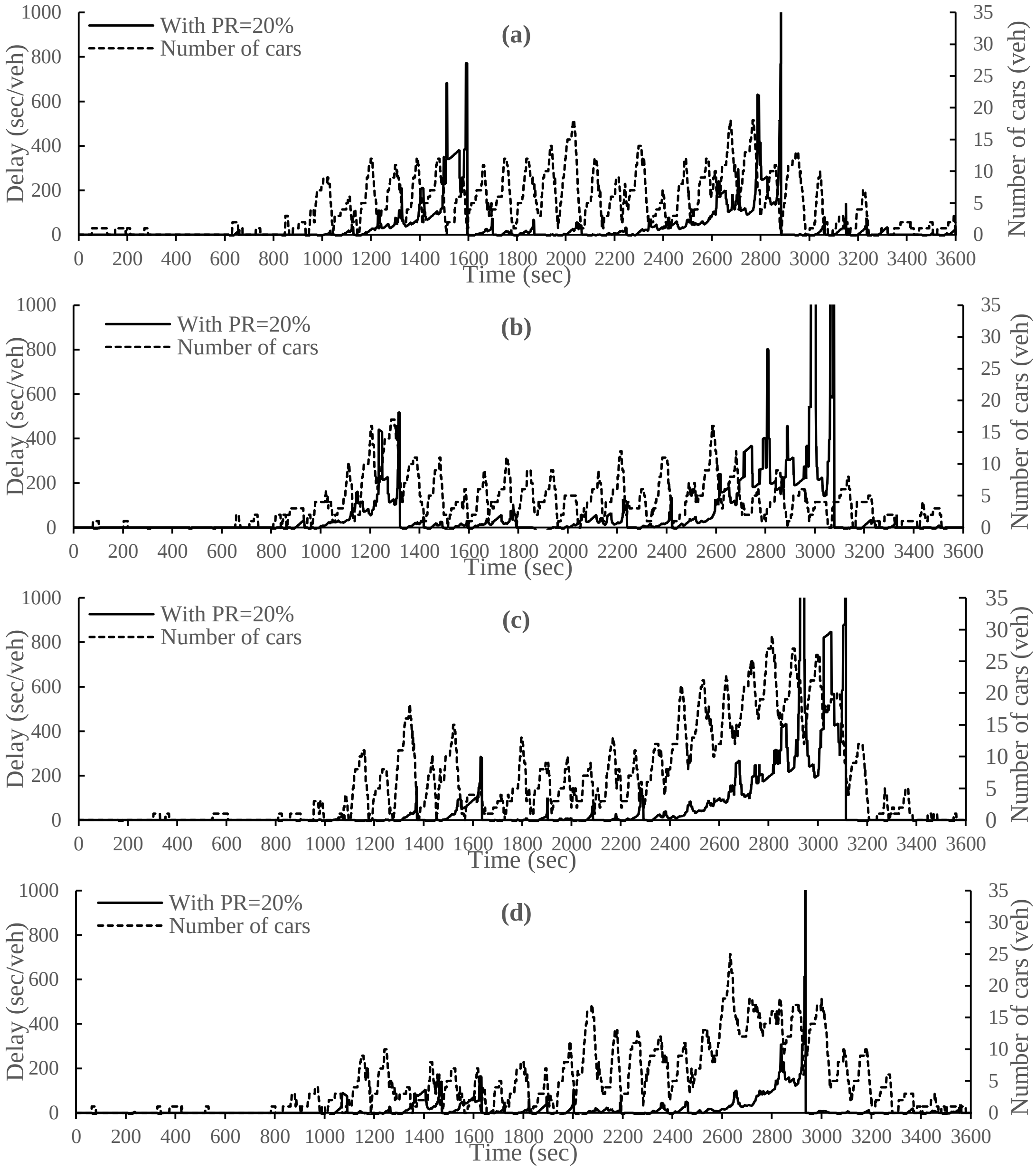

Figure 4.11 Estimated delay versus PR=20% for incoming edges with (a)180º (b)0º (c)90º and (d)-90º direction.

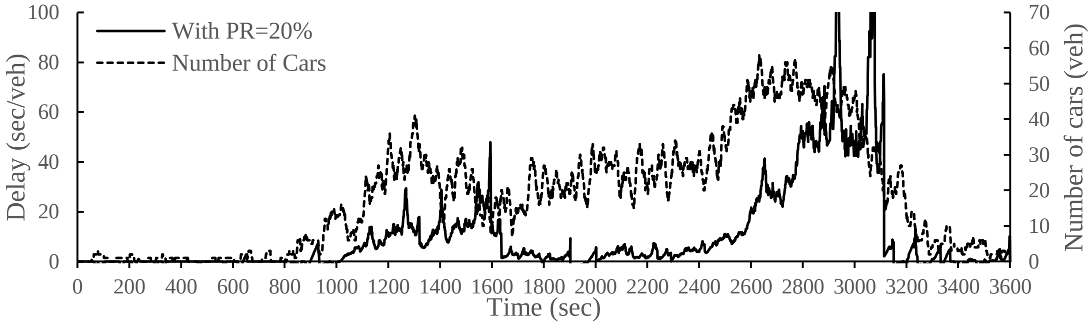

Figure 4.12 Estimated average patterns with PR=20% for all incoming edges.

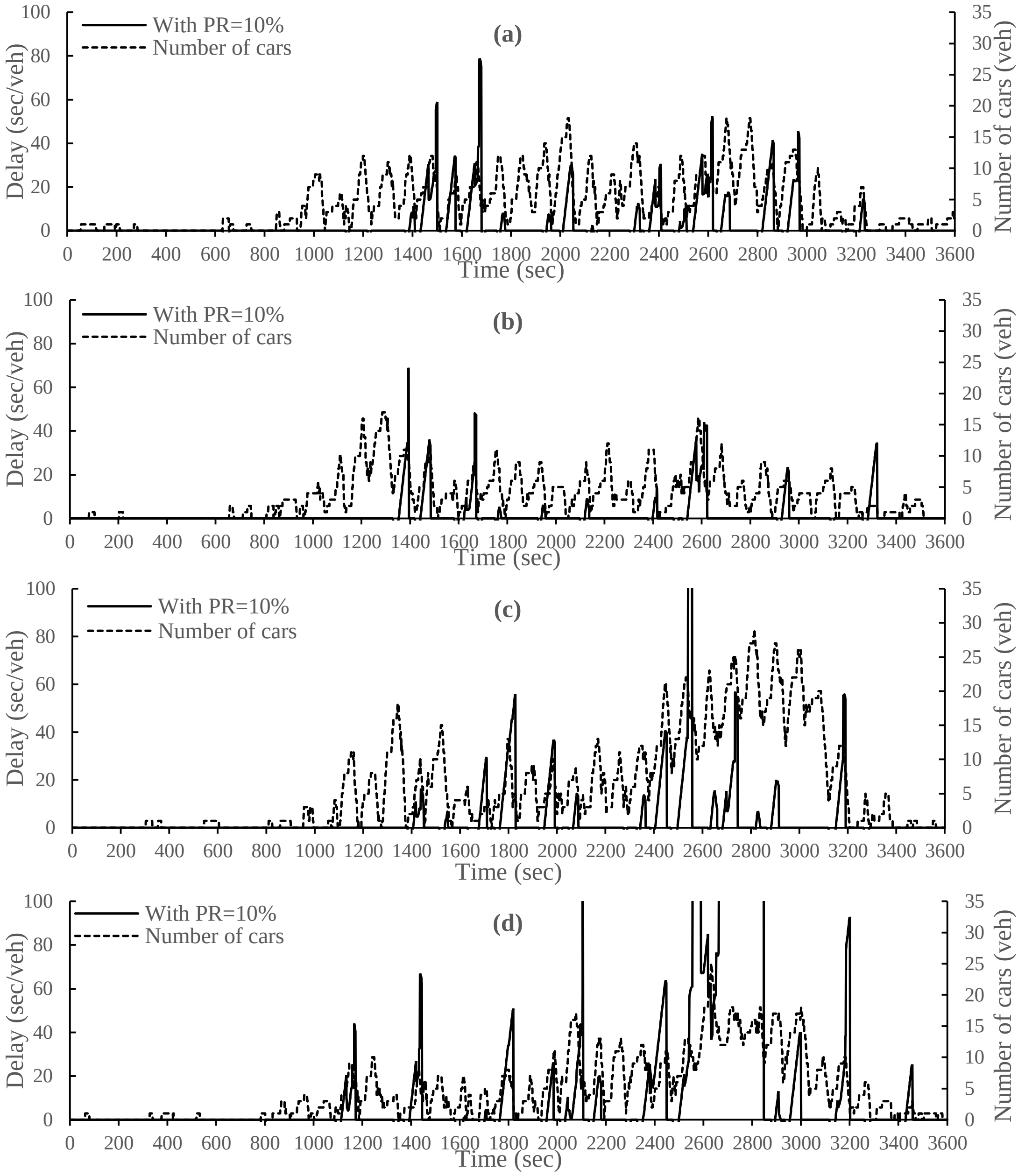

Figure 4.13 Estimated delay versus PR=10% for incoming edges with (a)180º (b)0º (c)90º and (d)-90º direction.

