Adaptive Fuzzy Control System for Transit Bus Application

Thesis submitted to the Faculty of Engineering & Technology IIU Islamabad in partial fulfillment of requirements for the Degree of MS Electronic Engineering with Specialization in Control.

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Dedication

To my Parents

Because their Prayers

Are always with me

Acknowledgement

All praises and glory go to Almighty Allah (Subhanahu Wa Ta'ala) Who gave me the courage and patience to carry out this research work. Peace and blessing of Allah be upon His last Prophet Muhammad (Peace be upon him) and all his Sahaba (Razi-Allaho-Anhum) who devoted their lives for the prosperity and spread of Islam.

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May Allah help us in following preaching of Islam according to Quran and Sunnat, (Amin).

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Abstract

Different factors in the traffic control system affect the traffic flow at intersections, especially in urban areas, these factors are; phases sequences, signal timing, vehicle arrival rate and cycle length. So different algorithms are used to adjust these parameters to accommodate vehicles adequately at an intersection.

In this thesis, we present MATLAB Simulink model of Fuzzy adaptive transit bus priority system in a traffic control system. The proposed model is based on discrete event simulation model using queuing theory.

A 4-way single isolated intersection is considered here, the flow of traffic in each approach is consisting of 2 lanes. The flow of stream in each lane is modeled as M/M/1 queue. Vehicles queue length, average waiting time and phase sequence of whole intersection are points of interest in this model.

queue length and average waiting time are utilized by fuzzy logic as inputs to adjust signal timing and phase sequence.

As general vehicles and transit buses share the common intersection, so these transit buses need priority to reduce bus delay time at an intersection, meanwhile less impact on other traffic flow. The controller after passing transit bus at an intersection will revert back traffic flow to a normal traffic situation.

The queue length and average waiting time of general vehicles and transit buses results are tested in MATLAB Simulink environment. The result shows that queue length and waiting time of general vehicles are not affected as the transit buses approach in non-conflict phase, whereas less affected in conflict phases.

Chapter 1

Introduction

1.1 Introduction

Traffic management and controlling is one of the serious problems, especially in urban areas due to increasing in a large number of automobiles and low volume road capacity around the globe. Achieving an efficient and smooth flow of traffic at an intersection is possible by a proper traffic signal control. Several parameters affect traffic signal management, such as vehicle arrival rate, number of lanes and number of junction entries. The main purpose of traffic signal management and controlling is to minimize the average waiting time of vehicles at an intersection. This goal can be achieved by using different kinds of traffic signal controller.

The traffic signal controller is categorized into three types; Pre-timed, actuated and adaptive traffic controller. Pre-timed traffic controller is a conventional method, which is simple and fixed time is given to signal in cycle length. The disadvantage of a pre-timed controller is that it cannot be adapted to varying traffic flow. To remove the shortcoming in pre-timed traffic controller, adaptive traffic controller is preferred. It uses the sensor input data to adjust signal timing according to the real traffic flow.

The traffic signal model is complex and non-linear whereas traditional traffic signal model cannot fit in real the traffic situation. The traditional traffic model uses mathematical partial differential equations which are either micro or macro analytic system. Micro analytic system models focus on parameters such as traffic flow and traffic density, whereas macro analytic system models focus on parameters such as speed and time taken by vehicles to pass through the system. But neither of them can fit with all aspects in the real traffic system. Secondly mathematical partial differential equation is often hard to solve. So cellular automata models are used which eliminates the shortcoming in micro and macro analytic system model. But unfortunately a cellular automata model is applicable for one lane, and does not fit for more than one lane of traffic.

So the preferred model for traffic system is a discrete Event model based on queuing theory which is fit for traffic system in real situations. A queuing theory is a mathematical analysis of queue and waiting time in stochastic systems. Queuing theory consists of three concepts; customers, queue and server. In traffic engineering, server is assumed to be a traffic signal intersection, customer acts as a vehicle and queue acts as vehicle queue length. The flow of vehicles streams in each lane, follow "**M/M/1**" queue model using FIFO discipline. Here the first M shows "Markovian arrival process (Poisson)", second M shows "Markovian service time (exponential)" and 1 shows single server. Traffic arrival and service time are independent random variables with a Poisson distribution.

Further fuzzy logic is used to deal with a non-linear model of a traffic system, as the fuzzy is human knowledge based; like traffic police standing at intersection observe the traffic flow and open the phase which has more queue length and give them maximum time to pass the vehicles across the intersection. The same decision can be performed with fuzzy logic. The value of vehicle queue length and average waiting time are selected as the input variable to a fuzzy controller. The output of fuzzy logic is extension time, which is fed into MATLAB Simulink model. Fuzzy logic is used for complex system which has a complex mathematical model. Fuzzy logic is very beneficial for a mathematical approach to the modeling transportation system.

Bus priority or transit signal priority (TSP) is our main research work here. It is a methodology by which service and delay of mass transit vehicles is improved and reduces traveling delay at traffic signal intersection. Although there are many other types of priority vehicles, but the term TSP is generally associated with buses.

TSP usually provides as "green time" of priority phases to transit vehicles as it approaches at intersection. So it is possible to extend the current non-conflict green phase or shorten the other conflict phase in red signal, in order to open the green phase of transit vehicles earlier.

TSP needs some conditions to open a transit bus phase for crossing the intersection, whereas emergency vehicles do not obey conditions, whatever traffic flow conditions may be, it will always take first priority. On the other hand TSP does not do so.

1.2 Problem Statement

Transit buses are providing services in most of the cities around the globe nowadays. They share the common signal intersection and need less delay time as compared to general vehicles at an intersection. A priority request call is generated by transit bus as it approaches near to an intersection. They need priority to pass through an intersection as compared to general vehicles, and need less waiting time for a green signal. Getting priority immediately in red signal affect the whole intersection traffic flow. Hence pedestrian safety and general vehicle movement are ignored.

1.3 Proposed Solution

The objective of the thesis is to develop a discrete event simulation model of adaptive fuzzy transit bus priority signal using MATLAB Simulink model based on queuing theory. As the transit bus approaches near to an intersection, priority request call is generated by detection device, and sends information to the local traffic controller. Here two separate phases are supposed for transit bus. When a transit bus, arriving at an intersection, is detected in green signal, the controller will only extend the timing of that phase till transit bus passes the intersection. But if transit bus, detected in red signal (conflict phase), the bus will wait till the conflict phase completes the threshold range, which is considered to be green minimum and clearness time of conflict phase here. Function block in MATLAB is suggested for that purpose in our model, which will check the conditions. This strategy will maintain pedestrian and other vehicle safety and less impact on general vehicle flow. In threshold range the pedestrian and other vehicles immediately clear the intersection for transit bus. After passing the transit bus through an intersection, the controller will revert back normal traffic flow.

Six phases are considered here, 4 phases of general traffic flow one for each side and 2 phases for a transit bus priority signal. The proposed solution is described by the flow chart given in figure 1.1.

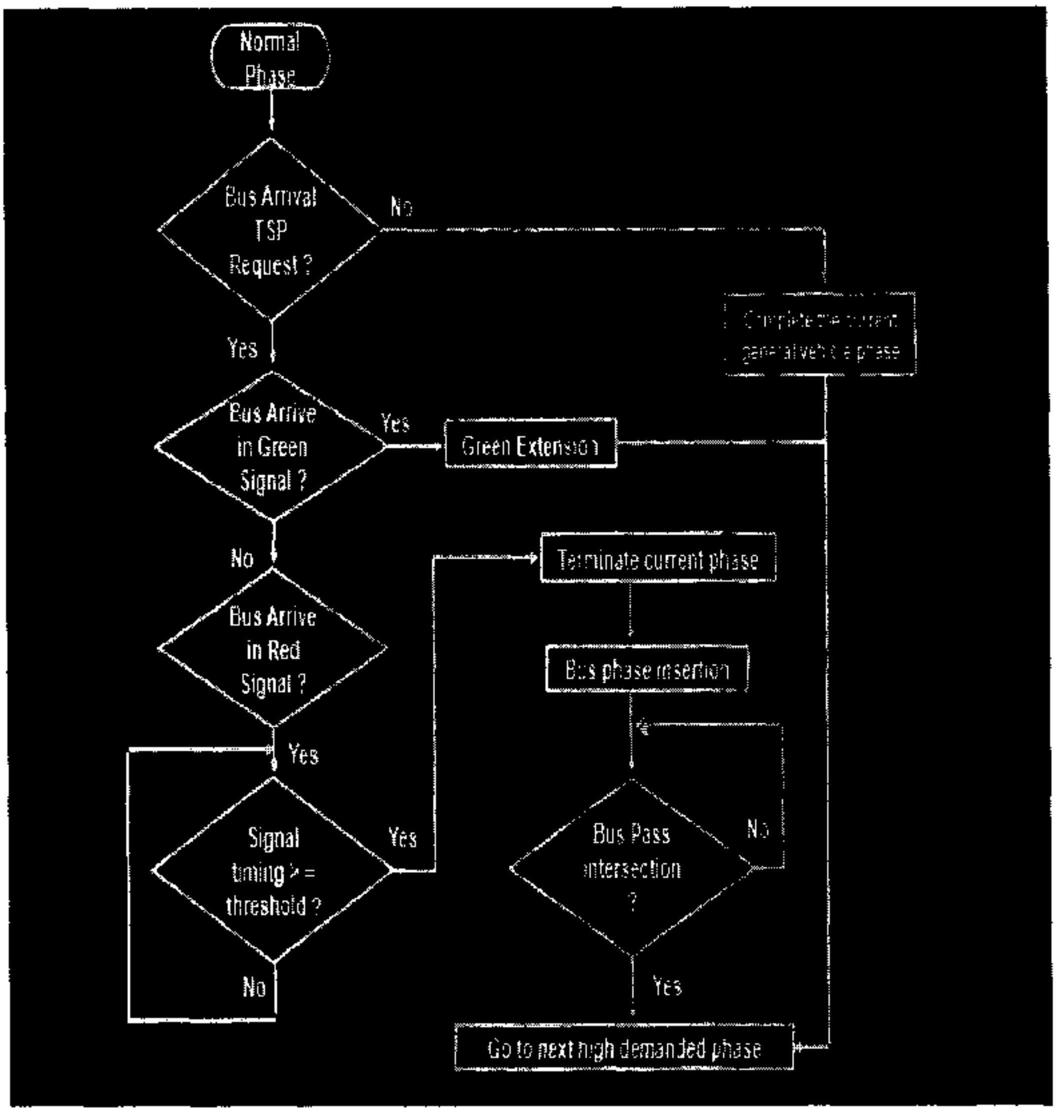

Fig1.1. Flow chart of proposed adaptive transit bus priority signal

1.4 Thesis Layout

The formulation of this document comprises of six chapters. Chapter 1 gives an introduction of the research work, problem statement and proposed solution. In chapter 2, the literature review about pre-timed, adaptive and transit signal priority model of signal control and fuzzy logic is presented in detail. In chapter 3, pre-timed traffic controller model is designed in MATLAB Simulink. Queue length, average waiting time and phase pattern are determined. In chapter 4, designing and development of MATLAB Simulink model for adaptive traffic signal using fuzzy logic is presented. Mamdani type fuzzy logic is applied on each approach of traffic flow. In chapter 5, transit bus priority traffic controller model is also developed in MATLAB Simulink. Two special phases are considered for transit buses. In chapter 6 comparisons and discussion of models are discussed in term of queue length, average waiting time and phase pattern. In chapter 7 conclusions of the present work and future work is described.

Chapter 2

Literature Review

2.1 Overview of traffic signal control methods

Traffic controlling and management, especially in urban areas, is a serious problem due to growing large number of automobiles and low volume road capacity. To achieve a smooth and efficient traffic flow at an intersection, a proper traffic signal control is required. There are some parameters which affect traffic flow, such as an arrival rate, number of lanes, road capacity and number of junction's entries. The main purpose of traffic signal controlling and management is to minimize the average waiting time of vehicles at intersection [1].

The first traffic signal was installed in London in 1868 for railway system, which was electromechanically based and the first green wave signal was developed in 1918. The very beginning of traffic control technology was based on electromechanical devices, latter on semiconductor based controller was introduced, and nowadays microprocessor based controllers are introduced. In later years by detection devices and telecommunication devices, intelligent traffic system develop [2].

Today, most of traffic signal intersections are based on conventional method which is called fixed time controller. Fixed time is given to each phase in a cycle length. Although it is simple and easy, yet it does not cope with real traffic situation, the shortcomings in fixed-time control signal can be eliminated by new methodology such as actuated and adaptive traffic controller.

There are three methods for traffic signal control [3].

(i) Pre-timed or fixed timed mode: In this method, fixed green time is given to each phase in a cycle length. The fixed sequence of phases is repeated regularly, regardless of traffic flow. It does not need to have detection devices for traffic flow.

(ii) Actuated mode: In this method green time of a phase varies with the traffic situation by detecting devices. Cycle length also varies with detecting devices.

(iii) Adaptive mode: Adaptive control is designed to take account of the traffic conditions for the entire intersection. It has the ability to adjust signal timing in response to real-time traffic demands from all approaches. The green time of a phase is adjusted by detecting device. A phase can also be skipped if no vehicle is detected in a cycle length. Thus, it saves more time and gives opportunity to other phases which have more queue length.

2.2 Vehicle Detection devices

In Intelligent system, detectors are used to sense the traffic flow at intersection [4], and controller adjusts signal timing with traffic flow condition. Today, many vehicle detecting devices are used; e.g. inductive vehicle loop detectors, microwave radar sensors, video image processors, passive infrared sensors, ultrasonic sensors, passive acoustic sensors and RFID Devices. Some of them are described below [5].

(i) Inductive vehicle loop detectors: Several turns of wire are made in the slot cut of road pavement, the ends of these wires are connected to feeder cable, which are further connected to a detector sensor unit in a traffic controller. When a vehicle (metal) passes over a loop, it reduces the loop inductance of the coil. The change in loop inductance is sensed by a sensor unit, which activates their output and sends the feedback to a traffic controller to adjust signal timing to the traffic situation [6].

(ii) Microwave RADAR sensors: A device, mounted on traffic pole or some other supporting material, transmits electromagnetic signals from the transmitter and receives echoes by a receiver from objects (i.e., vehicles). Its frequency ranges are in micro. RADAR is an acronym for RAdio Detection And Ranging.

(iii) Video Image Processors; It also detects vehicles flow in single or multiple lanes. The monitored area detection is a line-of-sight view.

2.3 Traffic signal control models

Model for traffic signal is complex, nonlinear and consisted of more parameters. It plays a very important role today and has to play its role in the future work of research and in many traffic applications such as traffic flow prediction, incident detection and traffic control etc. Modeling provides fundamental understanding of traffic dynamics and behavior [7].

2.3.1 Traditional traffic models

Traditional traffic model uses mathematical partial differential equations which are either micro or macro analytic system. Micro analytic system models focus on parameters such as traffic flow and traffic density, whereas macro analytic system models focuses on parameters such as speed and time taken by

vehicles to pass through the system. So neither of them can tackle all aspects in real traffic situation.

Secondly, the mathematical partial differential equation is often difficult to solve, On the other hand, cellular automata models provides the features of both macro and micro analyticity at the same time. But unfortunately a cellular automata model is applicable to one lane, and not to more than one lane of traffic [7].

2.3.2 Discrete Event simulation model

To eliminate shortcomings in the above traditional traffic model, discrete event simulation model, based on queuing theory, is preferred [8].

SimEvent [9] tools in MATLAB are used for modeling and simulating discrete-event systems. The Discrete event simulation model consists of discrete items which are called entities. Each entity carries data known as attributes.

Queuing theory is mathematical analysis of queues and waiting time in stochastic systems. Mostly transportation system follows "M/M/1 queue model" with FIFO discipline using queuing theory. Queue theory has three important parameters, they are; customers, queues, and servers. Here in traffic signal model, server is assumed to be a traffic signal intersection, customer acts as a vehicle and queue acts as a vehicle queue length. The flow of vehicles streams in each lane, follow "**M/M/1**" Queue model using FIFO discipline. Here the first M shows "Markovian arrival process (Poisson)", second M shows "Markovian service time (exponential)" and 1 shows single server. Traffic arrival and service time are independent random variables with a Poisson distribution. In Poisson process inter-arrival times are independent and exponentially distributed [10].

Traffic arrival at an intersection is Poisson process which is an independent random variable to obtain service. The traffic flow arrival rate is denoted by λ, while inter-arrival time is denoted by $1/\lambda$ which is the time duration of two successive arrivals of vehicles.

The Poisson distribution function is given by equation 2.1 [11]

Where

P (n) = probability of exactly n vehicles arriving over time t

n = number of vehicles arriving over time t

λ= average arrival rate

t = duration of time over which vehicles are counted

Vehicles arrival and departure in any lane, follow FIFO (first-in-first-out) discipline in the real traffic model, it means first vehicle in any lane will be served first and second vehicle (after first vehicle) will be served secondly and so on [12].

Thus the advantage of discrete event simulation model is that it can be easily tested and verified by any real traffic signal.

2.4 Fuzzy Logic

Fuzzy logic was first introduced by Lotfi Zadeh in 1965 at the University of California in Barkley, which is a human knowledge based system or rule based system [13].

