

University of Bahrain

College of Engineering

Mechanical Engineering Department



Modeling Traffic Control Management System for Over-Saturated Signalized Traffic Intersections in Kuwait Using Artificial Intelligent Technique

Volume 1

A Thesis Submitted in Fulfillment of the Requirements for the Ph. D.
Degree in Mechanical Engineering

Submitted By:

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University of Bahrain, Bahrain

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الاعتماد من قبل لجنة التحكيم

Defense Committee's Approval

Abstract

A traffic signal is among the most important traffic control devices that are used to administer traffic flow efficiently, but it may cause congestion, if it is not well administered. Most traffic signals are controlled by either a fixed time signal or an actuated control system. Controlling an isolated traffic signal is easy especially when the demand on the intersection is below capacity, but it can be difficult when the intersection is part of a larger network. An adaptive control system is developed utilizing a fuzzy method to improve the traffic control system performance and to reduce the traffic average delay for four phases simple intersections within a grid network. Fuzzy method is a linguistic tool that can be applied to deal with complex traffic control problems providing an intelligent green time based on actual traffic flow data. The main functions of the developed control system are to accelerate the cycle time by shorting the cycle times and reducing the lost time by determining the green time for each phase based on the traffic flow. The control system was developed through four stages. The green time distribution models are designed at the first stage based on the intersection geometries. Second stage set of fuzzy rules are designed to determine the signal timing. Third stage, the system is initialized and finally, the system is executed. An Excel program and a Visual Basic language are used to design and run the developed control system. The developed control system was applied to five intersections in a simulated network in Kuwait during four different peak periods; 6:45 - 7:00, 14:15 - 14:30, 17:15 - 17:30, and 21:30 - 21:45 of Monday 11th Jan. 2016 by using the intersections geometries, average vehicle length and traffic flow from each phase. The results showed that the number of intersections' cycles remained constant during the specified peak periods, while the number of vehicles passing the various phases through the network for each tested intersection increased by 7.3%, 22.1%, 5.3% and 12.7%, respectively. The total green time necessary to pass through these phases decreased by 1.0% and 4% for two periods, while it is increased by 3.6% and 0.1% for the other two periods. This indicated that the developed control system distributed the green time based on the traffic situation. The developed control system can be applied on a simple intersection with four perpendicular phases that may consist of any of the following roadway combination: collector road, major arterial and minor arterial roads.

Dedication

To

My Mother

For teaching me how to believe in hard work and keep being strong.

My Grandmother

For being a protective soul through the tough moments.

My Friends

For their generous love through the disappointment times.

Special Dedication to my Lovely Family

For supporting and encouraging me to believe in myself.

Acknowledgment

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Glossary of Abbreviation

Symbols	Abbreviation
AASHTO	American Association of State Highway and Transportation Official
HCM	Highway Capacity Manual.
KPACI	Kuwait Public Authority for Civil Information.
MTDD	Manual of Traffic Detector Design.
MUTCD	Manual on Uniform Traffic Control Devices for Streets and Highways
Mass Highway	Massachusetts Highway Department.
MOI	Ministry of Interiors Kuwait
MPW	Ministry of Public Works Kuwait
RDM	Road Design Manual
SCOOT	Split Cycle Offset Optimization Technique
SCATS	Sydney Coordinated Adaptive Traffic System
TRUM	Traffic and Road Use Management
NCHRP	National Cooperative Highway Research Program

List of Symbols

Symbols	Abbreviation
$(L_d)_{ave}$	Average (Minimum and maximum) distance between two intersections.
V_l	Average vehicle length.
c	Capacity.
$Z_{critical}$	Critical zone.
T_{Cycle}	Cycle time.
$T_{default}$	Default time.
$^{\circ}$	Degrees.
L_d	Distance between two intersections.
E	East.
T_g	Effective green time.
T_{ϕ}	Green time.
d_g	Gridlock detector.
hrs	Hours.
ϕ	Intersection phase.
km	Kilometer.
km^2	Kilometer squared.
L	Left turn.
LOS	Level of service.
$(T_{cycle})_{max}$	Maximum cycle time.
$(L_d)_{max}$	Maximum distance between two intersections.
$(T_{\phi})_{max}$	Maximum Green Time.
m	Meter.
$(L_d)_{min}$	Minimum distance between two intersections.
$(T_{\phi})_{min}$	Minimum phase green time.
T_{min}	Minimum green time.
N	North.
$No.$	Number
n	Number of lanes.
d_q	Queue detector.
I_z	Ratio between the interval length to the length distance.
T_c	Red clearance time.
R	Right turn.
SFR	Saturation flow rate.
$Sec.$	Second.
S	South.
S_p	Speed.
ds	Stop line detector.