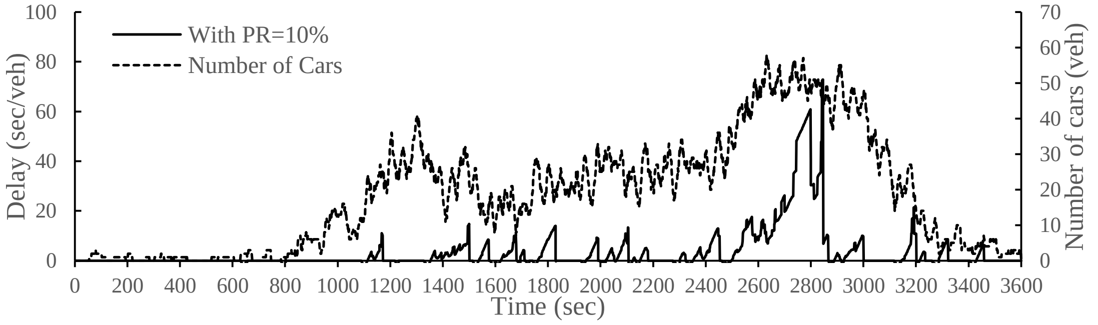

Figure 4.14 Estimated average delay with PR=10% for all incoming edges.

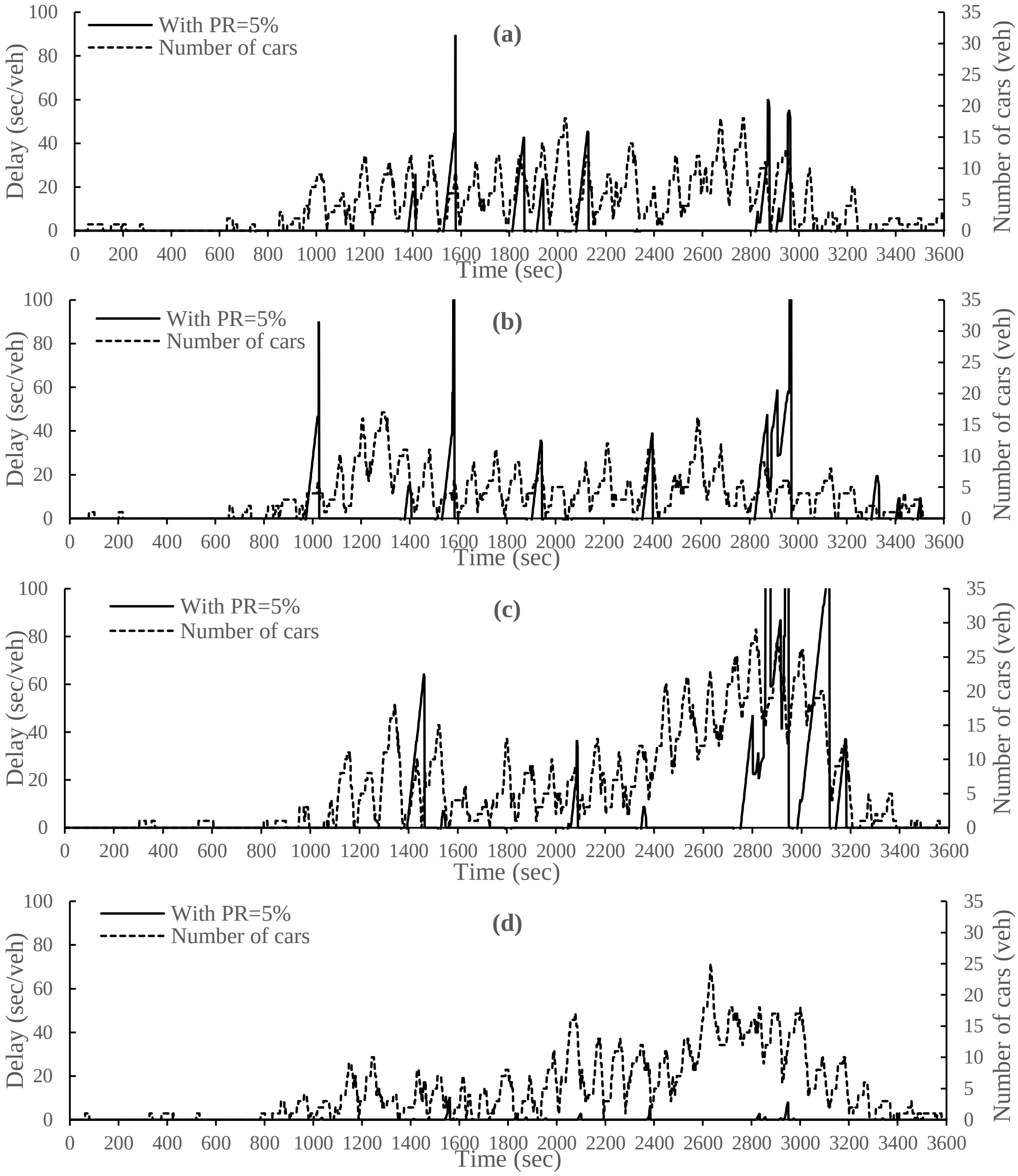

Figure 4.15 Estimated delay versus PR=5% for incoming edges with (a)180º (b)0º (c)90º and (d)-90º direction.

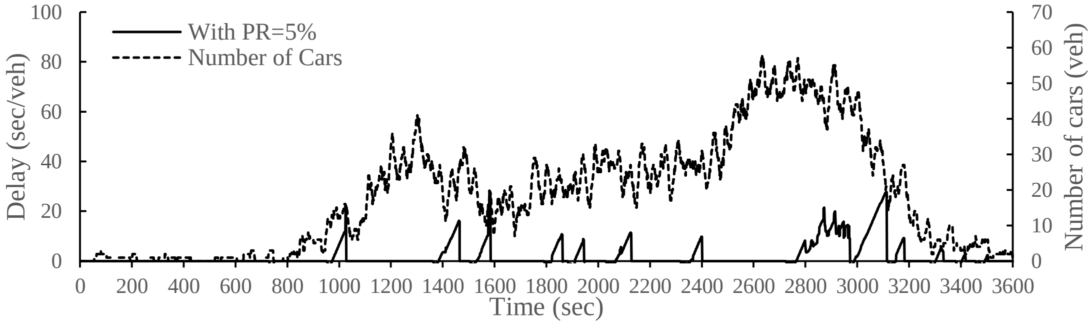

Figure 4.16 Estimated average delay with PR=5% for all incoming edges.

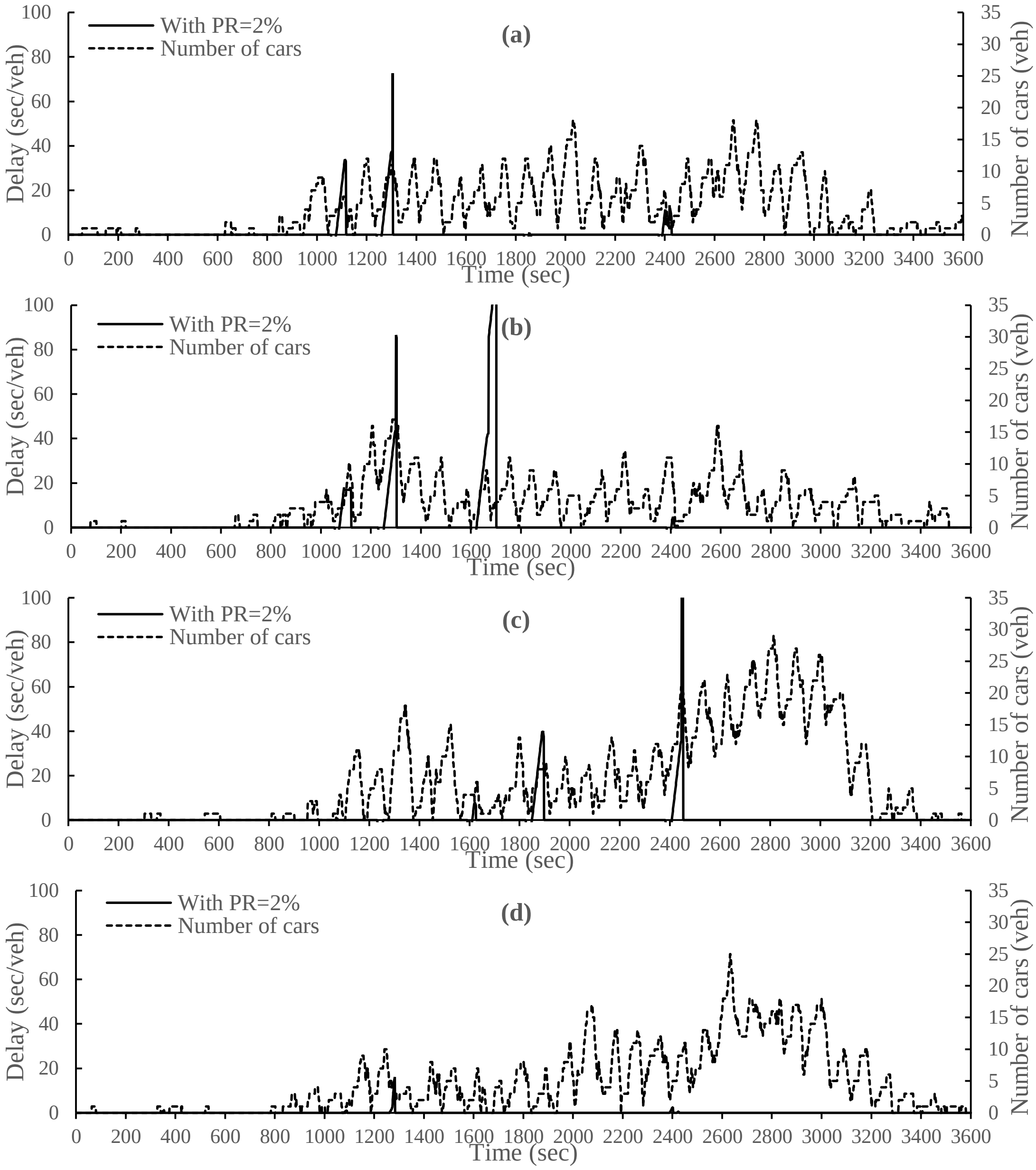

Figure 4.17 Estimated delay versus PR=2% for incoming edges with (a)180º (b)0º (c)90º and (d)-90º direction.