Fuzzy logic uses the experience and knowledge of human operators in terms of linguistic variables, which is called fuzzy rule. Linguistic variable is the input and output variable of a desired control object. Hence the experienced human operator knows how to adjust the input to get desired output without information of the system's dynamic and interior parameter variations. The implementation of fuzzy rule by human operator does not need a mathematical model for the system. Therefore, a fuzzy logic controller (FLC) is used for complex, uncertain and nonlinear to get the desired action without requiring of mathematical model and parameter variations [14].

A fuzzy logic control system has four basic parts [15] as shown in fig 2.1.

(i) Fuzzification (ii) Fuzzy rule base (iii) Inference engine (iv) De-fuzzification

2.4.1 Fuzzification: Fuzzification block is used to take the crisp input value of an input signal and transforms them into a membership grade of linguistic variable of fuzzy sets. A grade is associated with each linguistic variable in membership function.

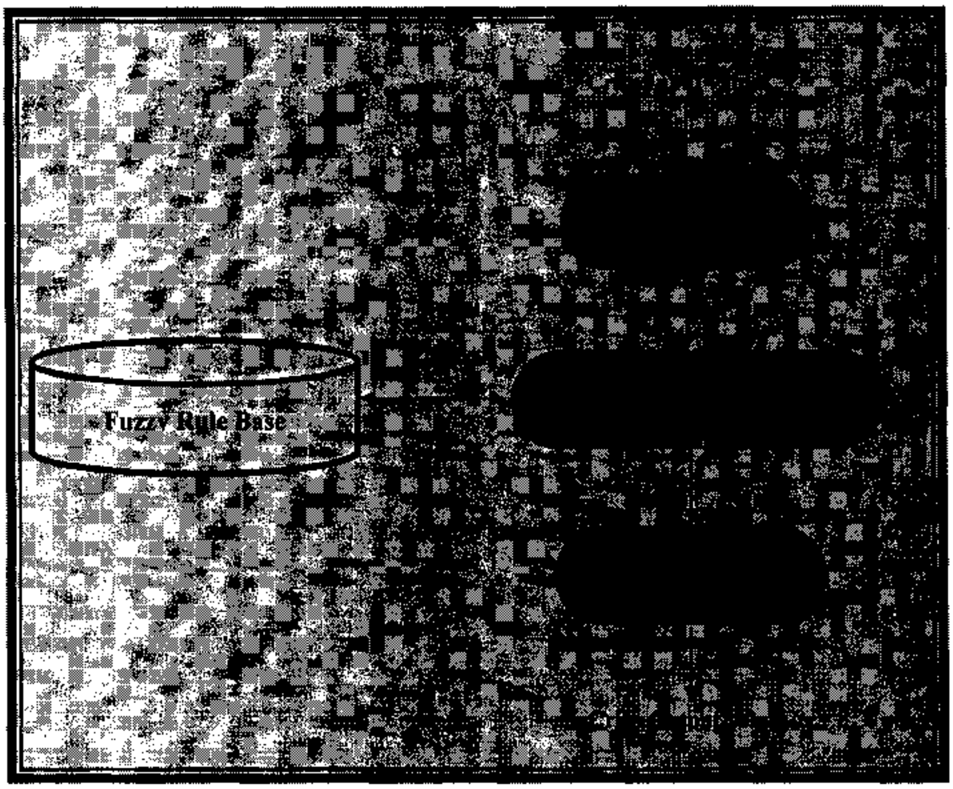

Figure 2.1 Fuzzy logic flow chart

2.4.2 Fuzzy rule base: It makes a relationship between fuzzy input variable and fuzzy output variable. The output fuzzy variable membership grade is that of fuzzification. When an input is received by a user, a rule base is applied. The input part of the block is called the antecedent, whereas the output block is called consequent. e.g. If x is A then y is B, the if part of rule "x is A' is called the antecedent and the then part of the rule "y is B" is called consequent. Here A and B are linguistic variables [16].

2.4.3 Inference Engine: The most important part of the FLC is inference engine, which keeps relationship between Fuzzification input and defuzzification output. The inference engine gives the rule's conclusion, which is obtained from membership grade. So the Inference engine transforms the designer's control rules from linguistic variable in fuzzy set to final numeric output [17].

2.4.4 Defuzzification: The final step of fuzzy logic is defuzzification. Input of deffuzifier has a raw fuzzy output. So this output fuzzy rule base is converted by defuzzification into crisp values.

2.5 Fuzzy system popular models

Fuzzy system has two popular Models; Mamdani model (in 1975) and the Takagi-Sugeno-Kang (TSK) models (in 1985) [17].

2.5.1 Mamdani Model: In 1975, Professor Ebrahim Mamdani at London University built fuzzy system to control boiler and steam engine combination. He applied fuzzy rule by experience of the expert system human operator. In Mamdani models, fuzzy rule base consists of a linguistic variable in both the antecedent and consequent parts. Each rule is a statement of a condition action that may be clearly interpreted by the users.

2.5.2 Takagi-Sugeno-Kang (TSK) or Sugeno model: Sugeno has the same model as that of Mamdani's, the only difference is that of consequent part, i.e. TSK's consequent is represented by a function of input variables.

2.6 Why use fuzzy logic

Here is a list of general observations about fuzzy logic [18].

- Fuzzy logic is easy to understand, does not need mathematical model. It only needs knowledge about the system.
- Fuzzy logic can model non-linear and complex system.
- Fuzzy logic can be built by using the experience of experts.
- Fuzzy systems don't replace conventional control methods. Fuzzy systems augment them and simplify their implementation.
- Fuzzy logic is based on natural language of human communication.
- Relatively simple, fast and adaptive.
- Based on intuition and judgment.

2.7 Application of fuzzy logic: Though fuzzy logic system was first initiated in the USA and was implemented for industrial application in Europe. But Japanese researchers have major contribution in the fuzzy logic implementation, and they have more than 2000 patents in the area of fuzzy logic [19].

Sanyo and Fisher use FL for camcorder and camera that adjust auto-focus system.

Nissan also apply FL on breaking systems, fuel injectors and transmission control.

Matsushista and AEG also apply FL with elegant sensors for washing machines. The sensors sense the kind and color of cloth and the quantity of stones, and fuzzy microprocessor chooses the most suitable combination of temperature, water, detergent amount, wash and spin cycle time. Mostly FL application is increasing for domestic electronic appliances [20].

Huang and Zhang have currently developed a new fuzzy approach for the process plan selection by using fuzzy set theory [21].

Gindy and Ratchev proposed a linguistic approach for the selection of feasible machine tool configuration that was based on a particular set of shape, generating requirements, attained from a work content analysis of group.

Following are some small applications of Fuzzy logic [13].

- Sewer level control
- A pumping station control
- A tank level control
- Control of gas and air supply to a temperature control system
- Crane operational control
- Control of jacks for building construction
- Car movement control on an intelligent superhighway
- Fuzzy GA controller for inverted pendulum control

2.8 Implementation and background of fuzzy logic in traffic signal

In our real life fuzzy logic plays the same role as human being plays, who have been gifted with the power of thinking [22]. For example; a policeman, deployed at an intersection, will control the traffic situation in this way. If traffic is heavier in the west and east direction approaches than in the north and in south directions, the policeman will give longer green time to the west and the east approaches, whereas less time to the north and the south approaches. Such rules, as applied by a policeman, can easily be accommodated by a fuzzy logic controller. So a traffic signal controller, making use of the fuzzy logic, will adjust the signal timing according to fluctuating traffic flow. The objective is to minimize average waiting time at an intersection. The objective of the fuzzy traffic controller is to control strategy by human expert knowledge instead of modeling them [23].

Fuzzy logic was first implemented for the purpose of traffic signal by Pappis and Mamdani [24].

They simulated 2 phased signal isolated intersection, consisting of one way traffic flow without turning traffic. The main focus was on green time extension.

There are many journals and conference papers about using fuzzy logic on traffic system.

Abdel Nasser H. Zaied [25] also developed a fuzzy traffic system for 2 intersections, consisted of two phases; the objective was to control signal timing with the traffic situation. The proposed fuzzy system was tested and compared with pre-timed system. The result shows that the fuzzy traffic signal has better performance in respect to waiting time.

Chih-Hsun Chou [26] also presented a fuzzy logic base traffic signal controller for consecutive junctions, number of lanes, lengths of vehicles, and length of the streets. 9 fuzzy rules were applied. The experimental results under low, medium and high traffic load showed the best performance.

Mohammad Hussain [27] applied fuzzy control system for isolated traffic control intersection, which contained two main functions; phase selector and phase extender. The phase selector selects and changes appropriate phase, whereas phase extender extends and terminates phase time as required. The fuzzy signal control system was compared with pre timed signal, and FSCS system showed better control strategy than pre timed.

Jarkko Niittymäki [16] applied fuzzy logic for multilevel (traffic situation, phase selection and extension inference) traffic signal, which was compared with vehicle actuated (VA) traffic system. Between them the significant difference is that, extension in VA mode controls just a green phase extension, whereas fuzzy logic controller controls the whole intersection; not only current phase extension but also queue length in other red signal groups. Finally the fuzzy logic controller was tested in many intersections, and its result was better than VA mode.

Paothai Vonglao [28] Proposed fuzzy traffic signal timing at an intersection of Thailand. A queue system was used to generate the performance of traffic flow.

Fuzzy logic was used to calculate the maximum green time of a phase in cycle length. The traffic signal timing of fuzzy logic was better than a conventional traffic controller.

Yousaf Saeed [29] applied fuzzy logic for multi-agent based traffic light, consisting of two junctions. The main focus was to overcome the problems like congestion, accidents, speed and traffic irregularity by using wireless sensors. The motive for an agent based approach was, to reduce delay for emergency vehicles by using fuzzy logic in passing two intersections. The result shows that by using fuzzy logic, the emergency vehicles face less traffic flow in passing two junctions, and at the same time collisions are avoided in case of multiple emergency vehicles inter from different directions.

T. Royani, J. Haddadnia [30] applied fuzzy neural network of real traffic signal at an isolated intersection. Here fuzzy neural network was used to control fluctuating traffic flow, such as oversaturated or unusual load conditions. The objective was to minimize the vehicle delay time and improve vehicular throughput. Finally, a fuzzy neural network algorithm was compared with the traffic control method, and proposed fuzzy neural network showed better performance and adaptability than traditional traffic control.

Ehsan Azimirad [31] also presented a classifier system, using fuzzy logic for isolated signalized intersection. The classifier classified and controlled signal timing and phase sequence to ensure smooth traffic flow with queue length. From simulation result, it became clear that queue length in any lane reduced as compared to fixed time control.

B.Madhavan Nair [32] presented a fuzzy logic controller to control signal timing and phase sequence for smooth traffic flow with minimal delay for isolated signalized intersection. The maximum time of a phase was controlled by considering road traffic conditions such as road blocks and road accidents. For that purpose a new fuzzy traffic controller was proposed to control traffic flow under both normal and exceptional traffic conditions. In that case sensors were placed for incoming and outgoing vehicles in lanes and controller took the sensors' input data to get traffic condition for normal and abnormal situations. Results proved that performance of the proposed traffic controller was better for both normal and abnormal traffic conditions.

Ehsan Azimirad [33] presented a novel fuzzy model and a fuzzy logic controller for an isolated signalized intersection. Vehicles queue length and average waiting time were considered state of variables in any lane, traffic abnormality was also considered. Its result made it clear that percentage of improvement of the novel fuzzy traffic signal controller had increased regarding reducing average waiting time in any lane as compared to fixed-time traffic control.

Zhenyang Li [34] also implemented a dynamic left-turn phase control system by using phase four-level fuzzy logic control model to reduce relatively traffic intensities for leading or lagging signal phase at signalized intersection. The performance of this dynamic traffic signal left-turn phase fuzzy logic control system was compared with fixed time control and actuated control using field data in turns. The result showed that the proposed dynamic traffic signal left-turn phase fuzzy logic control system was a superior and efficient tool for reducing intersection traffic delay.

Hamid Mir-Mohammad Sadeghi [35] developed fuzzy intelligent traffic control system to manage the traffic flow intersection utilizing four input parameters. The Fuzzy traffic controller was used for adjusting green time extension of a phase. The result made it obvious that the performance of the fuzzy traffic controller even in complex intersections is better than the performance of the conventional fixed time controller. Fuzzy traffic controller showed a minimum delay of vehicles at intersection.

Funny Bhushan Sharma [36] described an adaptive fuzzy logic signal controller for four-way isolated intersections by using a weather sensor signal. The input sensor data are; Inductive sensor, field equipment, supervision, incident detection/ traffic flow analysis, weather condition detection and intelligent speed limit control. Fuzzy logic base rules were used to determine the congestion parameters and warning information to take appropriate action. The final result made it easy to understand that fuzzy logic delivers more reliable results by using metrological expertise as compared to conventional traffic system, which is susceptible to faulty weather sensor signal.

Wenge Ma [37] also proposed multi-phased fuzzy controller for a single intersection by using Genetic Algorithm to optimize fuzzy membership functions. The proposed control method was suitable for different traffic state in different times and membership functions could be adjusted according to traffic state at different times. Thus proposed method can achieve satisfactory control performance.

Azura Che Soh, [38] presented fuzzy traffic controller for isolated signalized intersection consisting of two lanes. The controller was based on vehicles queue length and waiting time. A vehicle actuated controller (VAC) was also developed to compare with fuzzy traffic controller under different conditions.

The result of both fuzzy traffic controller and vehicle actuated controller was compared with each other, and the former showed to be of better performance.

Budi Yulianto [39] described adaptive traffic signal controller based on fuzzy logic for four-way isolated intersection considering mixed traffic. The video image device was used to capture traffic data. The proposed fuzzy logic traffic signal controller's result was tested in simulation program VISSIM. The simulation result was compared with fixed time, vehicle actuated controller at four- way intersection for different situation, and simulation results shows that proposed FLTSC result was better than fixed and actuated traffic controller in varying traffic flow.

2.9 Literature review of Transit Bus priority signal

Guangwei Zhou [40] presented adaptive transit signal priority (TSP) strategy. He applied parallel genetic algorithm (PGA) to adaptive traffic signal control in TSP presence. PGA can optimize cycle length, green split and phase plan for both transit bus and general vehicles' performance at isolated intersection. VISSIM simulation software was used to check the performance for PGA-based adaptive traffic signal control with transit bus. The simulation result proved that PGA-based controller could produce TSP timing plan which could improve transit vehicles movements, having less impact on general vehicles.

Xianyan Kuang [41] similarly proposed a method to reduce delay of special vehicles and passenger. He grouped priority into absolute priority and relative priority. Special vehicles, arriving in red signal, was called special phase. Multi-layer neural network was used for fuzzy controller. Fixed time control and fuzzy control methods were compared and simulation result showed that proposed method had better performance in decreasing the delay of special vehicles and passengers.

Fergyanto E.Gunawan [42] proposed a computational frame work on the basis of discrete event system for modeling bus rapid transit system. The established model produced well observed phenomena of actual BRT system in limited numerical trials.

Liu, H., W. Lin, and C-W. Tan [41] developed a methodology, consisting of bus arrival time information in AVL based TSP system, to improve its performance. A theoretical model was developed to identify priority call, based on bus arrival time information. The theoretical approaches were verified in simulation analysis and

Result declared that when a bus was away from intersection by 20 to 30 seconds, it produced better result for transit bus and general vehicles.

Chapter 3

Pre-Timed Traffic Control Model

3.1 Description and model of single isolated intersection

In this chapter we propose a pre-timed traffic control model, which is a single four way isolated intersection consisting of two lanes of traffic flow as shown in figure 3.1. Here the pre-timed model is based on discrete Event using queuing theory [8]. The objective is to find out queue length, waiting time and phase sequence.

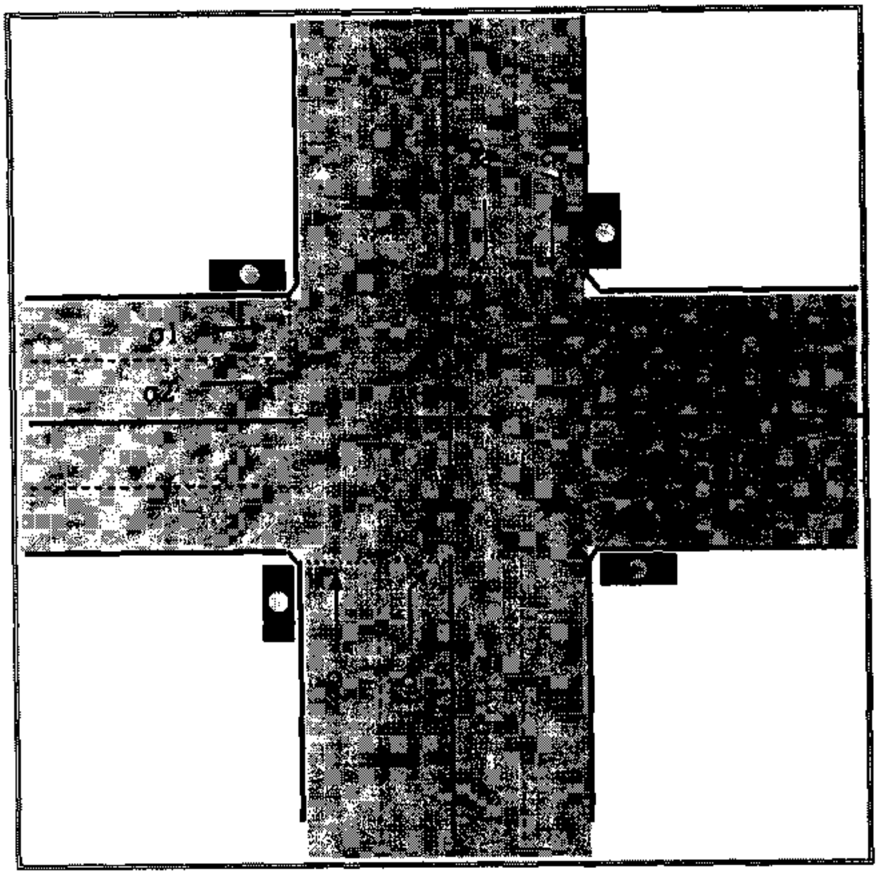

Figure.3.1. Pre-timed single intersection traffic stream model

Here four phases (approaches) are considered in this model, consisting of eight vehicles groups (streams). Vehicles approach from west, south, east and north directions. Each approach is consisting of 2 streams. The vehicles from west approach are consist of two streams σ1, σ2; stream 1 (σ1) showing straight going vehicle flow in a lane, whereas stream 2 (σ2) showing right turning going vehicles in a lane. Similarly the vehicles from south approach are consist of two streams σ3, σ4. The vehicles from east approach are consist of two streams σ5, σ6. Moreover, vehicles from north approach are also consist of two streams σ7, σ8, as shown in figure 3.1. The phase sequence is shown in figure 3.2.