S_T	Straight through.
T_{Total}	Total determined green phase time.
F	Traffic flow.
D₁	Uniform delay.
U	U-turn.
Veh	Vehicle.
PR	Vehicle passing rate (vehicle/sec./lane).
veh. /hr	Vehicle per hour.
Z_q	Queue length
R	Vehicle residual.
v	Volume.
v/c	Volume to capacity ratio.
W	West.
T_y	Yellow time.
Z	Zone number.
Z_{unit}	Zone unit.

Chapter One

Introduction

1.1. Overview

1.2. Problem Statement

1.3. Research Questions

1.4. Research Objective

1.5. Research Assumption, Limitations and Constraints

1.6. Research Significance

1.7. Methodology

1.8. Structure of The Study

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Chapter One

Introduction

1.1. Overview

During the past years, the huge growth in the vehicle fleet has caused traffic congestions and delays in delivering products and services, in completing work, and all these have led to a negative impact on the economy. Traffic congestion results from different sources, exceeding capacity, poor traffic management, poor infrastructure and bad driving behavior. There are different strategies to assist in resolving the traffic congestion problem, as improving geometric characteristics to increase the intersection capacity which is the maximum rate at which vehicles can pass through the intersection under prevailing conditions (NCHRP, 2008). However, this strategy is too difficult financially and technically. Another strategy is to motivate people to change their travel system from using vehicles to walking, cycling and taking public transportation. Another strategy is to maximize the flow of traffic for a prevailing condition to near capacity by good traffic signal timing management.

Synchronization of a series of signals along a predetermined route is an effective way in improving traffic movement at the intersection. However, in over-saturated conditions, coordinated control of traffic signals become a very complex task since it involves complicated modeling and calculation processes for the network that lead to an adaptive control system. The adaptive control systems feature sufficient surveillance capability to provide a detailed profile of traffic when approaching an intersection (Gordon, 2005).

Within the context of this research it is intended to reduce the cycle time and to reduce the green lost time based on actual traffic flow. The green lost time is defined as the time (s) during which an intersection is not being effectively used by any movement, or the amount of time in a cycle, which is effectively lost to the traffic movement in the phase because of starting up delay (Davara, 2016).

1.2. Problem Statement

The world is struggling with the rapid growth of personal vehicles that has resulted in excessive congestion. The Green Mobility Report estimates that, there will be an additional 1.2 billion vehicles on the road by 2030, which is double of today's total (Pandey, 2017). Traffic congestion affects a business's operational management, energy consumption and tourism. Traffic congestion reduces human productivity and leads to delay in products and services in small and big cities. Figure 1 shows the percentages impact of the traffic congestion in the city of Dhaka as an example.

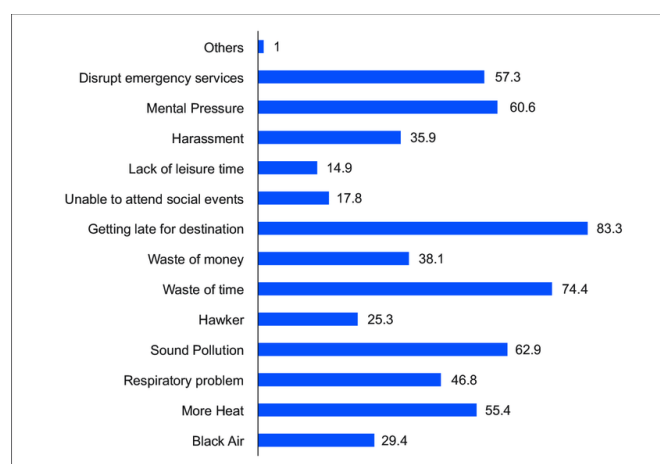


Figure (1)

Percentages of the Traffic Congestion Impacts in the City of Dhaka
(Brac, 2016)

According to Figure 1, traffic congestion has a negative impact on emergency services delaying them by more than 50%. The average impact of traffic congestion on human productivity (mental pressure and harassment) is 50%. The impact of traffic congestion on pollution, respiratory problems and black air exceeds 45%.