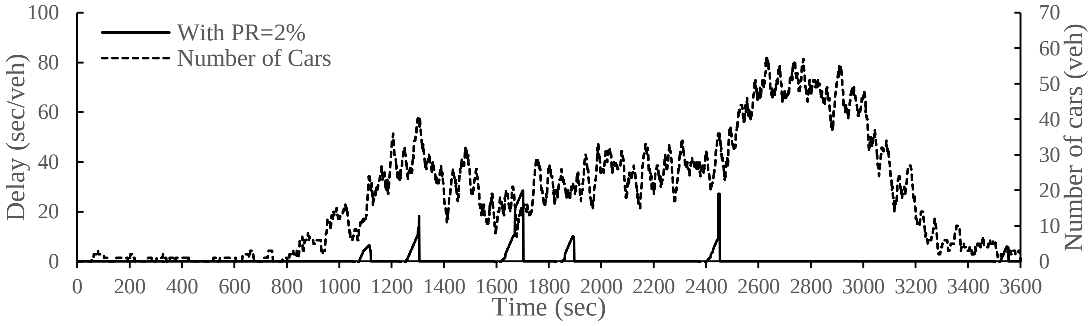

Figure 4.18 Estimated average delay with PR=2% for all incoming edges.

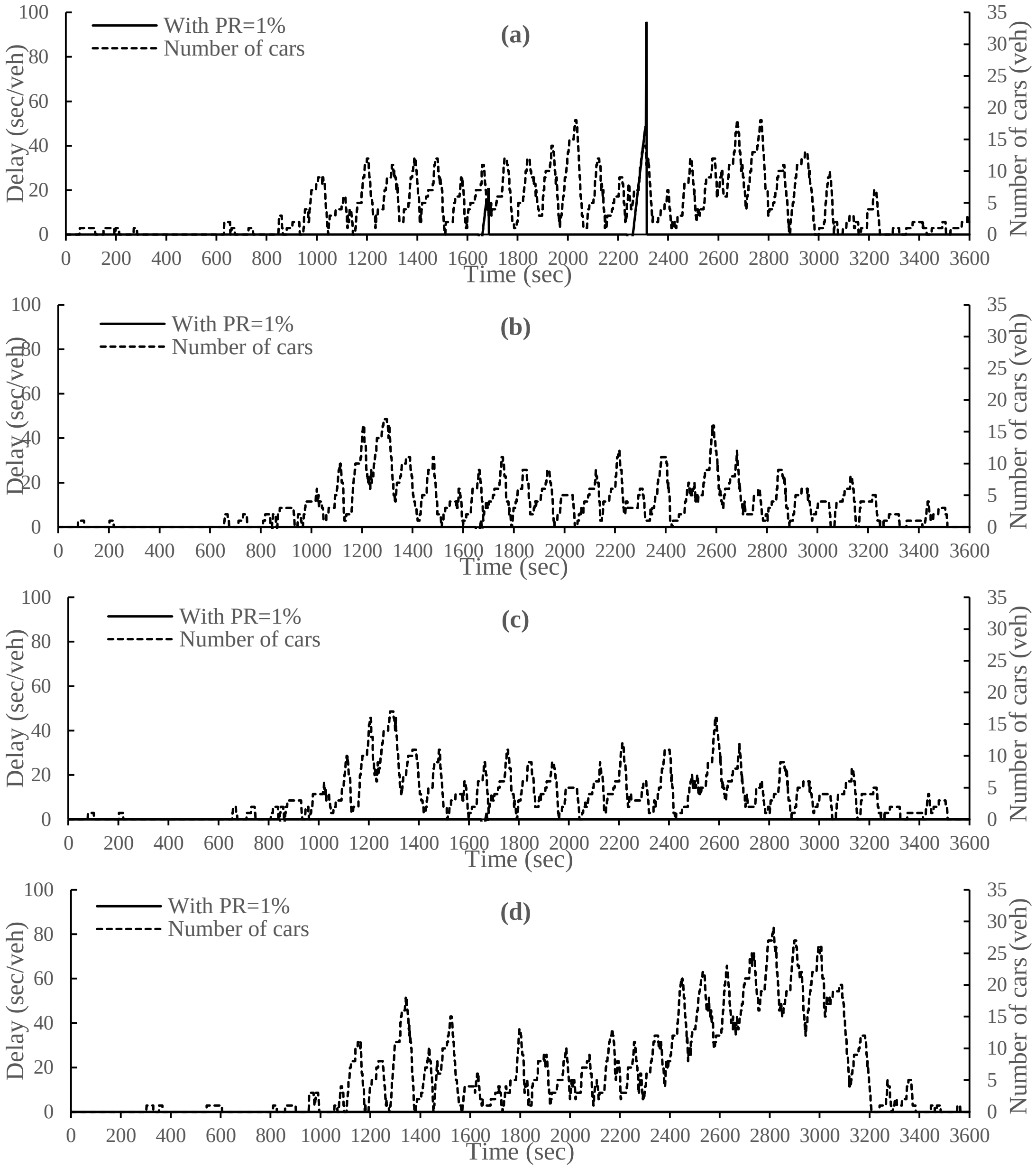

Figure 4.19 Estimated delay versus PR=1% for incoming edges with (a)180° (b)0° (c)90° and (d)-90° direction.

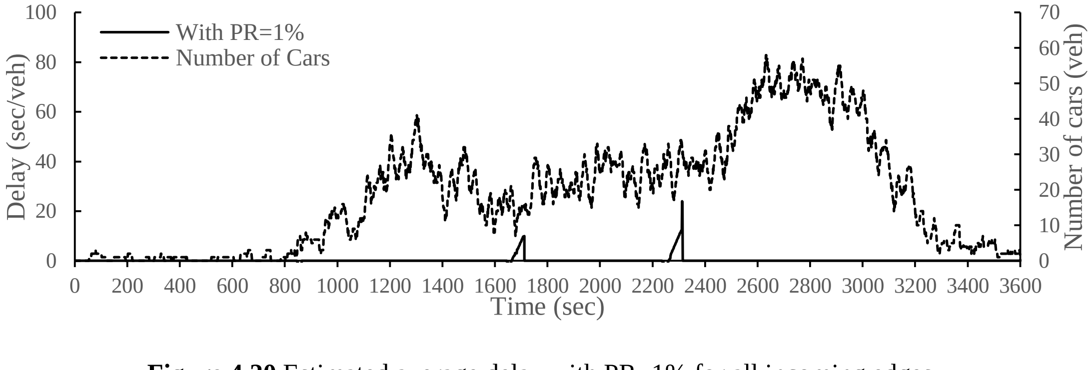

Figure 4.20 Estimated average delay with PR=1% for all incoming edges.

4.4 Comparison

In order to evaluate our approach under low PR, a simple comparison between our results with different PR and baseline result is done. First of all, **Figure 4.3** and **Figure 4.4** clearly indicate that there is a direct relation between approaching and leaving time with number of cars used in the simulation for each incoming edge as well as for the whole incoming edges respectively.

The edge is considered to have an increasing value of approaching and leaving time if its previous local estimations sustainable reported some stayed vehicle from previous cycle, and such cycle is not operated well to clear all the vehicles. In **Figure 4.5** and **Figure 4.6**, the estimated delay time for all incoming edges as well as the whole intersection are shown. In **Figure 4.7**, **Figure 4.9**, **Figure 4.11**, **Figure 4.13**, **Figure 4.15**, **Figure 4.17**, and **Figure 4.19**; the estimated delay time effected with decreasing PR from 100% to 1% for the incoming edges. In spite of this observation, the proposed approach is still considered as an effective measuring for traffic delay estimation for the intersection as a whole as shown in **Figure 4.8**, **Figure 4.10**, **Figure 4.12**, **Figure 4.14**, **Figure 4.16**, **Figure 4.18**, and **Figure 4.20** respectively.

4.5 Conclusions

Real time traffic delay estimation with V2X communications is difficult with low PR. In this chapter, a novel solution is proposed using fuzzy based system for approaching and leaving time estimating for an isolated intersection. These measurements are considered as an effective indicator for traffic delay estimation.