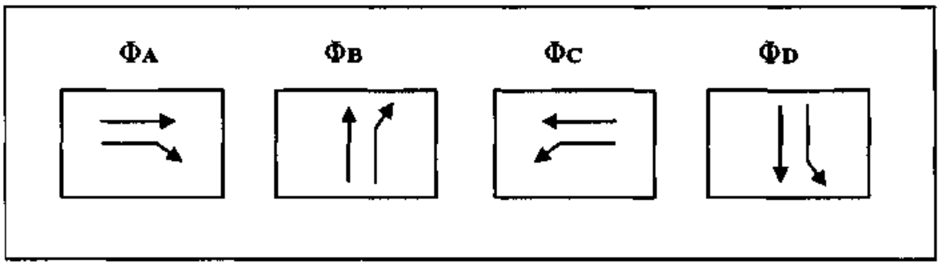

Figure 3.2. Pre-timed phases sequence

The timing of the first phase (west approach) is given 40 seconds, second phase (south approach) is given 25 seconds, third phase (east approach) is given 45 seconds and similarly for fourth phase (north approach) timing is 15 seconds. The timing of all phases is shown in table 3.1.

Table 3.1 Pre-timed signal timing

[illegible]	[illegible]	[illegible]	[illegible]
Φ_A	σ1 , σ2	West	40 seconds
Φ_B	σ3 , σ4	South	25 seconds
Φ_C	σ5 , σ6	East	45 seconds
Φ_D	σ7 , σ8	North	15 seconds

Traffic flow in each lane follows "M/M/1" queue model and FIFO discipline.

Vehicle arrival and service time at intersection follows a Poisson process [8].

Here, in Poisson process, vehicles enter at an intersection with mean arrival rate (vehicles per unit time) is λ, while inter-arrival time between vehicles is $1/\lambda$.Vehicles arriving at intersection follow a Poisson distribution.

3.2 Pre-timed traffic controller MATLAB Simulink/SimEvent block diagram

The single intersection traffic signal pre-timed model is developed in MATLAB, using Simulink and SimEvent block diagram, as shown in figure 3.3.

The discrete Event model is here a modification of Devdatt Lat [43] model, which is for single intersection single lane. But we are focusing on two lanes. Two input switches are used for traffic flow approaching an intersection [44], one switch for straight going vehicles and the other switch for turning going vehicles. Similarly, two output switches are used for outgoing vehicles as shown in figure 3.3.

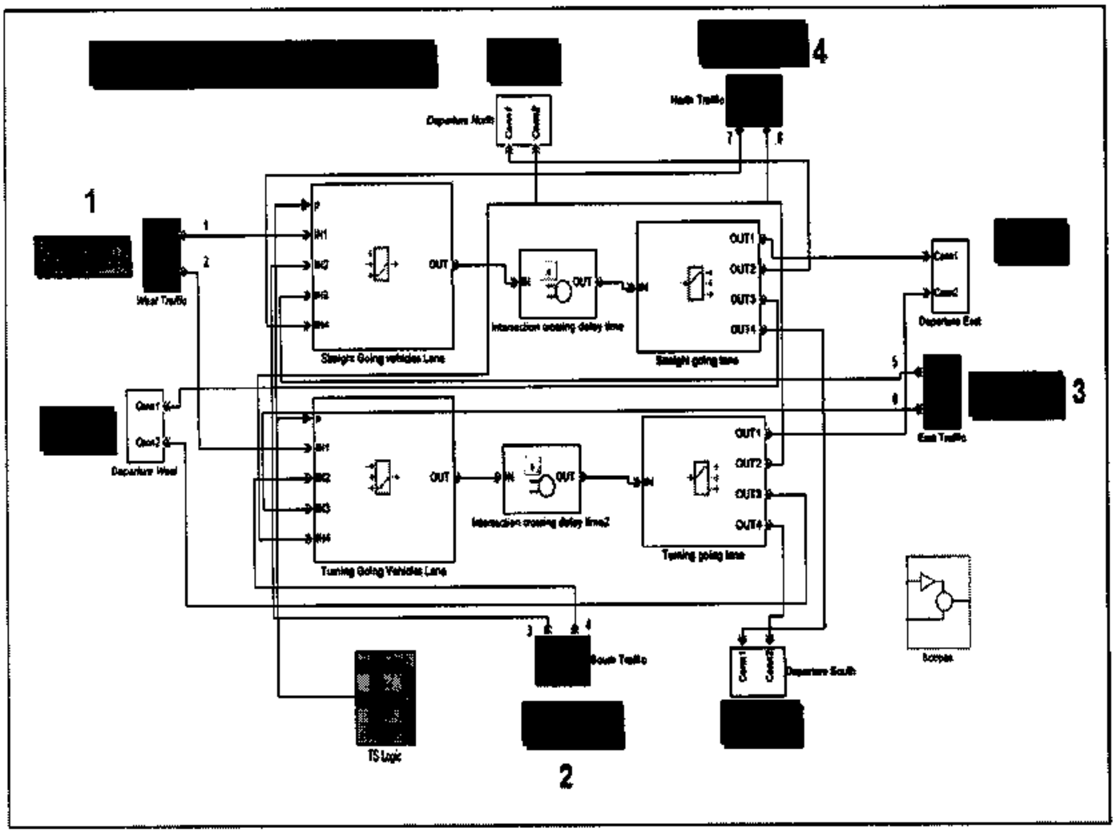

Figure 3.3. MATLAB Simulink block diagram of pre-timed signal controller

3.3 TS logic block diagram (pre-timed)

TS logic block is the main control unit of pre-timed traffic controller model as shown in figure 3.4. It controls the phase sequence and signal timing and selects an input flow path for traffic flow as approaching an intersection. Two event-based sequence blocks are used for signal timing and phase sequence, as named "phase timing" and "group selection" respectively, shown in figure 3.4. The phase timing block sets the timing of each phase, whereas, group selection block selects the phase pattern. The event-based sequence block signal timing is, then, executed by single server block. Finally the output port "outport block" is used to control the input switch 1 and 2 through input port "p" as shown in figure 3.4.

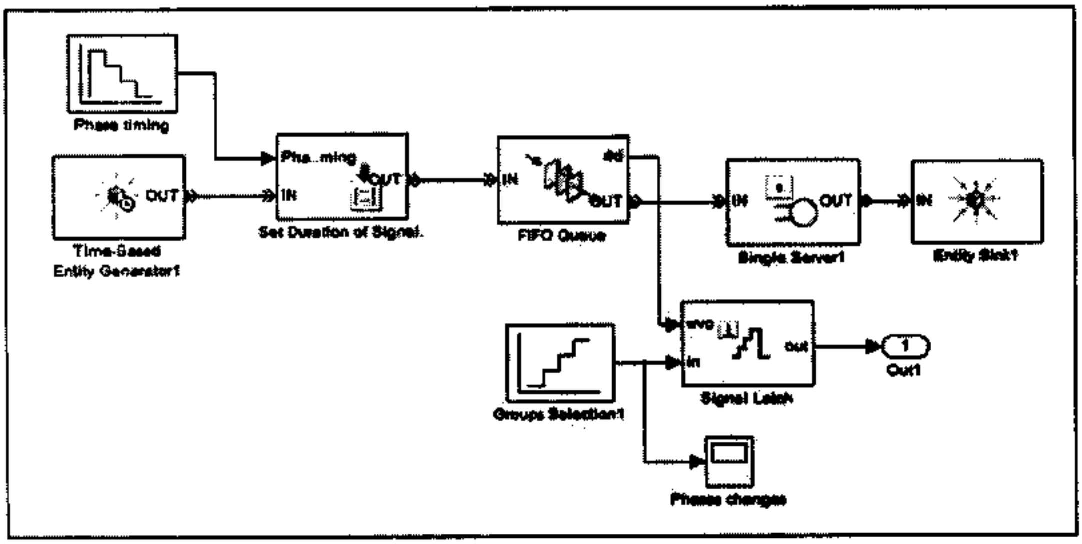

Figure 3.4 TS logic block diagram of pre-timed traffic controller

3.4 Traffic arrival pattern block at intersection

Traffic arrival flow from each side in lane follows a Poisson distribution as shown in block "event-based random number" in figure 3.5, and the meantime is set according to real traffic situation. Each lane of vehicles follows a FIFO discipline as shown in block "FIFO Queue" in figure 3.5. In red signal, queue length and average waiting gradually increases. And in green signal queue length and waiting time decreases.

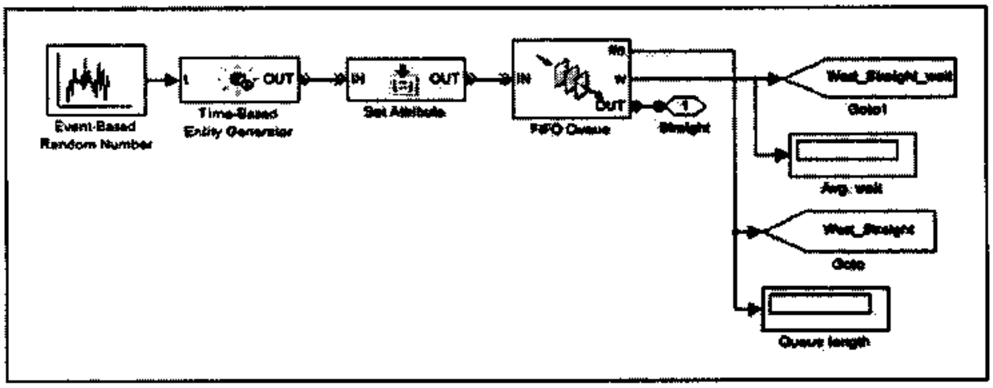

Figure 3.5 Traffic arrival pattern block at intersection

3.5 Simulation of pre-timed traffic controller queue length

In green signal, vehicles pass through intersection and queue length gradually decreases till signal red. The queue length vs. time (in seconds) for west approach is shown in figure 3.6. The horizontal axis shows time in seconds, whereas, the vertical axis shows vehicles queue length. A simulation time is about 1000 seconds. When the first phase (Φ_A) opens; vehicles stream in lane1 and lane 2 flows through an intersection, and their queue length gradually decreases till the end of phase A timing. Then next phase B (Φ_B) opens. The queue length of phase B gradually decreases and phase A queue length gradually increases. The timing of phase A is set for 40 seconds and the timing of phase B is set for 25 seconds. The total cycle length time is 125 seconds calculated. The queue length of first Phase, after 40 seconds, will gradually increase till the start of next cycle length, i.e. after 125 seconds, phase A opens and vehicle queue length again gradually decreases till the timing completes 165 seconds as indicated in figure 3.6 horizontal axis. Similarly, after 165 seconds phase B opens and vehicle queue length of phase B gradually decreases and phase A queue length gradually increases. The same pattern repeats for other phases as shown in figure 3.6.

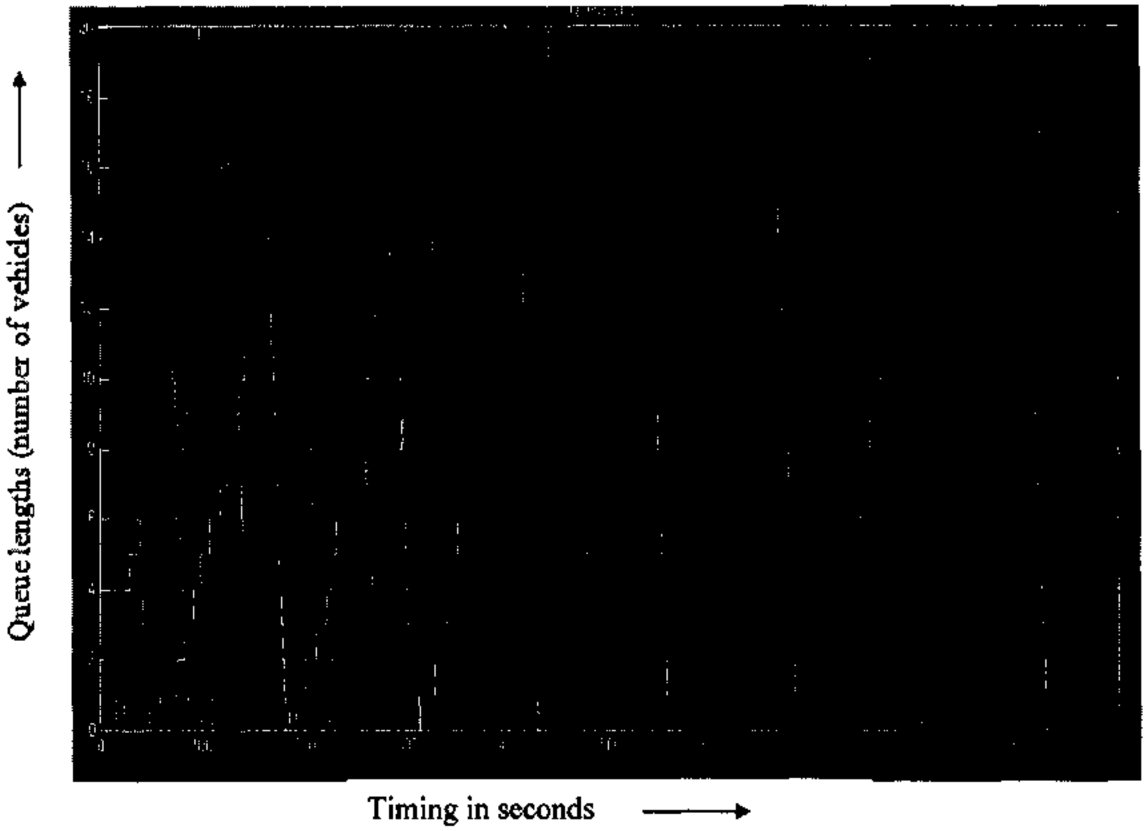

Figure 3.6 Pre-timed signal timing vs queue length

3.6 Simulation of pre-timed traffic controller average waiting time

The simulation of average waiting time is different from queue length. MATLAB always updates the graph of waiting time of phase which is active.

As shown in figure 3.7 when the first phase (west approach) is active for 40 seconds, the curve of average waiting time will be shown on the graph, but as soon as the first phase becomes deactivate, the average waiting time curve will not be updated in MATLAB. In the next cycle, when again the first phase becomes active after 125 seconds, the average waiting time curve will be shown on MATLAB as shown in figure 3.7. The average waiting time curve depends on time interval between a phase deactivation and activation. The same pattern repeats for other phases as shown in figure3.7.