As shown in Table 1, the hours delayed per traveler in USA increased between 1982 and 2011 from 15.5 to 38.0 hours and the fuel consumed increased from 0.53 to 2.88 billion gallons per year.

Table (1)

National Congestion Measures, 1982 to 2011 (Schran, 2012)

Year	Delay per Commuter (hours)	Fuel Wasted (billion gallons per year)
1982	15.5	0.53
1987	25.4	1.00
1992	32.0	1.50
1997	37.6	2.02
2002	40.9	2.67
2007	42.0	3.23
2011	38.0	2.88

Thus, normal and tradition projects and programs cannot be validated to meet the demand of a growing population and the growth in vehicle fleets. The traffic congestion occurs when the intersection demand, which is the volume of traffic at an intersection approaches, exceeds the capacity. The traffic control systems can provide a variety of options to ease traffic congestion for both isolated intersections and networks when they are at below saturation and at saturation conditions.

The existing control system models can handle few intersections because they run limited numbers of intersections. Therefore, there is a need for an improved model to accommodate time-varying based on the

traffic demands for different intersection geometries, practical to use and computationally efficient to facilitate online validation.

1.3. Research Questions

Does the traffic performance improve when the cycle time is reduced?
Does the number of vehicles passing the intersections increase if the green phase time is distributed based on traffic demands?

1.4. Research Objective

The main objective of this research is to improve the performance of traffic signals by reducing the cycle time and the green lost time under real-time traffic demands when considering several oversaturated intersections within a network. This is managed through the development of an adaptive traffic control system employing an artificial intelligent system. The structure of the developed system aims to enable easy future developments in adaptive traffic control, and easy validation of a single and network of intersections with minimal changes and cost.

1.5. Research Assumptions, Limitations and Constraints

A list of assumptions, limitations and constraints are specified when designing the proposed control system. The control system is designed for unsynchronized simple intersections with four perpendicular approaches, where each approach is defined as a phase in this research. Each phase consists of three movements of vehicles (straight through, left, and right

turns). The intersections are formed by any of the following combination of road types: collector road, major and minor arterial roads within a grid network. The timing parameters (the maximum cycle time, the minimum and maximum green time, the minimum and maximum distances between intersections, and queue detector location) for these road types are used in designing the control system. These timing parameters are mentioned in detail in sections 3.2.3 and 3.2.4.

Furthermore, the control system was designed to accommodate all traffic conditions (under-saturation, saturation, and over-saturation). Emergency situations (vehicle accidents, ambulances in service, drivers' behavior and nature crises, etc.) are excluded, during the process of developing the control system. As an assumption, the system is developed based on the flow arrivals and departures in a deterministic, uniform and equal distribution of traffic on the phases' lanes. Vehicle acceleration and deceleration are not considered in the model development. The red clearance time is assumed to be equal to 2 seconds. In addition, the average vehicle length is assumed to be equal to 7 meters including space headways.

Some of the development constraints specified in designing the control system were as follow: green time should not be less than a default time limit unless the green time equals the minimum green time. The total time should not exceed the maximum cycle time. In addition, when there are no vehicle passing over the queue detector during the minimum green time, then the next phase traffic signal would not take over unless the minimum green time had ended. This is considered for safety precautions.

1.6. Research Significance

There were several strategies which were employed to solve the traffic problem, but they are not efficient, especially when used at intersections within a grid of a network, so an adaptive control system may provide an effective solution by distributing the green time dynamically based on the traffic flow. This approach may reduce the cycle and green lost time and as a result, it may reduce the vehicle waiting time and therefore traffic delay. The developed control system may help in future studies by being a starting point to build over other rules to distribute the green time based on the vehicle queues at the previous and next intersections in a series.

1.7. Methodology

The developed control system was designed by reviewing and specifying the intersection geometries, traffic control system types, and the users of the traffic system users. Green time distribution models and artificial fuzzy rules were designed based on the system assumptions and constraints. Sets of fuzzy rules are designed by using the Excel and Visual Basic language to build-up the control system.

A simulation process was applied to the control system in order to evaluate its performance and to compare it with existing traffic control systems. The data used in the simulation process was collected from different sources such as the Ministry of Planning, the General Administration of Traffic, the Ministry of Interior, the Ministry of Public works, and other resources. The developed control system is highlighted in Figure 2.