The PR is the main factor that effects the performance of the estimation, but estimation interval should be taken into consideration as well. As the performance of traffic delay estimation in means of sufficient period should follow the evaluations of the overall TSC system, investigations on this topic have been performed. COLOMBO framework has been developed (i.e. instead of swarm algorithm, fuzzy logic has been used) to estimate the traffic under realistic delay.

The results suggested that the approaching and leaving time can be used as good indicators for traffic delay estimation of an isolated intersection even for low PR.

One obvious issue for intervals where no equipped vehicle was sensed is the lack of data. This depends on the aggregation interval's duration and the PR. The trade-offs between them should be investigated for future work.

As a result, our approach can provide the TSC with a fairly good indicators based on the estimation of the approaching and leaving time for each incoming edge as well as the intersection as a whole. These results were confirmed using simulations for an isolated intersection even under low PR (i.e. till 1%). Further investigations should be performed that use our approach to estimate the traffic under more realistic traffic.

CHAPTER 5

FUZZY TRAFFIC CONTROL WITH V2X COMMUNICATIONS

Traffic signal control can be self-organizing and adaptable to traffic condition changes by using VANET environment and an intelligent control algorithm. VANET environment provides extensive information of approaching vehicles for an intersection. Vehicles frequently transmit specific messages (e.g. BSM in United States (US), or CAM in European countries (EU)), containing all required relevant information (e.g. speed, position ...etc.). A traditional method to acquire data from VANETs is to receive messages with a central infrastructure RSU. After receiving the message, RSU extract the most important information that is suitable for TSC. This extraction depends on the message's information and what does it represent (i.e. traffic monitoring). Then, controlling an intersection through TSC required an algorithm that can deal with the RSU's information sufficiently.

In US and EU, several researches have been conducted for TSC of an intersection using vehicular communication protocols. Generally speaking, based on PR, two different approach for TSC can be observed. Either Full Penetration Rate (FPR) or Partial Penetration Rate (PPR).

FPR-based approach is built upon an assumption that all vehicles communicate with each other for compressing the description about the traffic conditions and give a suitable decision for TSC. With this approach, traffic condition indicators are able to determine without involving an RSU. Hence, it may be applied for virtual TSC (or Virtual Traffic Light VTL) of an intersection without real traffic signals infrastructure. In this context, VTL project [58] explored the benefits of vehicle-to-vehicle (V2V) communication for VTL using elected leader. The responsibility of creating the VTL and broadcasting the traffic signal messages is assigned. The main drawback for this approach is the assumption of full PR. Although VTL project contributors in [59] show that VTLs can offer benefits in both throughput and delay with partial deployment scenarios, they are based on the assumption that an external representation is required for the VTL. In this scheme, visibility and legislation aspects were not addressed. Hence, a deployment issue is grown in deciding what is the most appropriate representation for such assumption. Another attempt done in [60] to overcome the issue of PPR using game theory approach. Its results show that by using a dynamic strategy with the penetration ratio, one can provide strong incentives to drivers to adopt VTL technology. A decentralized algorithm for VTL applications, based on IEEE 802.11p V2V communications had also been proposed in [61]. The algorithm has been designed for those intersections where the deployment of traffic lights is not cost-effective. The algorithm effectiveness was validated based on open source software and low-cost hardware with wireless communication interface. In other study [62], the applicability of an in-vehicle traffic light system to assist drivers in passing through un-signalized intersections was tested. Specifically, a driving simulator to analyses the influences of the proposed system on driving operations and eye-gaze behaviors was used.

On the contrary, PPR-based approach is built upon an assumption that some vehicles are capable of communicate with each other and the available traffic signals infrastructure involve RSU. With PPR approach, to overcome the partial knowledge of traffic conditions, TSC can become more beneficial with an intelligent algorithm. In that time, the idea of self-organizing algorithm is merged in 2005 by Gershenson [19]. It proves that using simple rules, traffic signals are able to be self-organizing and adaptable to traffic condition changes. This is considered without direct communication among intersections. In the same paper, a simple self-organizing traffic signals algorithm proposed. The mean idea of which is to give preference to vehicles that have been waiting longer and to larger groups of vehicles (called platoons). These groups of vehicles (i.e. platoons) affect the behavior of traffic signals, made them to turn green based on demand.

Recently, the idea of exploiting VANET technology merged into the field of self-organizing TSC. For instance, in [63], a decentralized adaptive TSC algorithm using V2I communication was developed. Their algorithm was phase based and the objective was to minimize total queue length. Hence, TSC problem considered as an optimization problem and was solved by dynamic programming. In [64], a platoon based TSC algorithm under VANET environment was proposed. In this algorithm, two stages were served; standing queue of vehicles and vehicles approaching the intersection. The idea is that the travel time of vehicles can be obtained based on their location and speed. Results showed that the proposed algorithm was efficient even at 25% PR. In [65], a TSC framework for multi-modal under V2I communication was proposed. It was a platoon based algorithm solved for an optimal signal plan based on controller status, priority requests, platoon data and current traffic condition. In [66], another TSC algorithm under VANET environment was also presented. In this algorithm, a Kalman filter to estimate cumulative travel time was applied under low PR. Next phase was set to the highest combined travel time and at least 30% PR was required to achieve good results. In [67], a predictive microscopic simulation algorithm for TSC was proposed. The algorithm predicts the future traffic conditions based on data collected from vehicles within suitable strategy. A rolling horizon strategy was chosen to optimize either delay only or a combination of delay, stops and deceleration. Several PRs were considered in this algorithm based on estimating the states of unequipped vehicles from equipped vehicle states.

Previous researches [61-67] showed that the PR was a critical parameter in determining the efficiency of the TSC algorithms. From the literature review, it is clear that there are inefficiencies and trade-offs under different PR (e.g. efficient TSC under VANET environment with traffic conditions estimation) that need to be focus on. In this context, the EU FP7 COLOMBO (2012–2015) project [24] exploits V2X communications in the context of TSC. V2X communications were used to determine traffic surveillance information about local queue length (in proximity of an intersection). Such traffic indicators can be used dynamically to adapt TSC algorithms and timings. The contributors of this project focused on developing TSC algorithms using swarm algorithm under low PR. Since swarm algorithm, like any optimization approach, is time consuming, a TSC based on such algorithm requires more investigation to fill the gap between TSC algorithms and optimization algorithms.

In this chapter, in order to fill this gap, a simple fuzzy logic had been investigated in COLOMBO framework instead of swarm algorithm. This is the main contribution of this chapter and its done based on a dynamic delay model (i.e. more detailed information) that V2X communications can offer under different PR with fuzzy logic estimation system.

5.1 COLOMBO's TSC

This project is dedicated towards making self-organizing algorithms an effective principles for practical TSC [24]. In order to do that, many policies were considered under suitable selection algorithm. The common underlying principle of these policies is that each TSC collets information only on the traffic flow of its incoming and outgoing vehicles and operates independently of all other TSCs. Ideally, a bird's eye view of the traffic flow on the incoming and outgoing edges with full (i.e. position, speed and route) information about each vehicle should be available. With this information, TSC knows exactly the traffic condition of each incoming and outgoing edge. Both traditional and emerged VANET systems cannot deliver and process this big data (even with FPR-based approach). This means that TSC algorithms rely on estimates of traffic conditions to divide the approaching flow between signal groups. With PPR-based approach an assumption can be stated here. Information as absolute numbers measure (e.g. number of vehicles and sum of stops) hardly determined, while averaging measures (e.g. average speed) retrieved with a sufficient quality.

In this context, COLOMBO project is developed as an open source framework and confirms the previous assumption using simulations. COLOMBO framework uses swarm intelligence algorithm to estimate an abstract of traffic conditions (called pheromone) based on average speed and its derivative. With these pheromones, different TSC methods (i.e. policies such as phase, platoon, marching and congestion policy) were developed. Each policy performs under specific traffic condition and not for others. The following subsection give a brief summary for such policies.

5.1.1 Summary of COLOMBO's Policies

A set of TSC policies were defined and presented in COLOMBO project. For example, phase policy used to end current phase once another one has reached traffic threshold. This ending is done under satisfaction of minimum duration of the current stage in order not make the TSC switch a lot. It is designed to handle low-medium traffic conditions. This policy does not end the current stage if there are no vehicles opposing allowed traffic flow currently performing.

Another policy lets group of vehicles in the current green edges pass the intersection before ending green light. This policy is called platoon policy and designed to handle medium-high traffic conditions. Platoon policy does not switch phase unless green light is requested from another one. Even if there are approaching vehicles and in order to preempt the current phase execution, maximum phase duration is taken into account. In case of intense traffic conditions, each phase is executed for maximum allowed time. Hence, the performance of the system is greatly affected by the definition of the maximum allowed time for a phase.

When traffic looks too intense from all incoming edges to take any online decision, another policy is qualified. This policy is called marching policy and designed to handle very low/high traffic conditions. The approach implemented in COLOMBO project to solve this policy with simple rules is to fall back to a static duration for each phase. Finally, policy is used when there may be vehicles stopping in front of the intersection and the outgoing edges are congested. In this case, all input edges are inhibited to avoid what is called gridlocks. The system ends the current phase with minimum duration time. No other phase is activated when the red-light stage is reached until the congestion has been solved. This policy is called congestion policy and designed to handle congested traffic conditions. To this point, the goal of the policy selection procedure is to decide which policy should be executed in the TSC under current traffic condition.