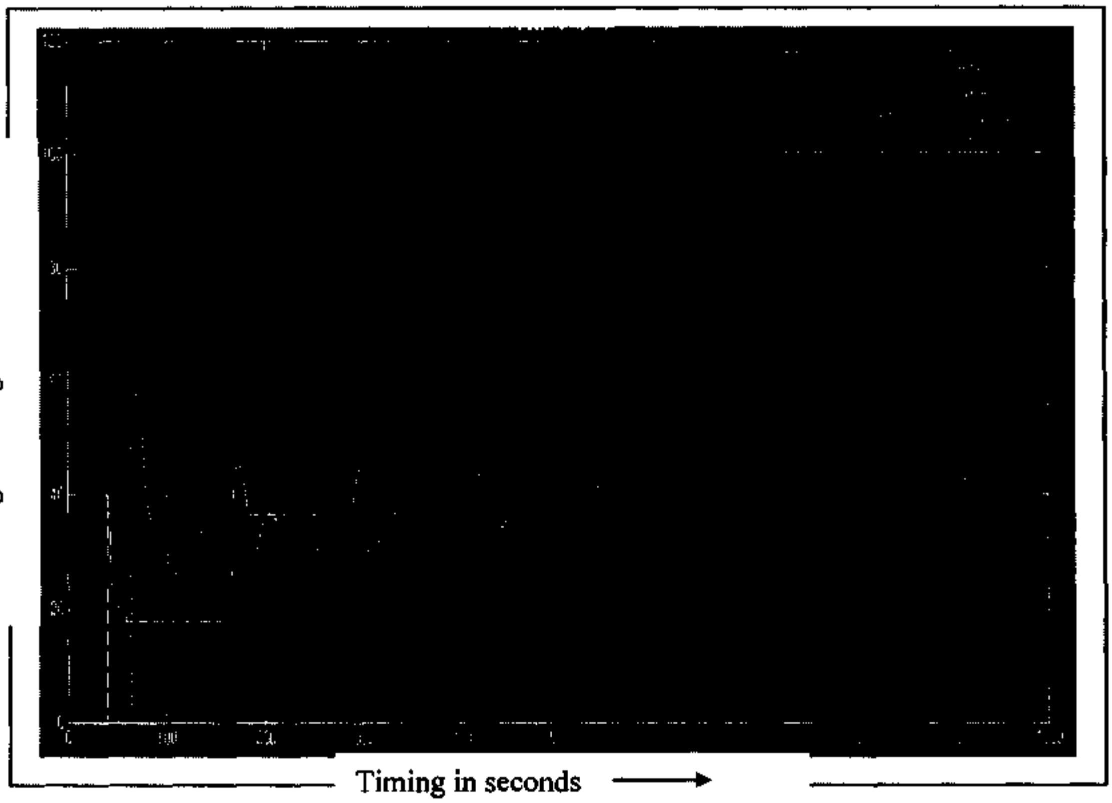

Figure 3.7. Pre-timed signal timing vs average waiting timing

3.7 Simulation of pre-timed traffic controller phase sequence

Figure 3.8 shows the phase sequence of pre-timed controller. From the figure 3.8 it is clear that pre-timed controller follows the fixed sequence of 1-2-3-4 showing four phases. The horizontal axis shows time in seconds, whereas, vertical axis shows phase numbers. When the first phase (west approach) is active for 40 seconds, the output switching waveform of phase A is shown for 40 seconds; which is also green time set for the first phase. After 40 seconds the phase B becomes active for 25 seconds and all the remaining phases become inactive. The output switching waveform of phase A shifts for 40 seconds to phase B till the end of 65 seconds. After 65 seconds the output switching waveform of phase B shifts to phase C for 45 seconds. The waveform for phase C comes to an end by 110 seconds. After 110 seconds the output switching waveforms of Phase C shifts to phase D for 15 seconds. The waveforms of phase D end up at 125 seconds, which is the first cycle length. After 125 seconds the same pattern repeats for 125 seconds in next cycle length as shown in figure 3.8.

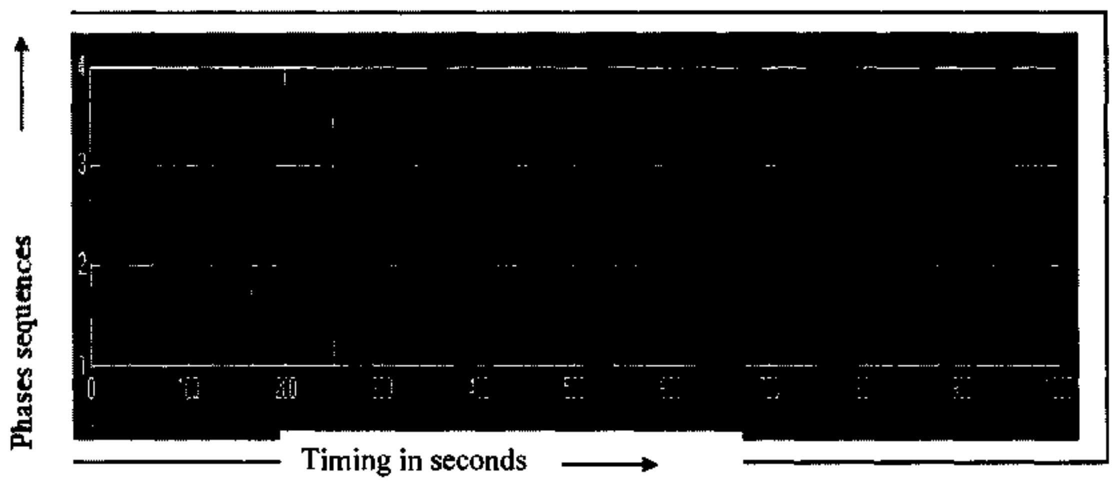

Figure 3.8. Pre-timed signal timing vs phase sequence

Chapter 4

Fuzzy Adaptive Traffic Controller Model

4.1 Description and model of single isolated intersection

The fuzzy adaptive traffic controller takes account of the traffic situation for the whole of intersection; collects data from detection devices, and adjust signal phases timing and phase sequence according to the real traffic flow. A four-way isolated intersection is also considered here, but each lane has independent front and rear sensor for detection of vehicles as shown in figure 4.1. A fuzzy logic is also applied to each lane traffic flow stream as shown in figure 4.1.

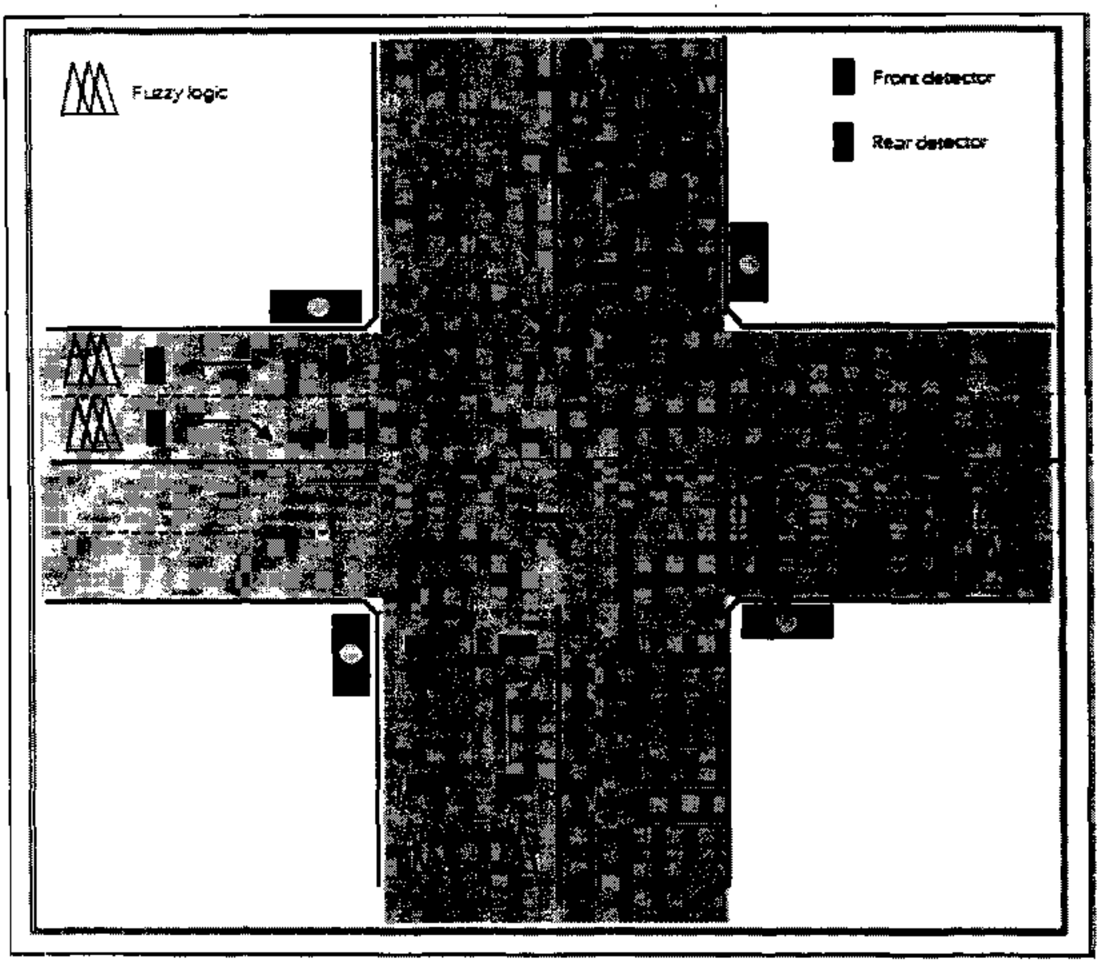

Figure 4.1- Fuzzy adaptive 4-way isolated intersection image

The fuzzy adaptive traffic controller follows the same M/M/1 queue model and FIFO discipline as in pre-timed traffic controller (chapter 3) but strategy is different from pre-timed traffic controller; Phases pattern and signal timing are variables in adaptive traffic controller. Green minimum and green maximum are set for each phase. When a phase is active, it must complete its green minimum timing, whereas green maximum timing depends on queue length. The extension block extends the time of phase, till reach green maximum time of phase. Then timing for the next phase starts in the same manner.

4.2 Input sensor installation guide

Different types of sensors are used for detecting vehicles like, inductive vehicle loop detector, microwave RADAR and video image processor, etc. The most popular detecting device is an inductive vehicle loop detector.

Loop detectors are installed in road pavement for each lane traffic flow. For each lane two loop detectors are installed as shown in figure 4.1; one loop is the front detector, which counts the number of vehicles passing over it and the second sensor is behind the first sensor, which counts the number of vehicles enter an intersection [2].

The number of vehicles (queue length) is determined by the difference between the two sensors.

4.3 Fuzzy logic operations

The input data, queue length and average waiting time are taken from each approach, and inputs are given to fuzzy logic controller. Since, total 8 streams of flow are considered here, fuzzy rule is applicable for each stream. So total 8 fuzzy logic controllers, from each side, contribute the system. The independent output of fuzzy logic controller is further given to SimEvent model. It makes the decision; which phase be opened and given how much time etc. Thus two input variables for fuzzy logic are; Queue length and average waiting time, and their output is extension time. The algorithm is shown in figure 4.2.

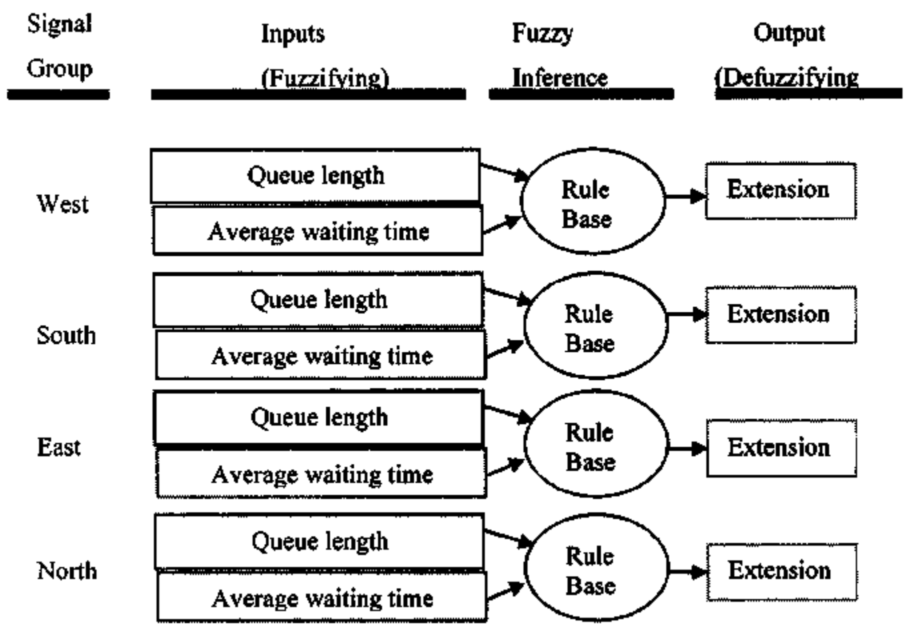

Figure 4.2. General structure of fuzzy logic for traffic control

Vehicles queue length Q and average waiting time Wt are the two input variables given to fuzzy inference system. The FIS structure, consisting of input Q, Wt and output Ext is shown in figure 4.3. As queue length, average waiting time develops non-linearly in real time, that is why Gaussian membership function is considered here.

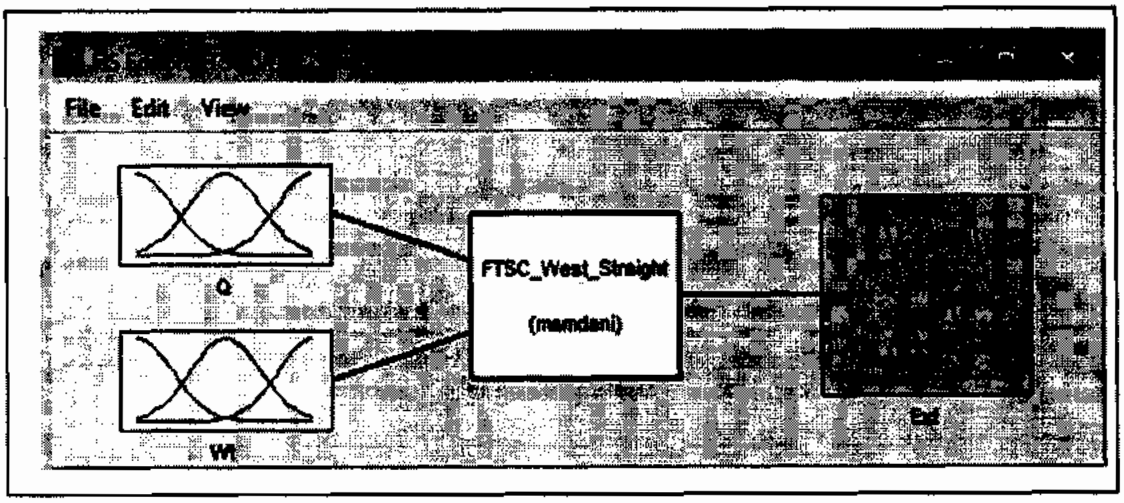

Figure 4.3. Queue length, waiting time and extension FIS editor of fuzzy logic

Five Gaussian membership functions are used for inputs queue length Q, average waiting time Wt and extension Ext [38].

The input membership function for queue length ranges from 0 – 50, which possesses 0 to 50 vehicle capacity in any lane. The input membership function queue length Q is subdivided into five ranges: Very Short (VS), Short (S), Long (L), Very Long (VL), and Extremely Large (EL) as shown in figure 4.4. Here Gaussian membership function has a deviation ratio (σ) of 2 and constant of Gaussian membership functions of VS, S, L, VL, and EL are 0,10,20,30 and 40 vehicle, respectively. The input membership function range is not fixed everywhere; it depends on the traffic situation, and can be varied and adjusted according to the traffic situation for better performance.

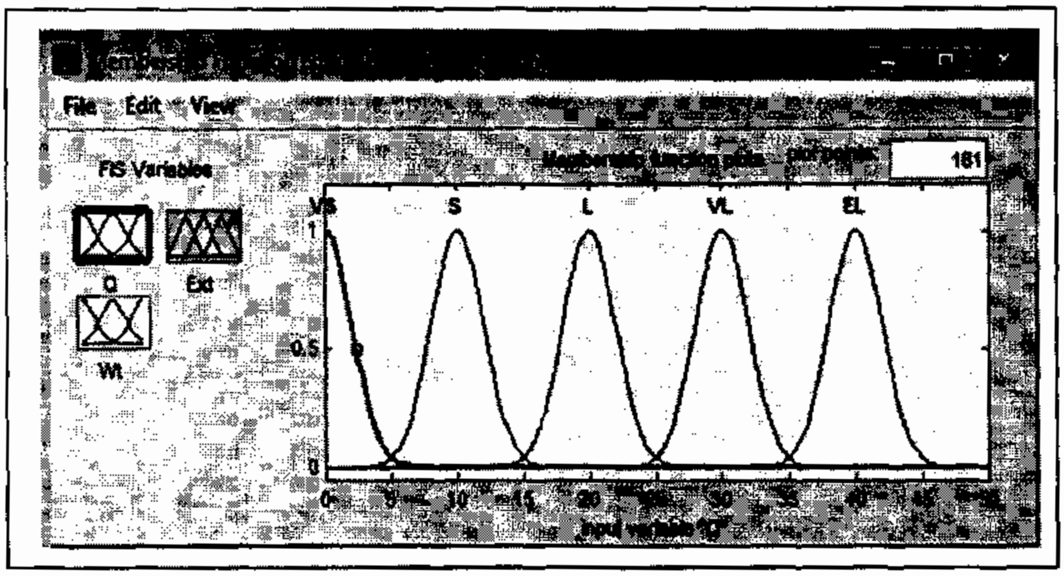

Figure 4.4. Input membership function editor of queue length (Q)

Similarly the input membership function for average waiting time ranges from 0 to 50 seconds for vehicles as shown in figure 4.5. The input membership function average waiting time Wt is subdivided into five ranges: Very Short (VS), Short(S), Long (L), Very Long (VL), and Extremely Large (EL). Here Gaussian membership function has a deviation ratio (σ) of 2 and constant of Gaussian membership functions of VS, S, L, VL, EL are 0,10,20,30 and 40 seconds, respectively.

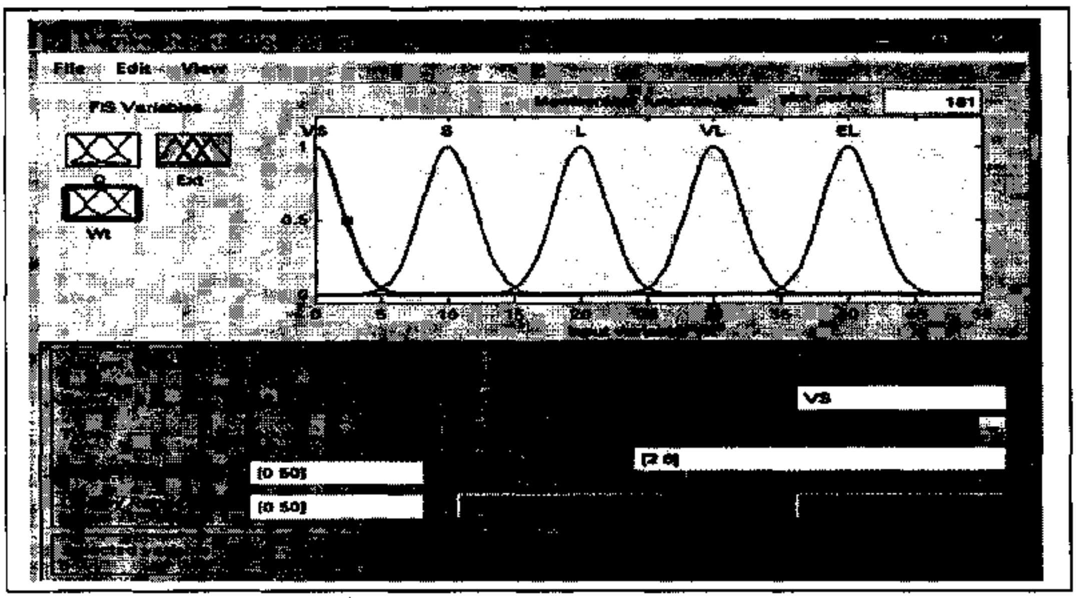

Figure 4.5. Input membership function editor of average waiting time (Wt)

Similarly the output membership function for extension (Ext) have five Gaussian membership functions, and is subdivided into five ranges Zero (Z), Small (S), Large (L), Very Large (VL), Extremely Large (EL) as shown in figure 4.6. The range is from 0 to 30.

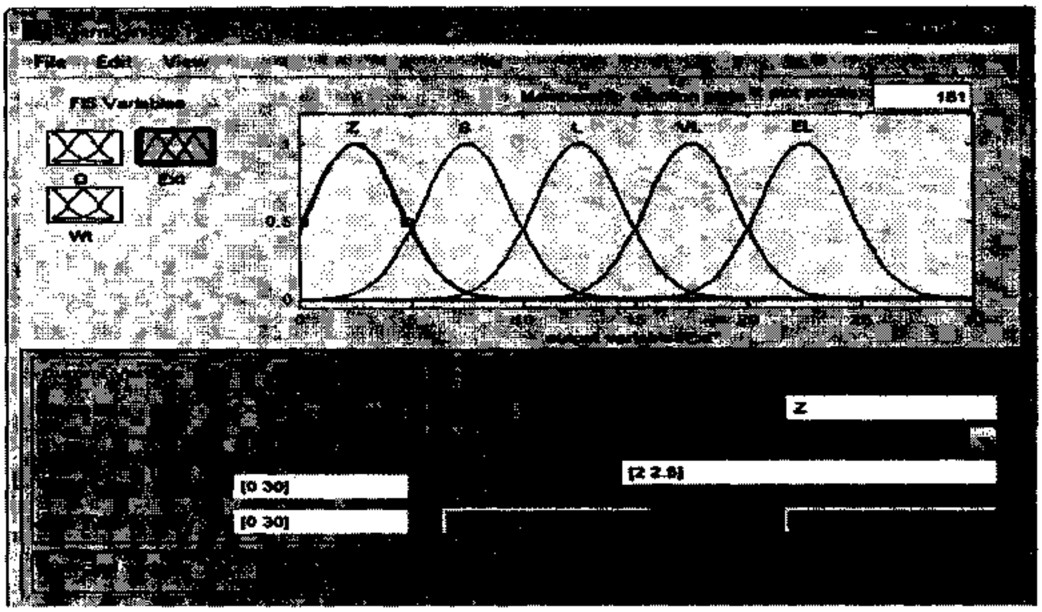

Figure 4.6. Output membership function editor of extension (Ext)

Mamdani-type fuzzy inference system consisting of total 25 rules are defined here as in Table 4.1.

TABLE 4.I. FUZZY RULES

Rules	Input Q	Input [illegible]	[illegible]
1	VS	VS	Z
2	VS	S	Z
3	VS	L	S
4	VS	VL	S
5	VS	EL	L
6	S	VS	Z
7	S	S	S
8	S	L	S
9	S	VL	L
10	S	EL	L
11	L	VS	S
12	L	S	S
13	L	L	L
14	L	VL	L
15	L	EL	VL
16	VL	VS	S
17	VL	S	L
18	VL	L	L
19	VL	VL	VL
20	VL	EL	VL
21	EL	VS	L
22	EL	S	L
23	EL	L	VL
24	EL	VL	VL
25	EL	EL	EL

4.4 Phase selection and time extension blocks

Two MATLAB function blocks are used in fuzzy adaptive model. One is "phase selection" and the other is "time extension" block. The phase selection block takes input data from all vehicles approach queue length. And then C language program is used by If–else statement to select the appropriate phase of the signal.

The time extension block takes input data fuzzy rule output extension from all approaches. Different conditions are set to give extension time to phase, keeping in view whole traffic situation. Fuzzy rule is applied to each side of lane by using queue length and average waiting time, while their output (extension time) is given to time extension block as shown in figure 4.7. The phase extension block extends or terminates a phase timing, according to traffic flow. Green minimum and green maximum timing are set in this block. Green minimum time is always fixed, which must complete the timing, whereas, green maximum timing depends on the traffic situation.

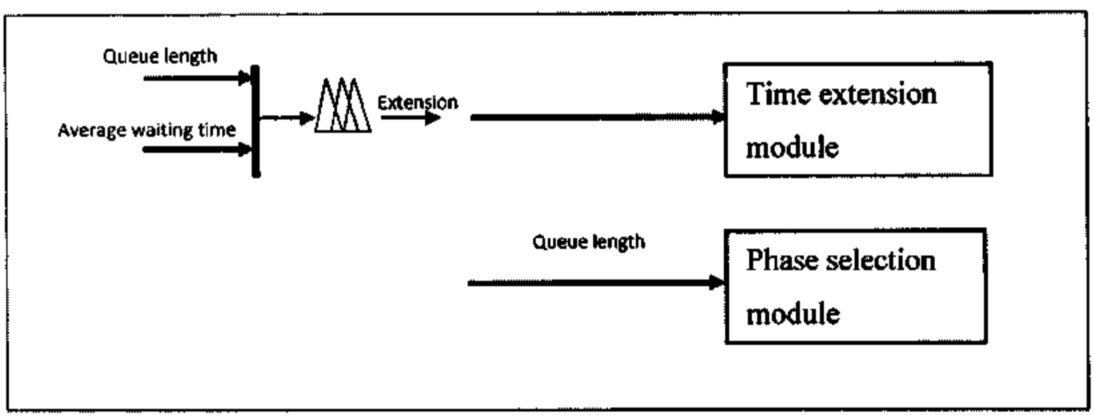

Figure 4.7. Block diagram of phase selection and phase extension module

4.5 Control unit block of fuzzy adaptive traffic controller

Control unit block is the main unit which selects the appropriate phase and signal timing in real traffic condition. In this control unit, two MATLAB function block are defined, one is "phase selection" and the other is "time extension" block as shown in figure 4.8. Phase selection and time extension block consist of C programming code, which uses different condition to select the required phase and their time setting. Green minimum time is set in this block. It completes its timing, after that extension in time is added. The control unit block also controls the input switch for entities passing. Average waiting time and queue length are the basis for extension time.

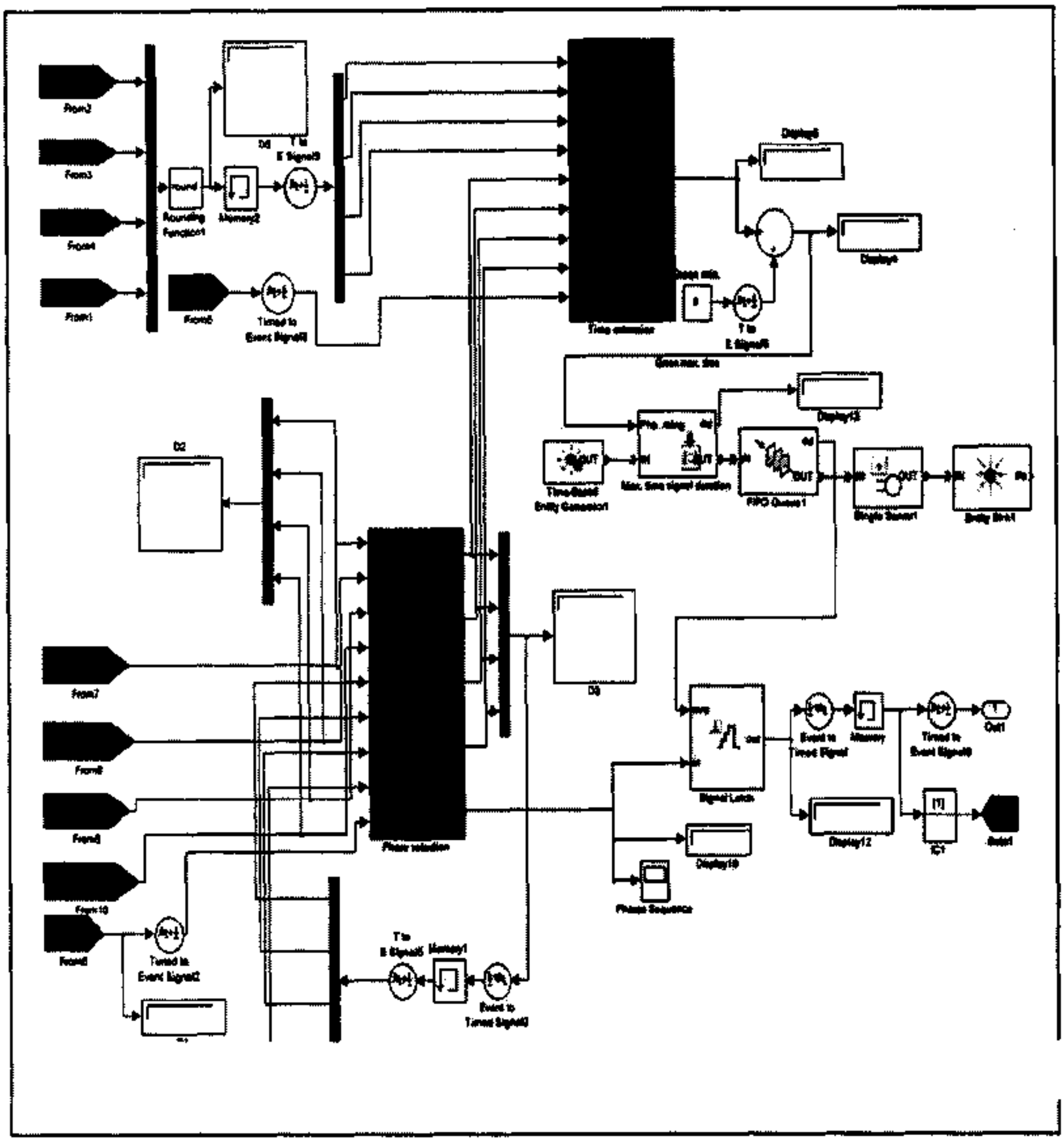

Figure 4.8. Adaptive traffic controller Simulink/SimEvent model of control unit block

4.6 Vehicles arrival block

In this block entities are generated randomly while their arrival processes are poison distribution. The generated entities are accumulated in FIFO order as shown in figure 4.9; when an input switch path is open, the entities depart from queue passing through server. The number of entities and average waiting time combination are event- based signal. As fuzzy logic controller with rule viewer needs time-based signal, so event-based signal is converted to time-based signal by event to timed signal block.

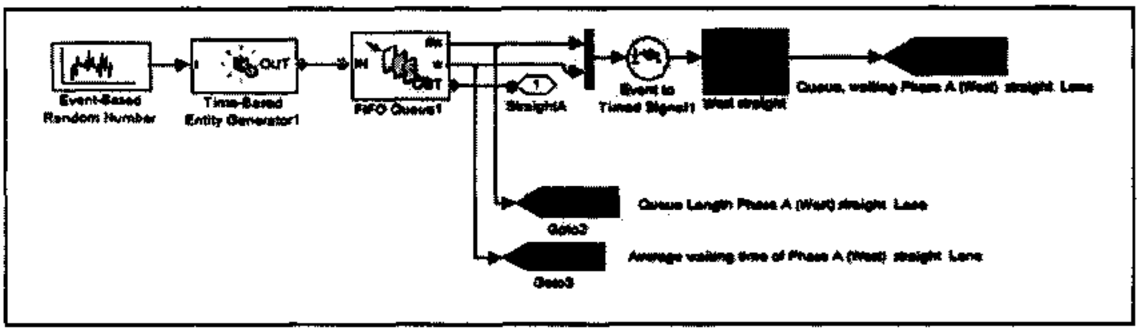

Figure 4.9. Vehicles arrival using fuzzy logic in adaptive signal mode

The "phase selection" and "time extension" block take their inputs as queue length and average waiting time respectively, from each lane of approach, the current phase status is also fed to these blocks. The C language code for MATLAB function blocks "phase selection" and "time extension" in control unit block is given in appendix A and B respectively.

4.7 Simulation of adaptive traffic controller queue length

The queue length simulation of adaptive traffic controller is different from pre-timed controller as shown in Figure 4.10. The vehicles approaching with large queue length, will take first priority to phase opening. The horizontal axis shows timing in seconds, whereas the vertical axis shows the vehicles queue length. In green signal vehicles pass through an intersection, and queue length gradually decreases till signal red. When a phase opens it will complete its green minimum timing regardless of red signal queue length. However, further extension time depends on current green signal queen length and red signal queue length. In figure 4.10 when the first phase (Φ_A) opens on 110 seconds, vehicles stream in lane1 and lane 2 flows through an intersection. The queue length of phase A gradually decreases; extension time takes place till vehicles of that approach pass the intersection. After that controller decides and opens next phase C after 140 seconds which has large queue length. Instead of opening phase B as in pre-timed traffic controller, here in adaptive mode controller opens phase C.

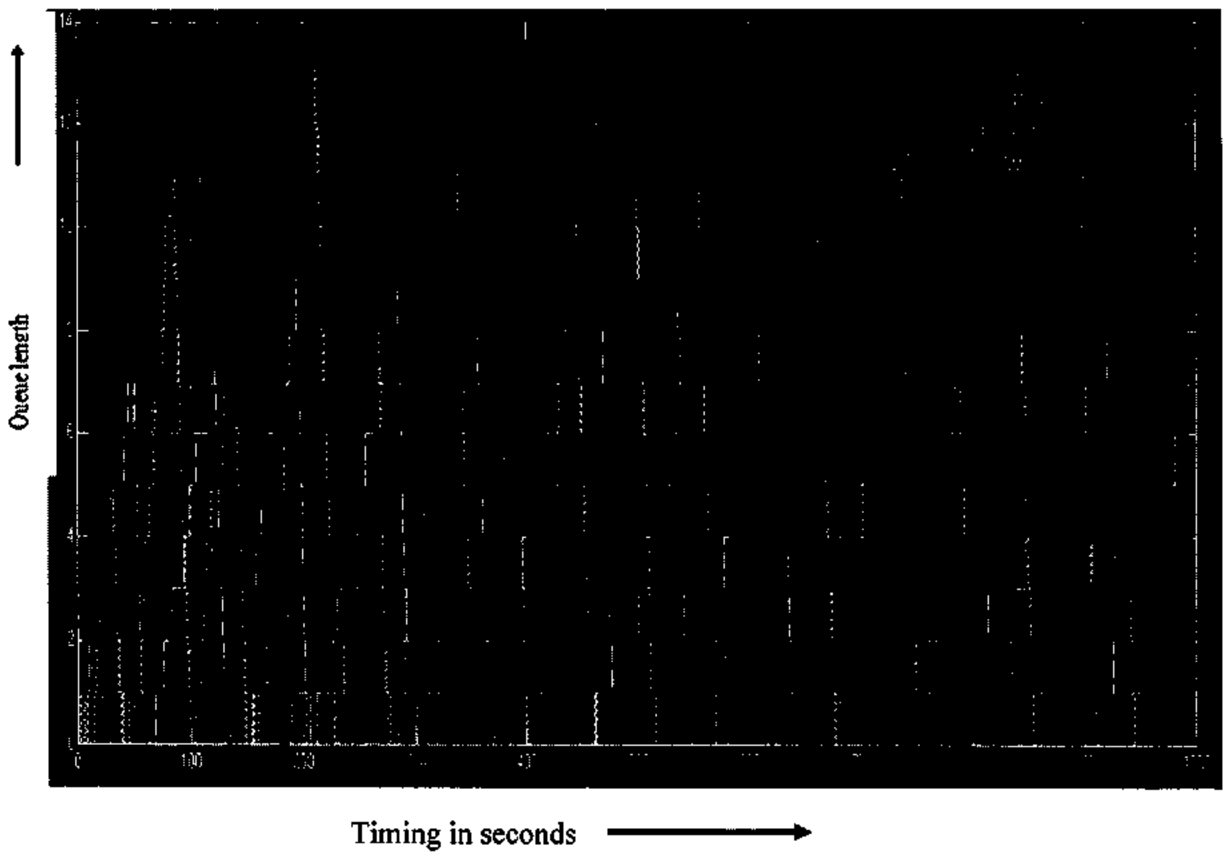

Figure 4.10. Adaptive signal timing verses queue length

After 160 seconds the next phase D becomes active for 12 seconds, then becomes inactive and next phase B becomes active. Similarly, same procedure is followed by other phases. In adaptive mode, phase numbers are variable contrary to pre-timed controller where numbers are fixed.