5.1.2 Selection Procedure of COLOMBO's Policies

In order to select a suitable policy, a large number of parameters need to be set in COLOMBO framework to achieve optimum performance. Thus, a parameter tuning optimization approach is performed in this project. This process is time consuming and requires a lot of traffic data to be aggregated in static or dynamic approach to overcome the whole traffic conditions. One drawback of this approach comes from the local traffic conditions sample aggregation areas. The challenge in static approaches is to determine the zone length that is neither too large nor too small. On the contrary, the challenge in dynamic approaches, although these approaches adjust to true traffic conditions, is to build and maintain dynamic groups and group leaders.

On the other hand, in COLOMBO framework, a number of vehicles that are approaching an intersection following common direction are grouped. In this case, the multitude of surrounding vehicles can be abstracted to RSU through group leader. Hence, it is chosen so that it can reach all other peers by simple single-hop communication (i.e. central position) and coordinate all group members. This grouping and group leader selection procedures under dynamic VANET environment made the grouping procedure results, with different PRs and traffic conditions, fuzzy and uncertain. Instead of using swarm algorithm to abstract traffic conditions, fuzzy logic had been used in this thesis to estimate accumulative delay time with respect to the total travel time.

Such indicators can be directly used for estimating the traffic conditions. This estimation, based on average speed and its derivative, is investigated with different PR for intelligent TSC design.

5.2 Proposed TSC

In this thesis, we propose to follow PPR-based approach for TSC design with different strategy. This is done by estimating vehicles delay time with respect to vehicles sensed time as a direct indicator for logical TSC design. This strategy uses V2X protocol under COLOMBO framework for average speed determination per moment, to estimate the delay time for each edge per moment. This delay time estimation done locally by the RSU of an intersection per moment. In order to design TSC, the estimated delay time should be accumulated for specific period. With this processing, two indicators can be determined, accumulated delay time and accumulated vehicle sensed time. The division of which, give a percentage delay indicator for the vehicles per edge. With this indicator a lone, i.e. delay percent, the traffic conditions can be estimated but not evaluated. In order to do that, i.e. traffic conditions evaluation, evaluation period time is required. The logical relation between traffic conditions estimation and evaluation can be used directly to make a TSC adaptive. Two logical approaches can express this relation, simple and fuzzy logic. The details of these logical approaches with traffic delay estimation is going to be explained in the following subsections.

5.2.1 Traffic Delay Estimation

In PPR-based approach, PR is neither known nor can be estimated for near future. Instead of that, average speed of vehicles per edge and its derivative can be used to estimate the delay time for each incoming and outgoing edge of an intersection, as well as for the whole intersection, per moment. Estimating the delay time is not just for traffic condition estimation but also gives an indicator for evaluation period for the intersection as a whole. In general, delay time can be defined as the sum of acceleration, deceleration and stopped delay time. Where acceleration time can be defined as the time that determined with low speed and acceleration for vehicle (or group of vehicles) entered to the edge under the RSU coverage area. While, deceleration time can be defined as the time that determined with high speed and deceleration for vehicle (or group of vehicles) entered to the edge under the RSU coverage area. And finally, stopped delay time can be defined as the time that determined with zero speed and zero derivative for vehicle (or group of vehicles) entered to the edge under the RSU coverage area. This will be done in the RSU instantaneously per moment so that the delay time per moment can be determined. Accumulative delay time can be determined as a good indicator for evaluating TSC continually.

For each moment, the information of the group is sent to the RSU of the intersection. Then, RSU uses these information for estimating the delay time and accumulated it for each edge separately. By averaging the accumulative delay time for all the edges of the intersection continuously, delay time for the whole intersection can be estimated. As the vehicle travels along an intersection encounters different degrees of delay, so the value of the average accumulative delay time varies accordingly. Intuitively, the higher value of the average accumulative delay time indicates the worse degree of traffic condition. Each RSU implementing our solution estimates accumulative delay time based on its average speed of vehicles and their derivative. The average speed of vehicles per edge can be obtained from V2X protocol described in pervious chapter. Therefore, in each edge accumulative delay time in terms of its average speed of vehicles and their derivative can be estimated through fuzzy delay estimation system.

For fuzzy system, input variables are first classified into categories or fuzzy sets. The possible fuzzy sets for average speed are L for low, M for medium and H for high. For average speed derivative, the defined fuzzy sets are N for negative, Z for zero and P for positive. In addition, output fuzzy sets corresponding to estimated average delay time have also been defined for one second time span, with L for low, M for medium and H for high. One particularity of fuzzy logic is that a fuzzy set can contain elements with partial degree of membership and consequently an input value can belong to several fuzzy sets at the same time. For example, an average speed value of 7.5 m/s (with maximum edge speed equal to 13.889 m/s) could be member with a different degree of membership, i.e. of both medium and high average speed fuzzy sets. In order to determine the degree of membership of the input values to each of the fuzzy sets, simple membership functions are employed. Here, the membership functions used, which have been implemented based on simple rating system, are illustrated in **Figure 5.1**.

Fuzzy rules have been established as shown in **Table 5-1** that relate input (average speed and its derivative) and output fuzzy sets (components of delay time per second).

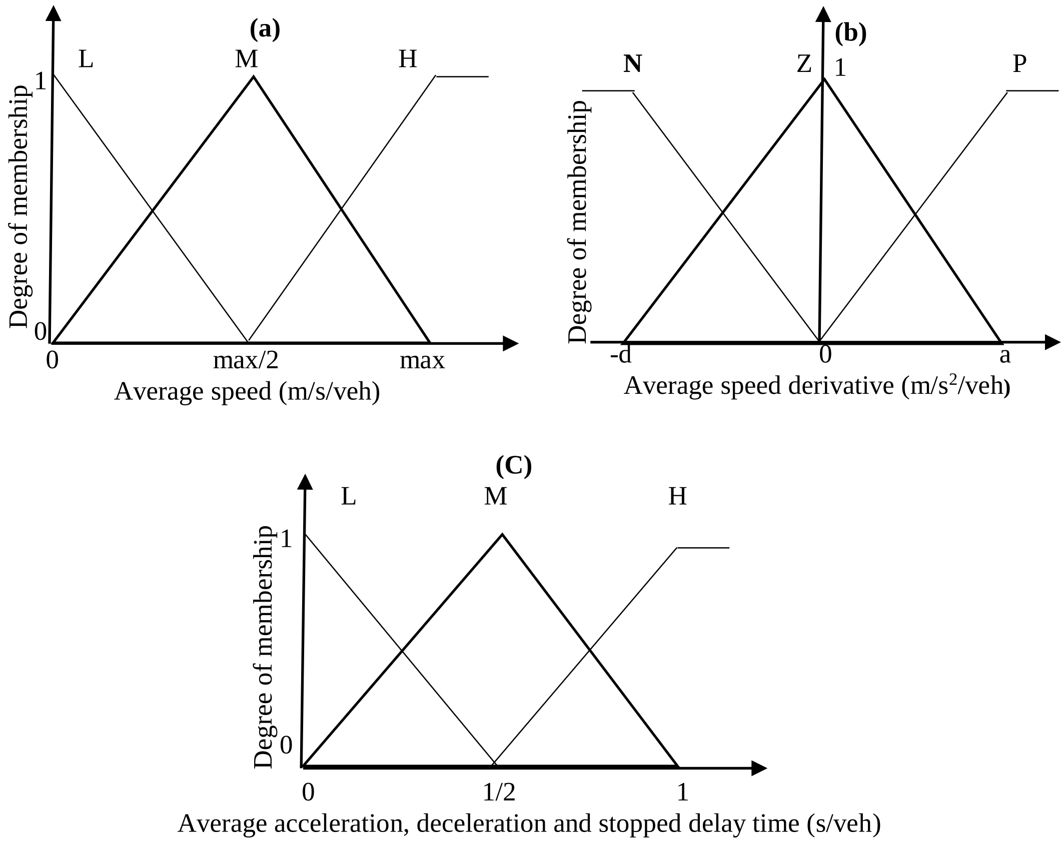

Figure 5.1 Fuzzy delay estimation system. (a) Average speed sets, (b) Average speed derivative sets, and (c) Output sets.

Table 5-1 Fuzzy rules relating inputs (average speed and its derivative) with outputs (average acceleration, deceleration and stopped delay time).