4.8 Simulation of adaptive traffic controller average waiting time

Average waiting time simulation of adaptive traffic controller is different from pre-timed controller as shown in Figure 4.11. The average waiting time in adaptive traffic controller is less than in the pre-timed controller. As shown in figure 4.11, the maximum average waiting time of phase D is less than 60 seconds, whereas in pre-timed controller, it is almost 110 seconds.

The output simulation result of average waiting time is shown in figure 4.11. The horizontal axis shows the timing in seconds and the vertical axis shows the average waiting time.

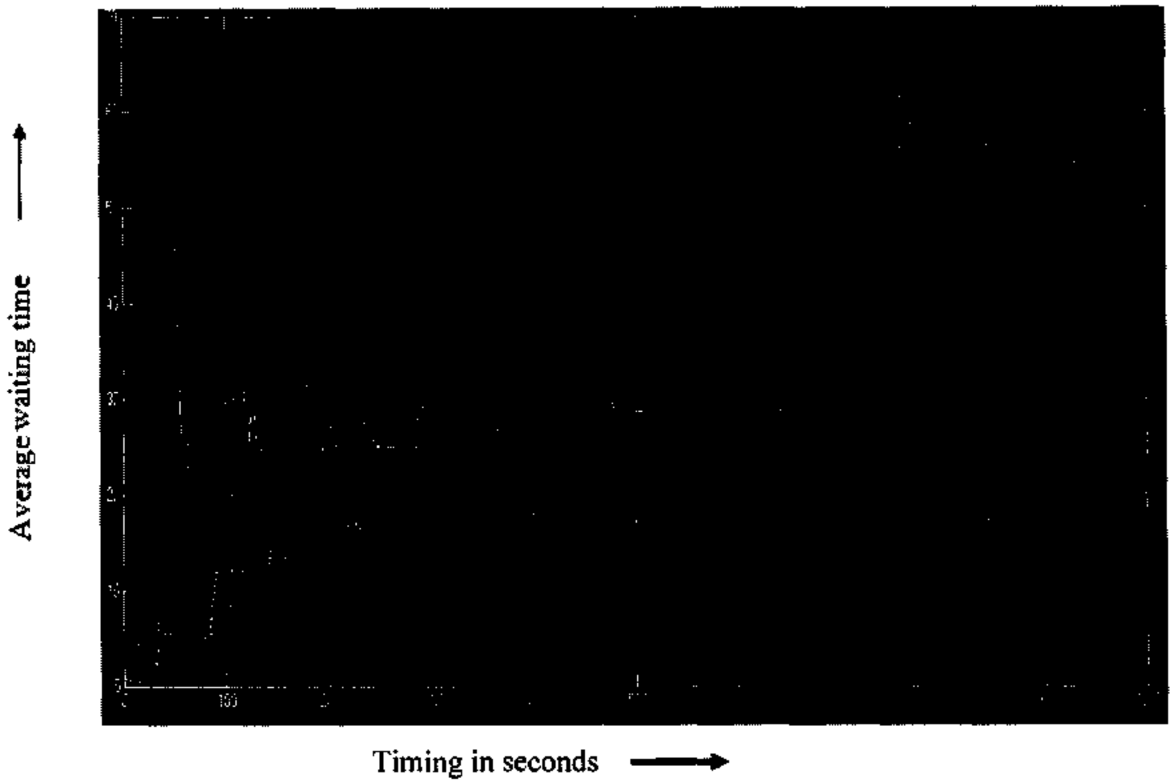

Figure 4.11. Adaptive signal timing vs average waiting time

4.9 Simulation of adaptive traffic controller phase sequence

The output simulation result of phase sequence is different from that of pre-timed traffic controller. Pre-timed traffic controller operates in sequence wise. It is variable and irregular sequence as shown in figure 4.12. On the other hand, pre-timed controller has fixed and regular sequence of phases. The horizontal axis shows the timing in seconds, whereas the vertical axis shows the phases number.

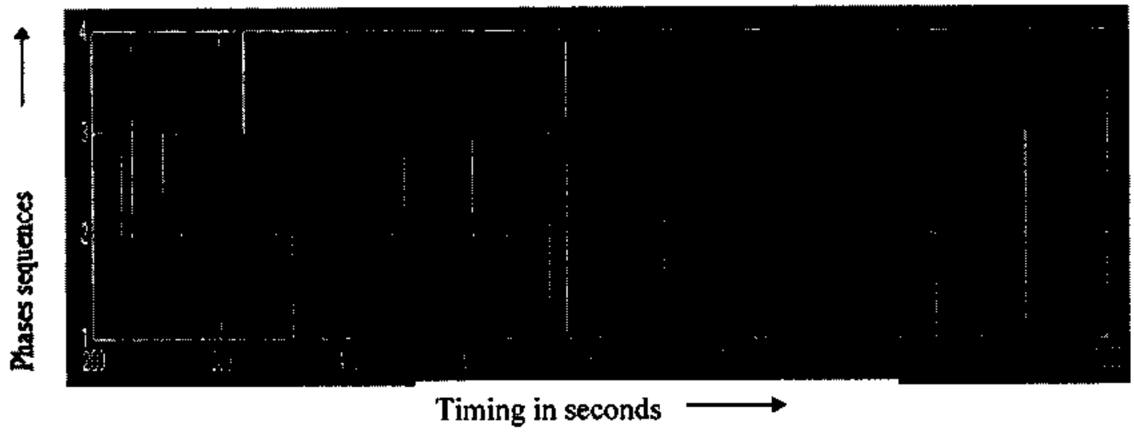

Figure 4.12. Adaptive signal timing verses phase sequence

The phase sequence of the fuzzy controller is dictated upon by the weight of each phase with the one with highest priority granted green phase.

Chapter 5

Adaptive Fuzzy Transit Bus Priority System

5.1 Overview of transit bus priority system

Bus priority or transit signal priority (TSP) is a methodology by which service and delay of mass transit vehicle are improved and reduced traveling delay at traffic signal intersection. Although there are many other types of priority vehicles, but the term TSP is generally associated with buses. As the buses share the common signal intersection of general vehicles, they need less delay time as compared to other vehicles to pass safely through the intersection, having less impact on other traffic flow.

TSP usually provides "green time" of priority phases to transit vehicles, as it approach at an intersection. So it is possible to extend the current non-conflict green phase or shorten the other conflict phase (red signal) in order to open the green phase of transit vehicles earlier.

TSP needs some conditions to open a phase for crossing an intersection, whereas emergency vehicles do not obey conditions. Whatever conditions may be, it always takes first priority, whereas TSP does not do so.

Recent bus rapid transit (BRT) was introduced in the world, which motive was to improve these bus services in world wide. Focusing on TSP will reduce fossil fuel; improve air quality, and safe traveling [45].

TSP better accommodates transit buses through Traffic signal intersection. It gives transit vehicle some extra green time or reduces the red time of waiting at an intersection, to reduce time delay, improving travel time, and reliability [46].

5.2 TSP control strategies

Transit signals priority strategies are commonly categorized commonly in three categories: (i) Passive priority (ii) Active priority (iii) Adaptive or Real-time priority [49].

(i) Passive priority: It was the first initial step for development of TSP development. Passive priority strategy is static and predetermined analysis, based on transit schedule. The passive priority system is often applied to fixed-time signal, and does not need any monitoring or detection devices for transit vehicle. It opens transit bus phase by reducing the cycle length or providing phase sequence, that give more frequent green time for buses [48].

(ii) Active priority: Active priority reduces the shortcoming in passive priority strategy, and utilized inputs detective devices to detect approaching transit vehicles and adjust signal timing in a predefined manner. It has ability to identify or detect transit bus approaching a signalized intersection. There are four types of active priority methodology. (a) Green extension (b) Early green/Red truncation (c) Special bus phase (d) Selective strategies

(a) Green extension: It extends the approaching transit bus green phase upon detection of the transit bus in green signal. The green times are held or extend until pass the transit bus or clear the intersection. Usually two types of detectors are used, one is check-in and the other is check-out detector, check-in detector is used for transit bus call to open transit bus route, while check-out detector is used to cancel that phase or green extension time.

(b) Early green/Red truncation; this strategy is used when a bus approaches at an intersection in a conflict phase (red signal) to provide early green phase to transit bus route upon detection in red signal in order to return the bus phase sooner. So some phase may be skipped or shorted conflict phases. So special care must be taken in designing early green time that green minimum time of general vehicles must be complete, so that vehicles and pedestrian safety may be considered.

(c) Special bus phase; a short duration of special bus phase is inserted into normal phase sequences [49]. This strategy is applicable which have more than two phases.

(d) Selective strategies; it may be conditional or unconditional, depending upon location and capabilities of bus detector. Under unconditional priority, signal priority is given to every transit vehicle upon request, regardless whether the priority is really "needed". It gives priority to transit vehicles "blindly". The result is that it creates more delay, queue length, and problem created for those transit buses which approach later. Condition priority give signal priory to transit vehicles upon request based on some predefined criteria. e.g. Schedule adherence, passenger occupancy, spare gap time, bus route progression, bus headway deviation.

(iii) Adaptive or real-time priority: adaptive priority system grants a priority to transit vehicles upon request and at the same time less impact on other traffic flow.

Usually adaptive priority consists of three important components; 1) a continuous detection that can detect transit vehicles approaching at intersection continuously, so that arrival can be detected in real-time manner ; 2) a communication link among transit vehicle, priority request system and controller to share transit Bus arrival time in real-time manner ; 3) a signal control methodology that adjust signal timing to provide priority while considering other traffic flow and pedestrian safety.

Usually the transit vehicle has their independent track over which transit bus flow, but some TSP has a jointly lane of general vehicles, but always both of them joining the common intersection in a local urban area. Whenever a bus comes into the detection zone it will send commands to the controller to open the phase for transit bus.

A general sketch of a transit bus priority sketch in intelligent traffic system is shown in figure 5.1.

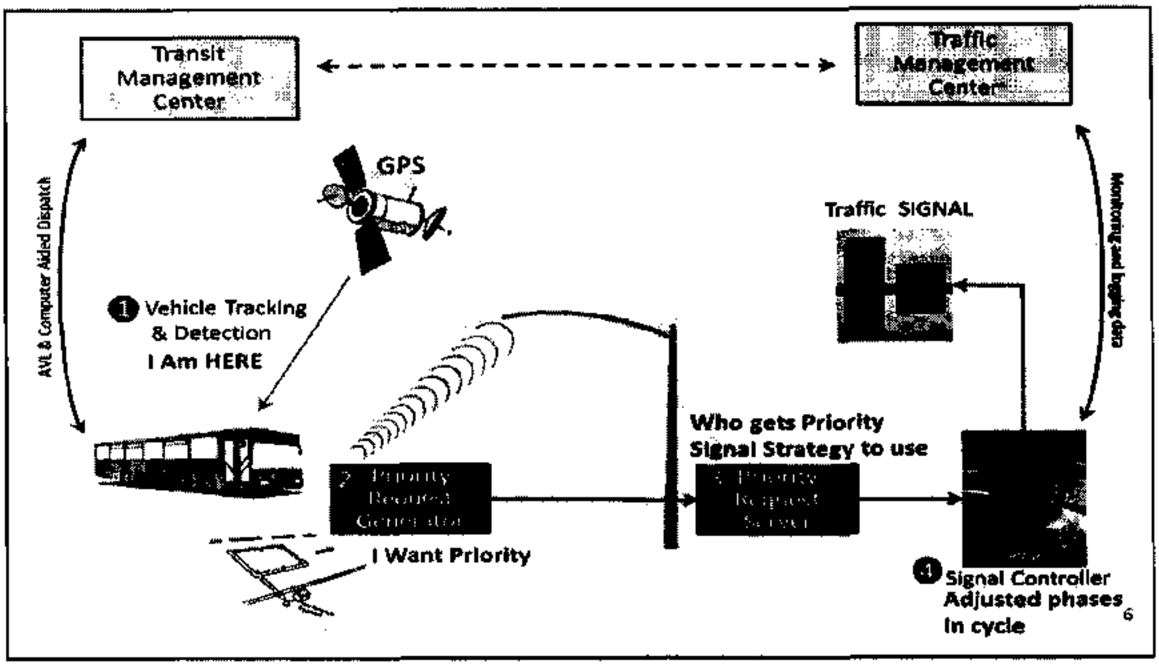

Figure 5.1 Transit bus priority sketch in intelligent traffic system

5.3 Control unit block of adaptive fuzzy transit bus priority signal

The controller follows the same M/M/1 queue model and FIFO discipline for general vehicle flow as in pre-timed and adaptive traffic controller. But transit bus follows only priority queue discipline ascending order instead of FIFO discipline. The priority queue discipline shows that a TSP will be served first. In this model two further MATLAB function block are also developed for transit bus phase and timing control as shown in figure 5.2. The MATLAB function block "TSP Priority phase selection" control transit signal priority special phase for bus arrival, and MATLAB function block "TSP priority time extension" only extend the timing of transit bus. If no transit bus is detected, then both MATLAB function block codes will not execute.

In red signal if a bus is detected, the controller will wait until complete their green minimum and clearness time, after completion of threshold range of time; bus priority phase will take place until pass transit bus. But if a transit bus is detected in green signal, it will only extend the time to pass the transit bus without disturbing general vehicle flow.

The transit bus from west approach is non-conflict with phase A, while conflict with phase B, phase C and phase D. Similarly the transit bus from east approach is non-conflict with phase C, while conflict with phase A, phase B and phase D.

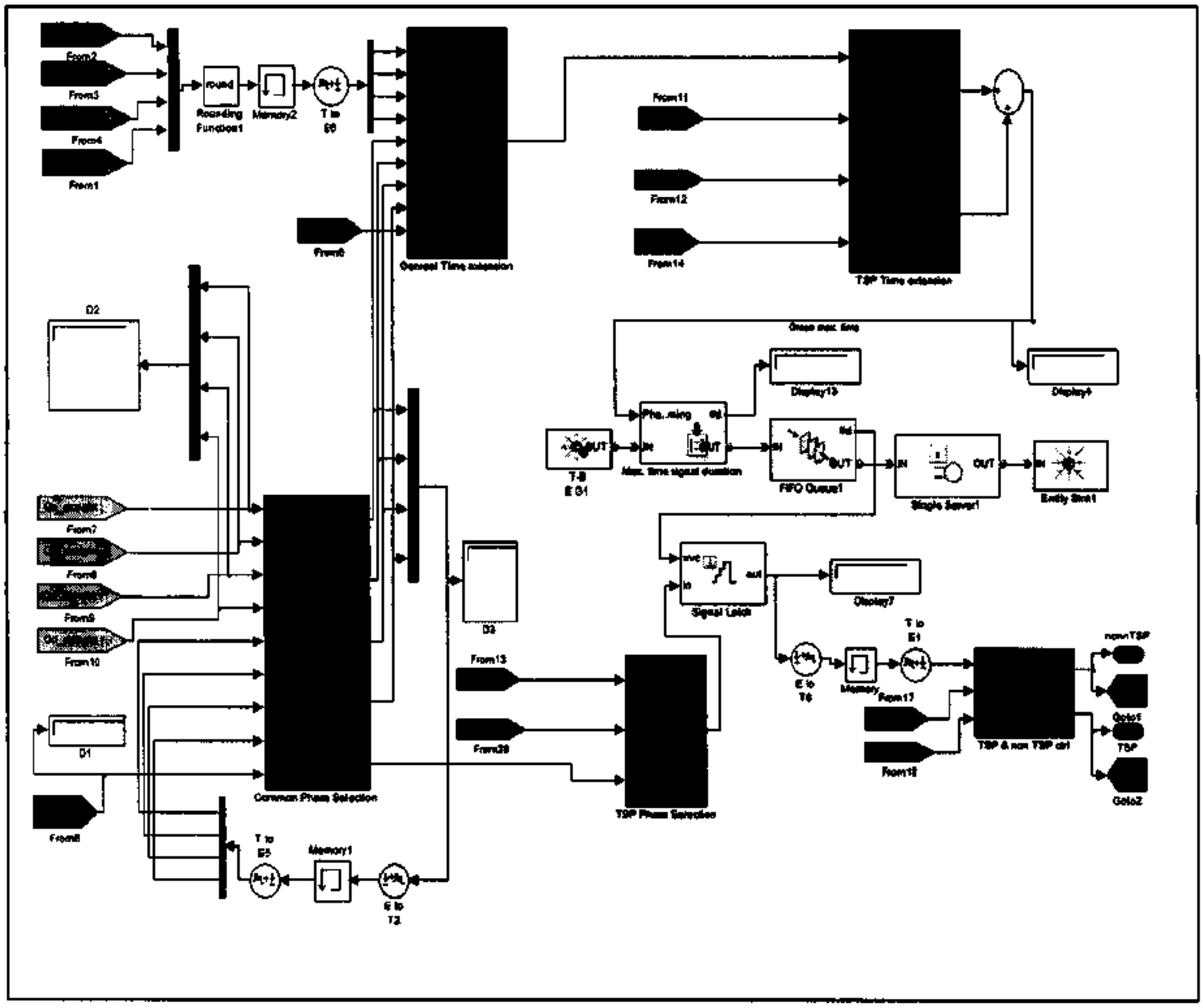

Figure 5.2 Transit signal priority control unit block Simulink SimEvent model

The transit bus approach at an intersection, follow priority queue discipline as shown in figure 5.3. Queue length and average waiting time of transit buses are given as inputs to their independent fuzzy logic controller while their fuzzy out is given to transit signal priority time extension block.