Average Acceleration, Deceleration and Stopped Delay Time		**Average Speed Derivative**		
		N	**Z**	**P**
Average Speed	**L**	L,H,L	L,L,H	H,L,L
	M	L,M,L	L,L,M	M,L,L
	H	L,L,L	L,L,L	L,L,L

The summation of the estimated acceleration, deceleration and stopped delay time from fuzzy system respectively, $Delay(k)$ can be given by the following equation:

$$Delay(k) = Acceleration(k) + Deceleration(k) + Stopped(k) \quad (5.1)$$

As described previously, every RSU in an intersection continuously monitors the individual estimated delay time for each edge per moment (e.g. per second) through fuzzy system. A key aspect in our traffic condition estimation is to identify the accumulative delay time close to the RSU of the intersection that will continue for specific time with suitable adaptation procedure. Adaptation procedure given here is open for further optimization. An edge is considered to have increase value of accumulative delay time if its previous estimation reported some stayed vehicle from previous cycle and such cycle is not operated well to clear all the vehicles. Every edge has a counter that represent accumulative delay time updated to the current moment according to the following equation:

$$AD_e(k) = \begin{cases} AD_e(k-1) + Delay_e(k) & if\ car_e(k) > 0\ and\ k \neq 0 \\ 0 & otherwise \end{cases} \tag{5.2}$$

where $AD_e(k)$ and $AD_e(k-1)$ are the new and previous value of the accumulative delay time for edge e at time (k) and $(k-1)$ respectively. $Delay_e(k)$ is the delay time estimated using the fuzzy system for edge e. Finally, $car_e(k)$ is the number of vehicles in edge e at time (k).

In order to determine the intersection delay time for all the incoming and all the outgoing edges separately, the individual $AD_e(k)$ for each direction are averaged as given in the following equations:

$$AD_e(k) = \begin{cases} AD_{in}(k) & for\ incoming\ edges \\ AD_{out}(k) & for\ outgiong\ edges \end{cases}$$

$$= \begin{cases} 1/n \sum_{e=1}^{n} AD_e(k) & for\ n\ incoming\ edges \\ 1/m \sum_{e=1}^{m} AD_e(k) & for\ m\ outgiong\ edges \end{cases} \tag{5.3}$$

where n and m is number of incoming and outgoing edges with sensed vehicles respectively.

The above equations determined for each incoming and outgoing edge of an intersection. Hence, intersection delay time $AD(k)$ as a whole can be determined by the following equation:

$$AD(k) = AD_{in}(k) + AD_{out}(k) \tag{5.4}$$

Now, TSC algorithm based on traffic delay estimation can be design with acceptable and logical evaluation approach. The details of which is given in the following subsections.

5.2.2 Simple Logic TSC

As seen in COLOMBO's TSC section, different TSC methods (i.e. policies) are developed and each one performs under specific traffic condition. Choosing suitable policy should be done in logical way rather than in an optimization way as done in COLOMBO's solution. With simple logic approach, TSC based on traffic delay time estimation is driven here to make TSC work with different policies through policy selection procedure. Traffic delay estimation based on threshold values can be extracted directly from LOS criteria.

At signalized intersections, the LOS is a simple grading function (from A to F) of the average delay time [68] as shown in **Table 5-2**. It may be calculated per intersection, per edge, or per lane group.

Table 5-2 LOS criteria.

LOS	Control Delay (sec/veh)
A	≤ 10
B	10–20
C	20–35
D	35–55
E	55–80
F	> 80

One issue should be mentioned here, the traffic delay estimation is done instantaneously based on delay time estimation for each edge as well as for the whole intersection. The policy selection procedure of the TSC for the whole intersection should be insensitive to very short peaks delay time estimation, e.g. a singular platoon in one edge. It should react to more persistent traffic conditions changes when traffic from a single direction will continue for specific period (e.g. fifteen to twenty minutes) is expected.

In order to do that, evaluation time interval $Ev(k)$ should be considered by the following equation:

$$Ev(k) = \begin{cases} k - LastPolicyUpdate & if\ Policy\ Changed \\ 0 & otherwise \end{cases} \tag{5.5}$$

where k is the current time in second and $LastPolicyUpdate$ is the last time in which policy had been changed.

Another important issue should be taken into consideration with low PR, several different policies can be implemented. The main difference between them is the release method that decides the actual stage duration for green light. This method returning Boolean decision result (i.e. true) when the current stage should be finished and the sequence stage should be activated based on threshold. This threshold is defined in COLOMBO project for each policy released method by multiplying the number of vehicles for each incoming lane that is currently red by the time they have been waiting (called cars times second).

With low PR, number of vehicles is effected, new proposed threshold value can be used, known as accumulated delay percent ADP. It is defined as the ratio of accumulated delay time to the total vehicles sensed period. Total vehicles sensed time can be calculated by the following equation:

$$Time_e(k) = \begin{cases} Time_e(k-1) + 1 & if\ car_e(k) > 0\ and\ k \neq 0 \\ 0 & otherwise \end{cases} \tag{5.6}$$

From which, $ADP_e(k)\%$ can be determined using the following equation:

$$ADP_e(k)\% = \begin{cases} AD_e(k)/Time_e(k) & if\ car_e(k) > 0\ and\ k \neq 0 \\ 0 & otherwise \end{cases} \tag{5.7}$$

Only when this value, i.e. $ADP_e(k)\%$ exceeds a predefined threshold value (e.g. 10%), RSU activate suitable control action (i.e. termination of the current green stage or not) as given by the following equation:

$$Terminate = \begin{cases} Yes & if \max\{ADP_e(k)\}_{e=1}^{n} > 10\% \\ No & otherwise \end{cases} \quad (5.8)$$

where *Terminate* is the activation Boolean result for termination of the current green stage to start the subsequent stage. $\max\{ADP_e(k)\}_{e=1}^{n}$ is the maximum $ADP_e(k)$ for n incoming edges of an intersection. After finishing all red stage, policy selection procedure should be activated based on delay time estimated for the intersection as a whole.

Each policy differs from others by the estimated traffic conditions to adjust the green time. Conditions based on predefined threshold value (e.g. average delay time and/or evaluation time interval) may be corresponds to LOS to be monitored for each edge or for the intersection as a whole.

The policy selection procedure is based on comparisons which are occurred when the group leader updates the fused data and sends it to the corresponding RSU. These comparisons are employed based on existing of vehicles and accumulative delay time estimated by different edges. In addition, the total delay time of last updating is exchanged to quantify the level of service for the intersection as a whole. With predefined threshold value, TSC policies can be changed in an adaptive way. Finally, RSU situated in the center of an intersection will get a global and complete vision of the level of delay time for the intersection as a whole as well as for each edge in the intersection.

Based on COLOMBO's solution [69], the following conclusions can be summarized:

- Platoon and phase policies are suitable for medium and high traffic conditions.
- Platoon and swarm are suitable for very high traffic conditions.
- Marching policy is selected when the incoming edges are congested and there is no other information available about vehicles in the outgoing edges.
- Congestion policy is selected when the outgoing edges are congested and there are vehicles waiting in the incoming edges.

If the evaluation process continues for a certain evaluation period of time (typically 15 min) with acceptable $ADP_e(k)$ (e.g. <10% with A LOS required), no change for intersection policy will required, otherwise policy selection procedure is activated to select new policy. With an acceptable threshold value for $AD_e(k)$ and $Ev(k)$ (e.g. 35 s/veh and 900 s respectively), the following simple selection rules can be driven as shown in **Table 5-3**.

Table 5-3 Simple logic rules for policy selection of TSC.

If	$\boldsymbol{Ev(k)}$	And	$\boldsymbol{ADP(k)}$	then	Policy
1	< 900	=	-	=	NoChange
2	≥ 900	=	≤ 10	=	Marching
3	$=$	=	$10 - 20$	=	Marching
4	$=$	=	$20 - 35$	=	Marching
5	$=$	=	$35 - 55$	=	Phasing
6	$=$	=	$55 - 80$	=	Platoon
7	=	=	> 80	=	Congestion

Since it is not preferred to work with specific threshold values, e.g. $AD_e(k)$ with 35 s/veh is suited under marching policy while $AD_e(k)$ with 35.1 s/veh is suited under phase policy, as well as for evaluation period, the above description for policy selection procedure can be done using fuzzy logic as described in the following subsection.

5.2.3 Fuzzy Logic TSC

Fuzzy logic had been used for TSC in many studies (e.g. [70] and [71]). But none of them used for selecting between different policies based on delay time measurements. Selecting policy based on simple logic with threshold values is not preferred with estimated measurements. Because of that, fuzzy proposed logic is considered here. Beside the major measurement of delay time, evaluation time should be take into consideration. Evaluation time is the time required to evaluate each policy. Most of the standards manuals, e.g. [68], typically used 15–20 min to evaluate TSC. This value may not be reached with low PR, though our fuzzy TSC will considered the evaluation time as the second input beside accumulated delay percent $AD_e(k)\%$. The possible fuzzy sets for the evaluation time are L for low, M for medium and H for high. For the $AD_e(k)\%$, the defined fuzzy sets are also L for low, M for medium and H for high. In addition, output fuzzy sets corresponding to policy output have also been defined as no-change, marching, phase, platoon and congestion. The membership functions used in our TSC, based on simple rating system, are illustrated in **Figure 5.2**.

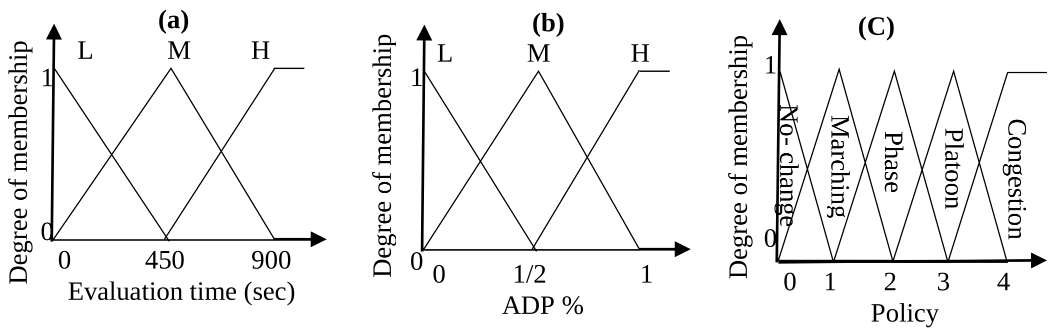

Figure 5.2 Fuzzy system. (a)Evaluation time sets, (b)ADP sets, and (c)Policy sets.

Fuzzy rules that relate input fuzzy sets (accumulated delay percent $ADP(k)\%$ and evaluation time $Ev(k)$ and output fuzzy set (policy) have been established as shown in **Table 5-4**. The fuzzy rules have been designed based on logical input/output relationship. As **Figure 5.2** (c) illustrates, the output of the fuzzy TSC system (i.e. policy selection procedure) is a continuous value within the interval [0 4] indicating the policies options.

Table 5-4 Fuzzy logic rules for policy selection of TSC.

Policy		**Evaluation Time $Ev(k)$ (sec)**		
		L	**M**	**H**
Accumulated delay percent ADP(k)%	**L**	NoChange	NoChange	NoChange
	M	NoChange	Marching	Marching
	H	Phase	Platoon	Congestion

Simulations have been run on Lenovo laptop with Core i5 processor under Linux operating system and results of the current proposed approaches are described in the following section. All figures are drawn in Microsoft Excel 2013.

5.3 Simulation results

For evaluating the proposed TSC approach, the same scenario taken from COLOMBO framework (RiLSA intersection with incoming and outgoing directions, under simulation shown in **Figure 5.3**).

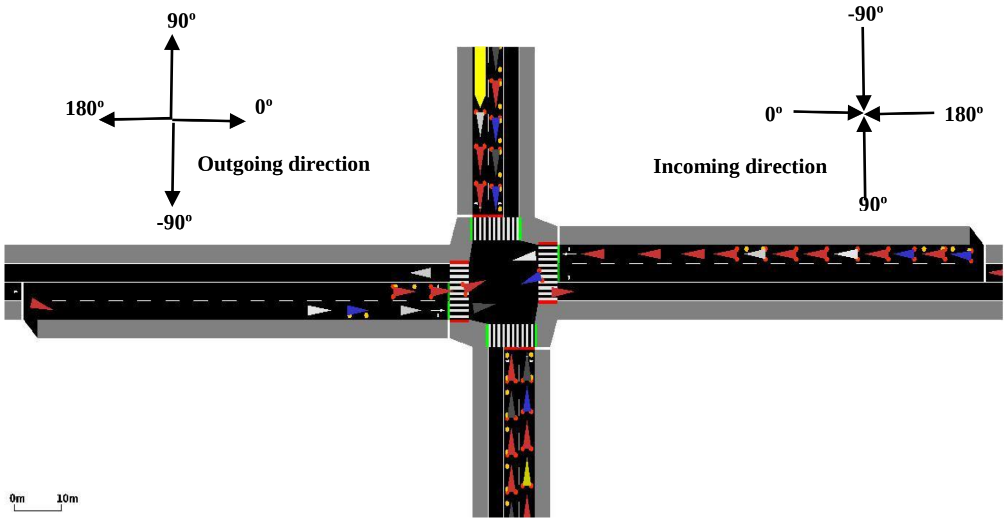

Figure 5.3 RiLSA intersection simluated with incoming and outgoing direction.

At COLOMBO framework, all simulations were performed in the same one hour time span. **Table 5-5** shows simulation parameters used.

Table 5-5 Simulation parameters.

Parameter	Value
Wi-Fi mode	802.11p/ETSI ITS 5G
Transmission mode	6 Mbps (OFDM)
Node radius	170 m
Propagation loss	Logarithmic
Propagation speed	Constant (3×10^8 m/s)
Penetration rate	100, 50, 20, 10, 5, 2, 1%
Simulation time	1 h

Vehicle densities and traffic conditions change dynamically with time according to the green and red timings by the TSC. Thus, the applied traffic conditions are dynamically generated with COLOMBO framework according to wave trend. In spite of that an approximate number of vehicles can be specified (i.e. around 1450 vehicle) as well as various edges with different traffic conditions shown in previous chapter (e.g. **Figure 4.3** and **Figure 4.4**).

First, simulations have been run using one single policy at a time to compare with. Simulated policies involved the following: marching, platoon, phase and congestion. Then, COLOMBO framework with swarm, simple and fuzzy logic algorithms are simulated. All of the above simulations had been run for measuring how the average waiting time varies depending on the PR. Average waiting time depicts the number of steps in which the vehicle speed was below 0.1 m/s measured in simulation steps from SUMO output. **Figure 5.4** show the first step for each policy (i.e. phase, platoon and marching) under different PR.

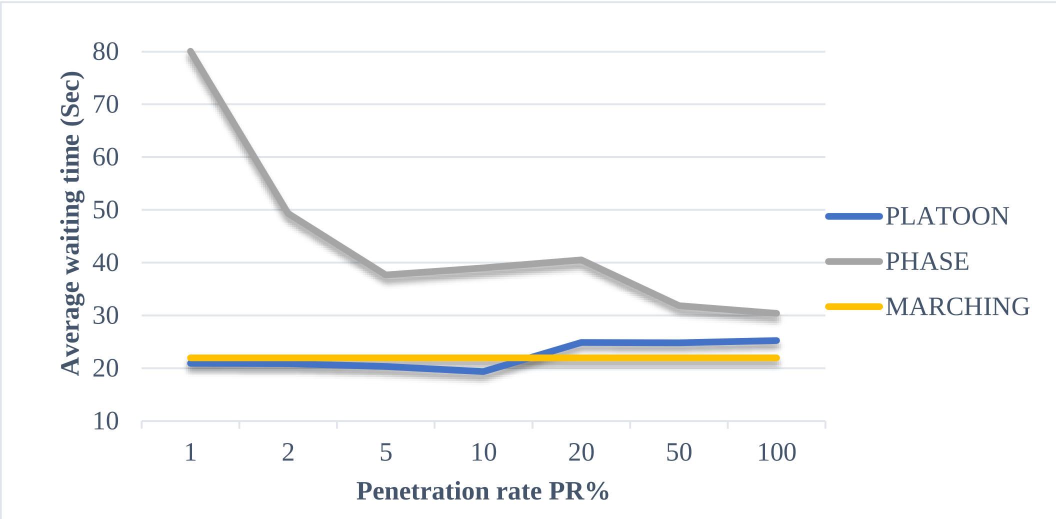

Figure 5.4 Average waiting time versus penetration rates with each policy alone.

Figure 5.5 shows the second step for COLOMBO framework with swarm, simple and fuzzy logic algorithms under different PR. These figures (i.e. **Figure 5.4** and **Figure 5.5**) show policies behavior when simulated each one alone as well as with swarm, simple and fuzzy logic algorithms in COLOMBO framework under different PR. To evaluate our approach and compare it with the over mentioned ones, a simple comparison can be made as shown in the following section.

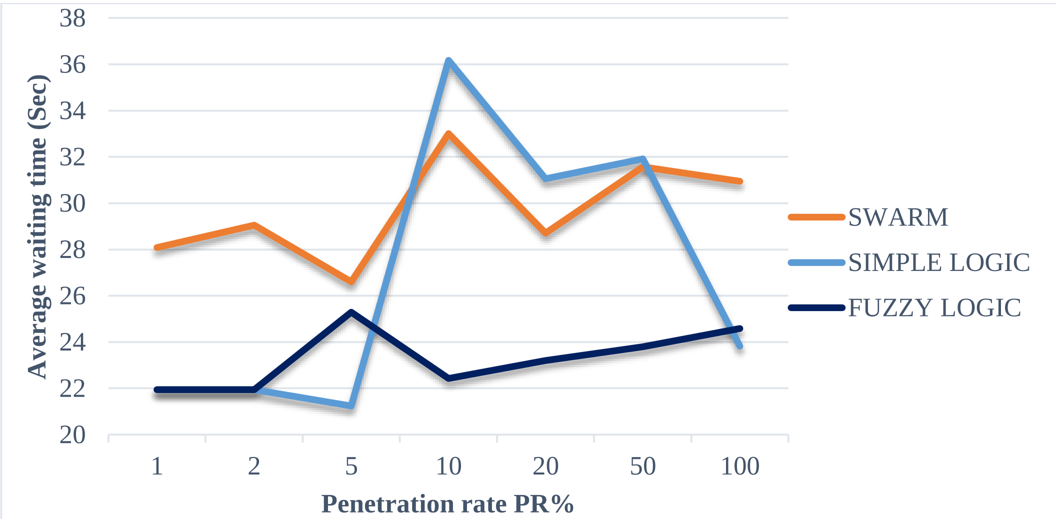

Figure 5.5 Average waiting time versus penetration rates with policy selection procedure algorithms.