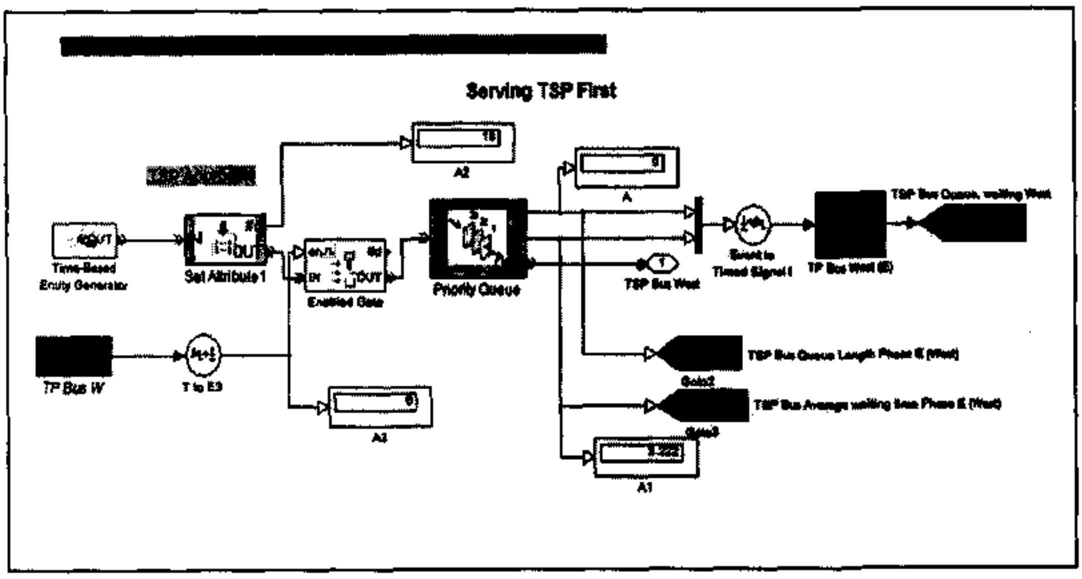

Figure 5.3 Transit signal priority approach Simulink/SimEvent model

The C language code for MATLAB functions block "TSP phase selection" in control unit block is given in appendix C. If no transit bus is detected than traffic flow will normal, but if a bus is detected, the controller will adjust the time to soon open the phase for transit bus.

Similarly the C programming code for MATLAB function block "TSP time extension" is given in appendix D. The fuzzy logic controller output extensions of transit buses are given to TSP priority phase extension block. The timing of all transit buses approaching at an intersection is controlled by this block.

5.4 Simulation of adaptive fuzzy transit bus priority queue length

The transit bus from west approach is non-conflict with phase A of general vehicles. As shown in figure 5.4 after 300 seconds a transit bus from west approach is detected, during this interval the non-conflict phase A was open, the simulation result show that bus did not take waiting time at intersection as shown in figure 5.5. There is no average waiting time curve shown in figure 5.5 as transit bus without waiting to cross the intersection. But after 530 seconds a transit bus from east approach is detected in conflict phase B as shown in figure 5.4. The transit bus waits slightly in the conflict phase for special phase opening. After a short interval of time the transit bus phase open and get pass the transit bus across the intersection. Again, after 900 seconds a transit bus from west approach is detected in conflict phase C as shown in figure 5.4. The transit bus waits slightly in the conflict phase for special phase opening. After a short interval of time the transit bus phase open and get pass the transit bus across the intersection.

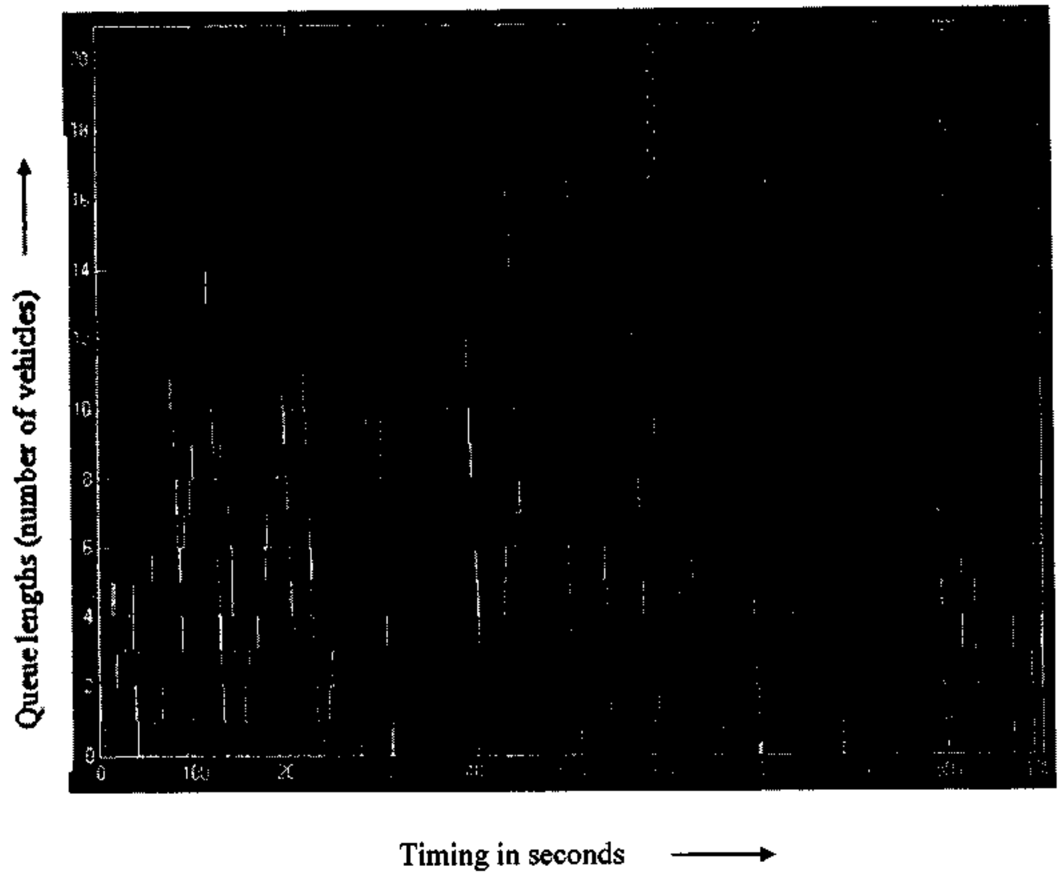

Figure 5.4. Simulation of TSP timing vs queue length

5.5 Simulation of adaptive fuzzy transit bus priority average waiting time

Figure 5.5 shows the average waiting time of general vehicles and transit bus. After a simulation time of 300 second a transit bus is detected from west approach, during this movement non conflict phase was already open, the transit bus without waiting at intersection pass the intersection, and did not affect general vehicle flow. But after 530 seconds a transit bus is detected from east approach in conflict phase so it wait slightly and open the special phase for transit bus, thus transit bus affects slightly general vehicle flow. The curve for average waiting time is shown in figure 5.5.

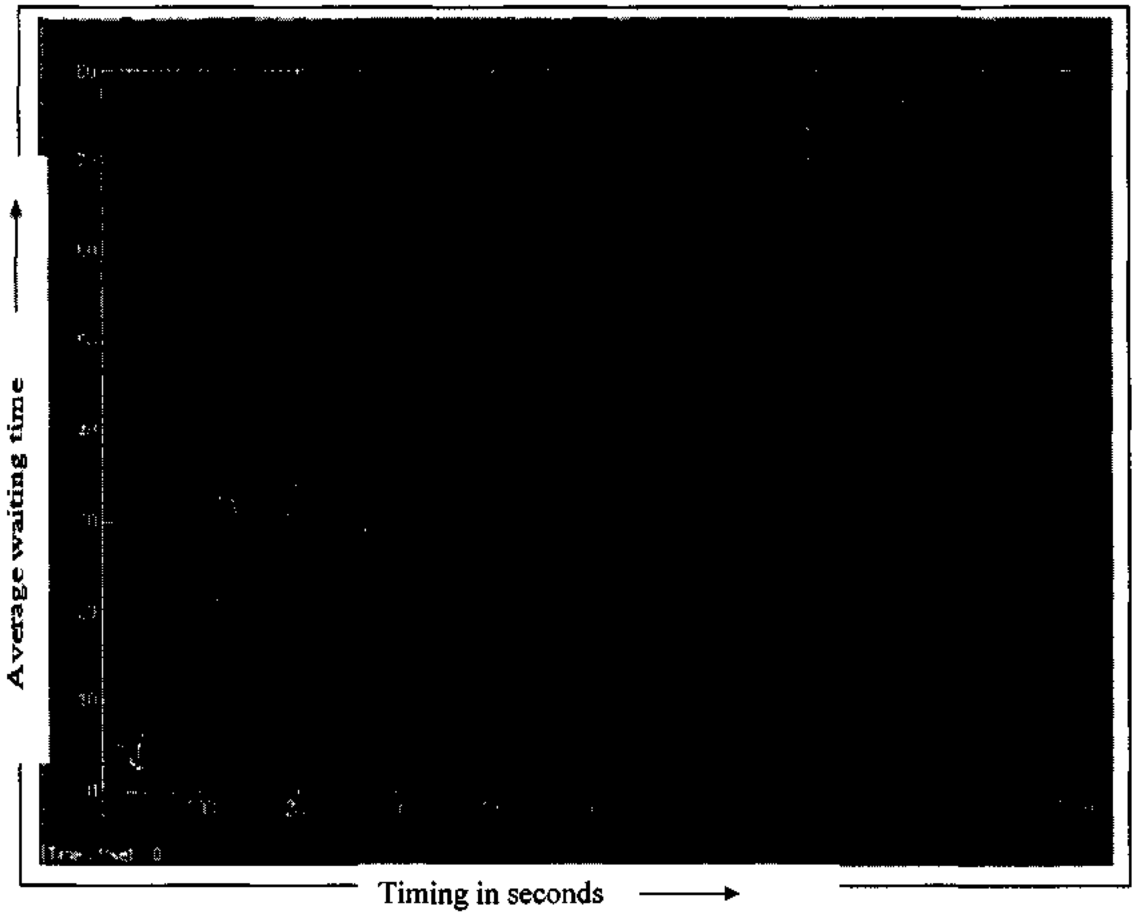

Figure 5.5. Simulation of TSP timing verses average waiting time

Chapter 6

Comparison and Discussion

6.1 Comparison of proposed adaptive controller with pre-timed controller

The performance of pre-timed and proposed fuzzy adaptive traffic controller is compared by simulating these controllers in isolated traffic intersection model. The comparisons are performed in three different scenarios. These three scenarios have different traffic volumes at the intersection and they are divided into low volume, medium volume and high volume, respectively.

The low traffic volume shows less vehicles flow, medium traffic volume shows average vehicles flow and high traffic volume shows heavy traffic flow through an intersection. Mainly three parameters of pre-timed and fuzzy adaptive traffic controller are compared under normal, medium and high volume. These three parameters are average waiting time, queue length and phase pattern.

The performance index average waiting time is the measure time of waiting for the vehicles to pass through the intersection. Average queue length is the measure of queue length of vehicles at the intersection over time.

The simulation time for the three scenarios is considered 1000 seconds.

The performance comparison between fuzzy adaptive traffic controller and pre-timed controller at low traffic volume are summarized in table 6.1. Based on Table 6.1, the performance of fuzzy adaptive traffic controller is better than pre-timed controller in terms of average waiting time and average queue length. From the Table 6.1, the fuzzy adaptive traffic controller shows improvement in average waiting time for West direction is 19.35%, South direction is 29.54%, East direction 26.31% and North direction is 26.22% over the pre-timed controller.

Table 6.1 comparisons of pre-timed and fuzzy adaptive performance at low volume

Performance measure	Phase	[illegible]	[illegible]	[illegible]
Average queue length (vehicles)	Φ_A (west)	8	7	12.50
	Φ_B (south)	9	8	11.11
	Φ_C (east)	9	8	11.11
	Φ_D (north)	7	7	00.00
Average waiting time (seconds)	Φ_A (west)	31	25	19.35
	Φ_B (south)	44	31	29.54
	Φ_C (east)	38	28	26.31
	Φ_D (north)	61	45	26.22

The performance comparison between fuzzy adaptive traffic controller and pre-timed controller at medium traffic volume are summarized in table 6.2. Based on Table 6.2, the performance of fuzzy adaptive traffic controller is better than pre-timed controller in terms of average waiting time and average queue length. From the Table 6.2, the fuzzy adaptive traffic controller shows improvement in average waiting time for West direction is 35.48%, South direction is 38.63%, East direction 39.47% and North direction is 46.62% over the pre-timed controller.

Table 6.2 comparisons of pre-timed and adaptive performance at medium volume

Performance Measure	Phase	Pre-timed control	[illegible]	[illegible]
Average queue length (vehicles)	Φ_A (west)	12	7	41.66
	Φ_B (south)	10	8	20.00
	Φ_C (east)	16	10	37.50
	Φ_D (north)	10	08	20.00
Average waiting time (seconds)	Φ_A (west)	31	20	35.48
	Φ_B (south)	44	27	38.63
	Φ_C (east)	38	23	39.47
	Φ_D (north)	61	36	42.62

The performance comparison between fuzzy adaptive traffic controller and pre-timed controller at high traffic volume are summarized in table 6.3. Based on Table 6.3, the performance of fuzzy adaptive traffic controller is better than pre-timed controller in terms of average waiting time and average queue length. From the Table 6.3, the fuzzy adaptive traffic controller shows improvement in average waiting time for West direction is 25.80%, South direction is 34.09%, East direction 47.36% and North direction is 29.50% over the pre-timed controller.

Table 6.3 comparisons of pre-timed and fuzzy adaptive performance at high volume

Performance measure	Phase	[illegible] control	[illegible]	[illegible]
Average queue length (vehicles)	Φ_A (west)	20	09	45.00
	Φ_B (south)	15	10	33.33
	Φ_C (east)	26	14	46.15
	Φ_D (north)	12	09	25.05
Average waiting time (seconds)	Φ_A (west)	31	23	25.80
	Φ_B (south)	44	29	34.09
	Φ_C (east)	38	20	47.36
	Φ_D (north)	61	43	29.50

From the three different scenarios, it is clear that the average waiting time remains fixed in pre-timed controller under low, medium and high volume, while in adaptive controller average waiting time varies, according to traffic situations. The average queue length varies both in pre-timed and adaptive controller depends on the traffic situation, as traffic flow increases randomly in several times in days especially in school and office time. From the three scenarios, it is clear that more the heavy traffic flow the more will be better performance of adaptive controller than pre-timed controller. However, in low traffic flow the performance of adaptive controller is less efficient than pre-timed controller. The fuzzy adaptive take less time for phase opening.

Fuzzy traffic signal controller produces lower waiting time, queue length and delay time as compared to the pre-timed signal controller because the fuzzy traffic signal controller is able to skip the phase where there is no vehicle detected on any approach and assign the right of way to other approach where vehicles are present. This means that green phase will not assign the approach where there is no vehicle so that more green time can be allocated to other approaches that have longer vehicles queue length. By this means, shorter average vehicles queue length on each approach at the isolated traffic intersection can be maintained at all time. Thus, fuzzy adaptive traffic controller is better than pre-timed controller.

6.2 Impact of transit bus on general vehicles in term of waiting time

The proposed model has 6 phases, 4 phases for general vehicles flow, while remaining two phases are used for transit bus approaches. And the impact of transit bus flow is monitored on general vehicles flow. During simulation after 300 seconds a transit bus is detected in non- conflict phase A as shown in figure 5.4. The transit bus passes the intersection without disturbing general vehicles waiting time. And no impact on general vehicles flow. After 530 seconds transit bus is detected in the conflict phase C from East approach. The transit bus waits less and then controller opens the phase. Again, after 900 seconds transit bus is detected in conflict phase A from west approach. The transit bus from the west approach wait less and then controller open the phase for transit bus.

The transit bus approach in green signal did not affect general vehicle queue length and average waiting time. But in red signal transit bus from east and west approach it affects general vehicles queue length and average waiting time.

The affected phase queue length and average waiting time are described here. The model is simulated for 1000 seconds in transit bus presence and transit bus absence. The impact of transit bus flow on general vehicles flow in term of average waiting time is derived.