5.4 Comparison

In order to evaluate our approach, a simple comparison with COLOMBO approach is done in this section. Since COLOMBO project investigates this comparison with the previous researches [72], the same thing can be done here with our approach.

Figure 5.4 shows that marching policy works well for almost all PR. This policy adopts a static approach (i.e. constant TSC setting) with dynamic phase selection. Since RiLSA intersection is simulated using only two phases (i.e. no need for dynamic phase selection) and using COLOMBO framework (i.e. with optimized parameters), this may reflect some sort of optimized results with this policy.

Phase policy fits well for low PR while it does not for high PR. The green light in this policy maintains since no cars on the other directions are sensed. This behavior is suitable for a dominant traffic flow (i.e. high traffic flow even under low PR) opposed by an irregular one.

Platoon policy gets significant results at low-medium PR (i.e. 2–20%) and minimum values at medium PR (i.e. 50%). As long as nothing blocks the vehicles after passing the central area, this policy creates platoons of vehicles that are free for leaving the intersection. Creating a platoon requires some characteristics, such as platoon size, length and period, to be available to study their behavior. Such characteristics are difficult to study especially under PPR approach for TSC adaptive problem. The above results clearly indicate that PPR approach should be handled under specific policies. Best TSC approach should be able to properly detect each policy situation and **Figure 5.6** shows all of them under different PR. Swarm algorithm (more specifically, policy selection procedure of it) select between the above policies with dynamic mechanism. This mechanism depends on parameters optimization that provide smooth transitions between policies. In spite of that, this transition has a clear oscillation effect with PR > 10%. In other words, swarm algorithm has an optimization solution with unstable transition effect rather than direct policy selection procedure. On the other hand, using simple and direct if-then rules (with fuzzy delay estimation) give the same behavior as for individual policies based on threshold values for policy selection procedure. Both of the above policy selection procedures give comparable results with different PR except at 10%.

Finally, the simulated approaches are combined in **Figure 5.6** to give clear comparison between them. The results of our proposal TSC show the capability to maintain almost the same performance versus different PR of equipped vehicles. These comparable results led us to the following section of conclusions.

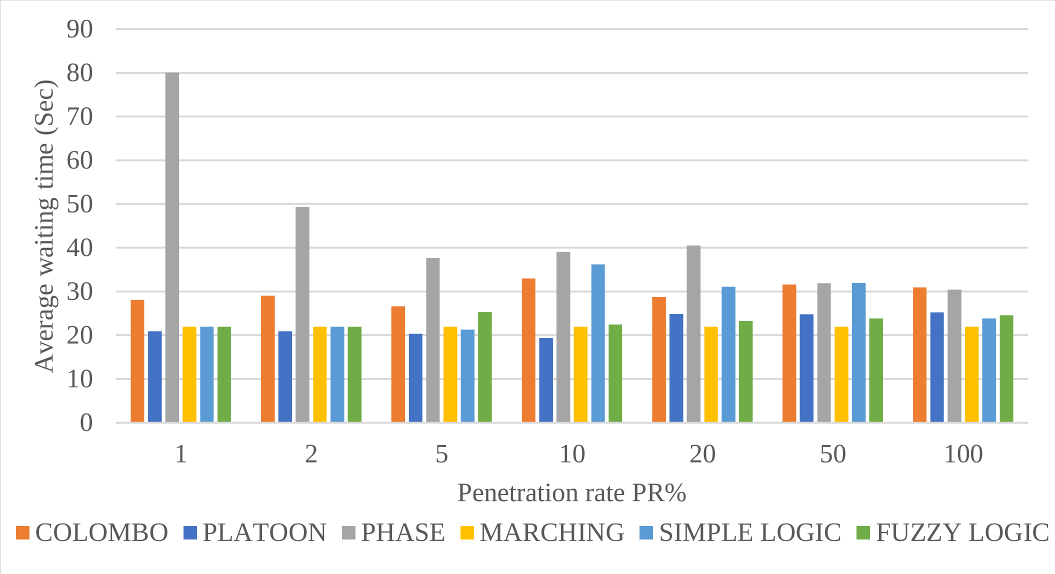

Figure 5.6 Average waiting time versus penetration rates for all simulated approaches.

5.5 Conclusions

From the previous comparable results, some conclusions can be stated. Our TSC solution includes several simplifications compared to COLOMBO's one, taking into consideration PPR based approach. The policy selection procedure in COLOMBO's solution is not relevant for the calculation of TSC setting with low PR because it is based on counting vehicles. This can be a serious issue if not all vehicles are sensible like in FPR based approach. That's why different versions of policy selection procedure had been proposed as an optimization problem in COLOMBO's solutions. On the other hand, our solution has a very positive logical behavior of policy selection procedure. The TSC evaluation strongly depends on the policy selection procedure. Using threshold values (based on LOS criteria), as in our solution for policy selection procedure, makes it open for further optimization. With these threshold values our solution can get almost the same performance even when one vehicle is sensed under the RSU communication range without relying on counting vehicle. This motivates the solution to be used for PPR based approach. At the same time, focusing on developing policy selection procedure with threshold values based on delay time estimation is not enough.

In fact, as shown in **Figure 4.3**, the duration for each vehicle to accomplish their route gives an indicator for another parameter that should be taken into consideration: evaluation period. Most TSCs are evaluated for typically 15 min as stated earlier. But none of the compared approaches for policy selection procedure had been taken this period into consideration. One disadvantage of our proposal is how to overcome longer time periods of TSC operation with no equipped vehicle. This had been considered in COLOMBO project but not in ours. Hence, our approach should be further investigated by taking evaluation period into consideration.

CHAPTER 6

Conclusions and future works

6.1 Conclusions

In this thesis, self-organize TSC algorithms under VANET environment are investigated. This is done under the two major systems for TSC system. They are traffic monitoring and intersection control algorithms.

The traffic monitoring which serves as the fundamental part of the entire system is first explored. Its performances with respect to different PRs is evaluated with different traffic conditions for an intersection. Two approach had been proposed. Traffic monitoring for patterns of vehicles approaching and leaving the intersection though time measurements. Then, developing this approach for traffic delay estimation under low PR. Our simulation results show that the proposed first method is capable to monitor traffic till 20% of PR while the second method reached 1%. With 20% PR, the first traffic monitoring method is able to provide information for traffic surveillance of the simulated intersection under various traffic conditions. This indicates that proposed method could be farther develop with a PR as low as 10%. Even with a PR of 10%, the information provided by this method still require a sophisticated TSC algorithm. The second method, developed one, overcome the previous issue to reach PR of 1%. Even with this PR, it is able to provide accurate traffic delay estimation for the simulated scenario. The main drawback is the lack of data when there is no vehicle with V2X capability passing through the intersection. The performance of TSC depends on measurement of traffic monitoring method but evaluation time interval should be taken into consideration as well.

In TSC algorithm, this thesis develop a new approach based on self-organizing TSC algorithm developed recently in this field. The idea is each self-organizing TSC algorithm is suitable for specific traffic condition and not for others. Here, a traffic conditions with standard LOS criteria are estimated. This is done based on traffic delay estimation using fuzzy logic under low PR. Based on the traffic condition estimated, the suitable self-organizing TSC algorithm can be selected. The evaluation time interval is considered with two approach based on the standard LOS criteria. Simple logic and fuzzy logic. The simulation results indicate that the fuzzy logic TSC algorithm have high performance (i.e. less traffic delay) in comparison with others.

In summary, this thesis provides fundamental support to an alternative TSC system for transportation networks supported solely by VANET environment. The envisioned system is self-organizing, and thus will provide desired redundancy and real time behavior. Also, it is particularly suitable for an intersection with different traffic conditions even under low PR.

6.2 Future works

Several areas for future research are identified that represent logical extensions of the ideas presented in this thesis.

This thesis concentrates on self-organizing TSC algorithms and only investigates the PR as the key factor. However, the analysis extended to include vehicle total time, evaluation period and average delay percent but farther investigation can be done. The monitoring system itself will not be affected by different TSC algorithms. The same evaluation methodology can be adopted without any change as well. It will be interesting to explore the impacts of multi intersection, real traffic conditions, and even different control modes on the system performance.

Furthermore, the relationship between the performance of the traffic monitoring system and TSC algorithm can be regarded by adopted statistical and machine learning methods (e.g. artificial neural network) to establish a more solid model. Moreover, the tradeoff between the performance of the traffic monitoring and mobility measures needs further investigation in the future research.

In addressing the potential of V2X communications between vehicles and infrastructure during the traffic surveillance process, the study only explores vehicles with no more specifications. Generalized solutions for the control system to be complete among vehicular networks is very important. Future study may consider working on generalizing the V2X communications cases and introduce handheld smartphones held by pedestrians to overcome the low PR issue. Another important thing is to enlarge the simulation scenario to cover large scale in order to mimic the real traffic conditions. The other important question with the TSC system is how to determine the LOS performance in global criteria all over the world. All the work in this study may be implemented in scale models as the first step towards implementations in the real world. The LOS definitions must be sufficient in terms of standardization so that the control goal can be evaluated. Furthermore, the TSC policies and the corresponding planning algorithm will be explored for an intersection with conflicted traffic as well in future.

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TOPICS OF INTEREST

- Computer Networks
- Artificial intelligence
- Computer Algorithms