Phase B is affected -3%

Phase D is affected -5%

From the above result, it is clear that low traffic flow phase D is affected from a transit bus approach which is minus 5%, while phase B is affected minus 3% in term of waiting time. Due to transit bus approach in east and west direction the average waiting time of general vehicles not affected in these directions. From the result, it is clear that minor sides traffic flow are affected while major side traffic flow are not affected overall.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

In this research, the main focus is to develop transit bus priority model based on fuzzy logics, and also pre-timed and fuzzy adaptive traffic model are develop to compare the performance of both models.

The mechanism for the development of models has been described.

The models are developed in MATLAB R2012a Simulink/SimEvent environment. Four way decentralized approach single intersection is considered here.

First fuzzy adaptive traffic controller is designed using fuzzy logic in MATLAB, based on M/M/1 queue model theory.

Then fuzzy adaptive traffic controller is compared with pre-timed traffic controller in term of average waiting time, queue length and Phase pattern under low, medium and high volume. From the result, it is clear that fuzzy adaptive traffic controller is more efficient and realistic than pre-timed controller.

Finally, fuzzy adaptive transit bus priority controller is also developed which is our main focus research work. A general vehicle flow is little affected as transit bus approach in the conflict phase at an intersection. While no general vehicle flow is affected when transit bus approach in green signal.

7.2 Future work

The main purpose of this reach work model is to reduce the delay of transit bus priority at signalized intersection while resides less impact on general vehicle flow. The method developed in this research work is decentralized approach and hence to optimized the delay at each intersection, traffic data are to be studied in each intersection. The influence is to be taken accordingly;

Calibrations of parameters as well as further analyses of the model are beyond the scope of this research. That should be dealt with by further studies.

The model can be further enhanced by considering multiple intersections in centralized system. The real transit bus approaching at any intersection to be monitored and controlled by GPS-base AVL (Automatic Vehicle Location) technology and installed field devices. Secondly fault occurring in transit bus detection devices at any intersection to be monitored on GUI (Graphical User Interface) window in alarm form. Thus, focusing on studies about transit bus passing through multiple intersections and fault detection in installed field deices are for future works.

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Appendix A

MATLAB function block “phases selection” C programming code

```
% Phase Selection
function [Ea,Eb,Ec,Ed,phase] = fcn(Qa,Qb,Qc,Qd,Oa,Ob,Oc,Od,P)
phase = 1;
Ea = 0;
Eb = 0;
Ec = 0;
Ed = 0;
%%Current Phase 1
    if((P==1)&&(Qa>=0)&&(Qa<15)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
      phase=1;
    elseif((P==1)&&(Qa>=15)&&(Qa<30)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
      phase=1;
    elseif((P==1)&&(Qa>=30)&&(Qa<40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
      phase=1;
    elseif((P==1)&&(Qa>=40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
      phase=1;
    elseif((P==1)&&(Qb>=0)&&(Qb<15)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
       phase=2;
    elseif((P==1)&&(Qb>=15)&&(Qb<30)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
       phase=2;
    elseif((P==1)&&(Qb>=30)&&(Qb<40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
       phase=2;
    elseif((P==1)&&(Qb>=40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
       phase=2;
    elseif((P==1)&&(Qc>=0)&&(Qc<15)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
       phase=3;
    elseif((P==1)&&(Qc>=15)&&(Qc<30)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
       phase=2;
    elseif((P==1)&&(Qc>=30)&&(Qc<40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
       phase=2;
    elseif((P==1)&&(Qc>=40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
       phase=3;
    elseif((P==1)&&(Qd>=0)&&(Qd<15)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
       phase=4;
    elseif((P==1)&&(Qd>=15)&&(Qd<30)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
       phase=4;
    elseif((P==1)&&(Qd>=30)&&(Qd<40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
       phase=4;
```

```
elseif((P==1)&&(Qd>=40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
   phase=4;
%%Current Phase 2
elseif((P==2)&&(Qb>=0)&&(Qb<15)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
   phase=2;
elseif((P==2)&&(Qb>=15)&&(Qb<30)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
   phase=2;
elseif((P==2)&&(Qb>=30)&&(Qb<40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
   phase=2;
elseif((P==2)&&(Qb>=40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
   phase=2;
elseif((P==2)&&(Qc>=0)&&(Qc<15)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==2)&&(Qc>=15)&&(Qc<30)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==2)&&(Qc>=30)&&(Qc<40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==2)&&(Qc>=40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==2)&&(Qd>=0)&&(Qd<15)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
   phase=4;
elseif((P==2)&&(Qd>=15)&&(Qd<30)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
   phase=4;
elseif((P==2)&&(Qd>=30)&&(Qd<40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
   phase=4;
elseif((P==2)&&(Qd>=40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
   phase=4;
elseif((P==2)&&(Qa>=0)&&(Qa<15)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
   phase=1;
elseif((P==2)&&(Qa>=15)&&(Qa<30)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
   phase=1;
elseif((P==2)&&(Qa>=30)&&(Qa<40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
   phase=1;
elseif((P==2)&&(Qa>=40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
   phase=1;
%%Current Phase 3
elseif((P==3)&&(Qc>=0)&&(Qc<15)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==3)&&(Qc>=15)&&(Qc<30)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==3)&&(Qc>=30)&&(Qc<40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
elseif((P==3)&&(Qc>=40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
   phase=3;
```

```
elseif((P==3)&&(Qd>=0)&&(Qd<15)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;
elseif((P==3)&&(Qd>=15)&&(Qd<30)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;
elseif((P==3)&&(Qd>=30)&&(Qd<40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;
elseif((P==3)&&(Qd>=40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;

elseif((P==3)&&(Qa>=0)&&(Qa<15)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;
elseif((P==3)&&(Qa>=15)&&(Qa<30)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;
elseif((P==3)&&(Qa>=30)&&(Qa<40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;
elseif((P==3)&&(Qa>=40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;

elseif((P==3)&&(Qb>=0)&&(Qb<15)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;
elseif((P==3)&&(Qb>=15)&&(Qb<30)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;
elseif((P==3)&&(Qb>=30)&&(Qb<40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;
elseif((P==3)&&(Qb>=40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;

%%Current Phase 4

elseif((P==4)&&(Qd>=0)&&(Qd<15)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;
elseif((P==4)&&(Qd>=15)&&(Qd<30)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;
elseif((P==4)&&(Qd>=30)&&(Qd<40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;
elseif((P==4)&&(Qd>=40)&&(Qd>Qa)&&(Qd>Qb)&&(Qd>Qc))
    phase=4;

elseif((P==4)&&(Qa>=0)&&(Qa<15)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;
elseif((P==4)&&(Qa>=15)&&(Qa<30)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;
elseif((P==4)&&(Qa>=30)&&(Qa<40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;
elseif((P==4)&&(Qa>=40)&&(Qa>=Qb)&&(Qa>=Qc)&&(Qa>=Qd))
    phase=1;

elseif((P==4)&&(Qb>=0)&&(Qb<15)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;
elseif((P==4)&&(Qb>=15)&&(Qb<30)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
```

```
    phase=2;
elseif((P==4)&&(Qb>=30)&&(Qb<40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;
elseif((P==4)&&(Qb>=40)&&(Qb>Qa)&&(Qb>Qc)&&(Qb>=Qd))
    phase=2;

elseif((P==4)&&(Qc>=0)&&(Qc<15)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
    phase=3;
elseif((P==4)&&(Qc>=15)&&(Qc<30)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
    phase=3;
elseif((P==4)&&(Qc>=30)&&(Qc<40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
    phase=3;
elseif((P==4)&&(Qc>=40)&&(Qc>Qa)&&(Qc>=Qb)&&(Qc>=Qd))
    phase=3;
end
%%Current Phase 1

if((P==1)&&((Qb>=40)||(Qc>=40)||(Qd>=40)))
    Ea=1;
elseif((P==1)&&(Oa~=1)&&(((Qb>=30)&&(Qb<40))||((Qc>=30)&&
(Qc<40))||((Qd>=30)&&(Qd<40))))
    Ea=2;
elseif((P==1)&&(Oa~=1)&&(Oa~=2)&&(((Qb>=15)&&(Qb<30))||
((Qc>=15)&&(Qc<30))||((Qd>=15)&&(Qd<30))))
    Ea=3;
elseif((P==1)&&(Oa~=1)&&(Oa~=2)&&(Oa~=3)&&(((Qb>=0)&&
 (Qb<15))||((Qc>=0)&&(Qc<15))||((Qd>=0)&&(Qd<15))))
    Ea=4;

%%Current Phase 2

elseif((P==2)&&((Qa>=40)||(Qc>=40)||(Qd>=40)))
    Eb=1;
elseif((P==2)&&(Ob~=1)&&(((Qa>=30)&&(Qa<40))||((Qc>=30)&&
(Qc<40))||((Qd>=30)&&(Qd<40))))
    Eb=2;
elseif((P==2)&&(Ob~=1)&&(Ob~=2)&&(((Qa>=15)&&(Qa<30))||
((Qc>=15)&&(Qc<30))||((Qd>=15)&&(Qd<30))))
    Eb=3;
elseif((P==2)&&(Ob~=1)&&(Ob~=2)&&(Ob~=3)&&(((Qa>=0)&&
(Qa<15))||((Qc>=0)&&(Qc<15))||((Qd>=0)&&(Qd<15))))
    Eb=4;

 %%Current Phase 3

elseif((P==3)&&((Qb>=40)||(Qa>=40)||(Qd>=40)))
    Ec=1;
elseif((P==3)&&(Oc~=1)&&(((Qb>=30)&&(Qb<40))||((Qa>=30)&&
(Qa<40))||((Qd>=30)&&(Qd<40))))
    Ec=2;
```

```
elseif((P==3)&&(Oc~=1)&&(Oc~=2)&&(((Qb>=15)&&(Qb<30))||
((Qa>=15)&&(Qa<30))||((Qd>=15)&&(Qd<30))))
    Ec=3;
elseif((P==3)&&(Oc~=1)&&(Oc~=2)&&(Oc~=3)&&(((Qb>=0)&&
(Qb<15))||((Qa>=0)&&(Qa<15))||((Qd>=0)&&(Qd<15))))
    Ec=4;

%%Current Phase 4

elseif((P==4)&&((Qb>=40)||(Qc>=40)||(Qa>=40)))
    Ed=1;
elseif((P==4)&&(Od~=1)&&(((Qb>=30)&&(Qb<40))||((Qc>=30)&&
(Qc<40))||((Qa>=30)&&(Qa<40))))
    Ed=2;
elseif((P==4)&&(Od~=1)&&(Od~=2)&&(((Qb>=15)&&(Qb<30))||
((Qc>=15)&&(Qc<30))||((Qa>=15)&&(Qa<30))))
    Ed=3;
elseif((P==4)&&(Od~=1)&&(Od~=2)&&(Od~=3)&&(((Qb>=0)&&
(Qb<15))||((Qc>=0)&&(Qc<15))||((Qa>=0)&&(Qa<15))))
    Ed=4;

end
end
```

Appendix B

MATLAB function block "time extension" C programming code

```
% time Extension
function Extension  = fcn(A,B,C,D,Ea,Eb,Ec,Ed,P)
Extension = 5;

%%Current Phase 1
if((P==1)&&(A>=3)&&(A<8)&&(Ea==1))
    Extension=25;
elseif((P==1)&&(A>=3)&&(A<8)&&(Ea==2))
    Extension=20;
elseif((P==1)&&(A>=3)&&(A<8)&&(Ea==3))
    Extension=15;
elseif((P==1)&&(A>=2)&&(A<8)&&(Ea==4))
    Extension=10;

elseif((P==1)&&(A>=8)&&(A<16)&&(Ea==1))
    Extension=30;
elseif((P==1)&&(A>=8)&&(A<16)&&(Ea==2))
    Extension=25;
elseif((P==1)&&(A>=8)&&(A<16)&&(Ea==3))
    Extension=20;
elseif((P==1)&&(A>=8)&&(A<16)&&(Ea==4))
    Extension=15;

elseif((P==1)&&(A>=16)&&(Ea==1))
    Extension=40;
elseif((P==1)&&(A>=16)&&(Ea==2))
    Extension=35;
elseif((P==1)&&(A>=16)&&(Ea==3))
    Extension=30;
elseif((P==1)&&(A>=16)&&(Ea==4))
    Extension=25;
%%Current Phase 2

elseif((P==2)&&(B>=3)&&(B<8)&&(Eb==1))
    Extension=25;
```

```
elseif((P==2)&&(B>=3)&&(B<8)&&(Eb==2))
   Extension=20;
elseif((P==2)&&(B>=3)&&(B<8)&&(Eb==3))
   Extension=15;
elseif((P==2)&&(B>=3)&&(B<8)&&(Eb==4))
   Extension=10;

elseif((P==2)&&(B>=8)&&(B<16)&&(Eb==1))
   Extension=30;
elseif((P==2)&&(B>=8)&&(B<16)&&(Eb==2))
   Extension=25;
elseif((P==2)&&(B>=8)&&(B<16)&&(Eb==3))
   Extension=20;
elseif((P==2)&&(B>=8)&&(B<16)&&(Eb==4))
........................

elseif((P==2)&&(B>=16)&&(Eb==1))
   Extension=40;
elseif((P==2)&&(B>=16)&&(Eb==2))
   Extension=35;
elseif((P==2)&&(B>=16)&&(Eb==3))
   Extension=30;
elseif((P==2)&&(B>=16)&&(Eb==4))
   Extension=25;

 %%Current Phase 3

elseif((P==3)&&(C>=3)&&(C<8)&&(Ec==1))
   Extension=25;
elseif((P==3)&&(C>=3)&&(C<8)&&(Ec==2))
   Extension=20;
elseif((P==3)&&(C>=3)&&(C<8)&&(Ec==3))
   Extension=15;
elseif((P==3)&&(C>=3)&&(C<8)&&(Ec==4))
   Extension=10;

elseif((P==3)&&(C>=8)&&(C<16)&&(Ec==1))
   Extension=30;
elseif((P==3)&&(C>=8)&&(C<16)&&(Ec==2))
   Extension=25;
elseif((P==3)&&(C>=8)&&(C<16)&&(Ec==3))
   Extension=20;
```

```
elseif((P==3)&&(C>=8)&&(C<16)&&(Ec==4))
    Extension=15;

elseif((P==3)&&(C>=16)&&(Ec==1))
Extension=40;
elseif((P==3)&&(C>=16)&&(Ec==2))
    Extension=35;
elseif((P==3)&&(C>=16)&&(Ec==3))
    Extension=30;
elseif((P==3)&&(C>=16)&&(Ec==4))
    Extension=25;
%%Current Phase 4

elseif((P==4)&&(D>=3)&&(D<8)&&(Ed==1))
    Extension=25;
elseif((P==4)&&(D>=3)&&(D<8)&&(Ed==2))
    Extension=20;
elseif((P==4)&&(D>=3)&&(D<8)&&(Ed==3))
    Extension=15;
elseif((P==4)&&(D>=3)&&(D<8)&&(Ed==4))
    Extension=10;

elseif((P==4)&&(D>=8)&&(D<16)&&(Ed==1))
    Extension=30;
elseif((P==4)&&(D>=8)&&(D<16)&&(Ed==2))
    Extension=25;
elseif((P==4)&&(D>=8)&&(D<16)&&(Ed==3))
    Extension=20;
elseif((P==4)&&(D>=8)&&(D<16)&&(Ed==4))
    Extension=15;

elseif((P==4)&&(D>=16)&&(Ed==1))
    Extension=40;
elseif((P==4)&&(D>=16)&&(Ed==2))
    Extension=35;
elseif((P==4)&&(D>=16)&&(Ed==3))
    Extension=30;
elseif((P==4)&&(D>=16)&&(Ed==4))
    Extension=25;

end
end
```

Appendix C

MATLAB function block "TSP phase selection" C programming code

```
% TSP Phase Selection
function phase   = fcn(Qe,Qf,Ophs)
phase = Ophs;
if((Qe>=1)&&(Ophs==1))
phase=Ophs;
elseif((Qe>=1)&&(Ophs==2))
phase=1;
elseif((Qe>=1)&&(Ophs==3))
phase=1;
elseif((Qe>=1)&&(Ophs==4))
phase=1;
if((Qf>=1)&&(Ophs==1))
phase=3;
elseif((Qf>=1)&&(Ophs==2))
phase=3;
elseif((Qf>=1)&&(Ophs==3))
phase=Ophs;
elseif((Qf>=1)&&(Ophs==4))
phase=3;

end
end
```

Appendix D

MATLAB function block "TSP time extension" C programming code

```
% TSP time extension
function [Extension,Green_min] = fcn(Ext,Qe,Qf,P)

Extension = Ext;
Green_min = 10;

if((P==1)&&(Qe==1))
   Extension=Ext;
elseif((P==2)&&(Qe==1))
   Extension=0;
elseif((P==3)&&(Qe==1))
   Extension=0;
elseif((P==4)&&(Qe==1))
   Extension=0;

elseif((P==1)&&(Qf==1))
   Extension=0;
elseif((P==2)&&(Qf==1))
   Extension=0;
elseif((P==3)&&(Qf==1))
   Extension=Ext;
elseif((P==4)&&(Qf==1))
   Extension=0;


end
end
```