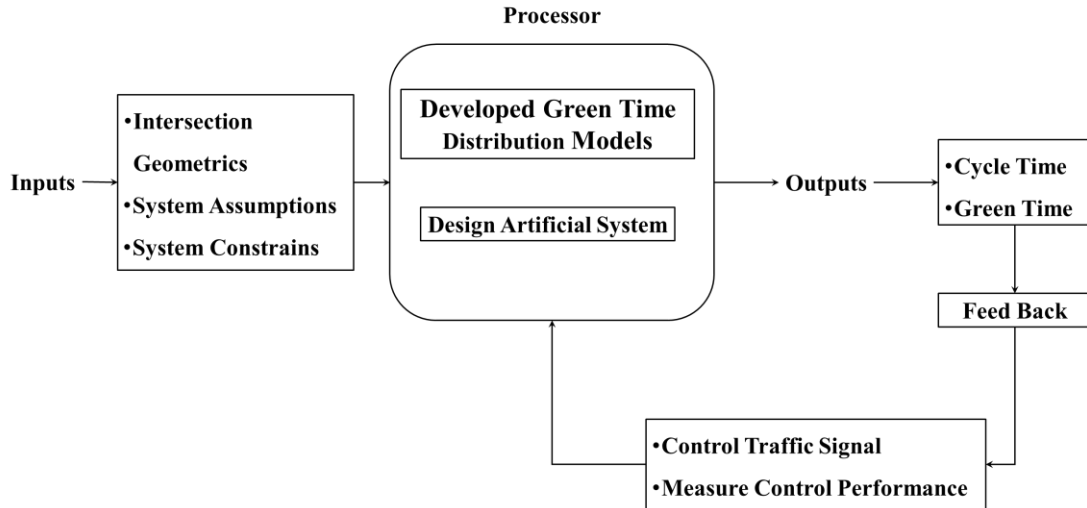


Figure (2)

Developed Control System Architecture

The intersection geometric characteristics, the system assumptions, and the constraints were used as inputs to the developed control system. Parts of the inputs were used in the development of the control system processor, while other parts were used for running the control system. Developing the green time distribution models and designing an artificial system takes place in the processor to specify the green phases and the intersection cycle times and are defined as system outputs. The system outputs were used to control traffic signals and to measure the performance of the control system. The developed control system was designed through four stages with several inputs, outputs, and steps (Figure 3). The general control system inputs were the intersections' geometries and specifications, system assumptions, and constraints, while the outputs are defined as the green and the cycle times. Each stage was designed using several steps, where each stage had different inputs and outputs and different functions.

Stage 1 was designed over 4 steps (Figure 3), to develop the green time distribution models. In step 1; the intersections' geometries and specifications (such as intersection type, road types and speeds,

intersections cycle times and phases green times, etc.) were reviewed and studied. Based on this revision, the control system's assumptions and constraints were specified in step 2. Based on the intersection of three roads' types and their different combinations, seven control system models were developed in step 3. Formulating the green time distribution models was dependent on the distance between intersections, the number of zones at each intersection phase and the road type timing specifications. Distances were specified as a system constraint and the zone length. Based on the number of zones at the intersection distances and their possible combination, eighty-one green time distribution models for each control system model were defined at step 4.

At stage 2 as shown in Figure 3, the inputs are the eighty-one green time distribution models for each of the seven-control systems, and the outputs are the green time and intersection cycle time. Two sets of fuzzy rules were further designed as step 5 from this stage; where the inputs of the first set are the distances between intersections and the output is the selection of the green time distribution model. The inputs of the second set are the vehicle queue lengths and the outputs are the selection of the phases' green times.

At stage 3, Visual Basic and Excel were used to construct a program which prepared the developed control system for running based on the designed green time distribution models and the specified artificial system. Stage 3 was designed through steps 6 to 9, as shown in Figure 3. Intersection roads' type was used as entry data in step 6 and designed fuzzy rules was applied to this data. This is followed by step 7 where one of the seven control systems were selected. In step 8, the distance between intersections was used as an input to calculate the number of zones at each phase. Then another set of fuzzy rules were used in step 9 to select one of

the eighty-one green time distribution models for the selected control system.

The main output of stage 4 was to give the traffic signals the action with the planned timing parameters. Where, the inputs of this stage are the green time distribution model, designed fuzzy rules and vehicular flow in and out. Steps 10 to 15 were designed to validate the developed control system (Figure 3). The output of stage 3 was used as an input into stage 4, in addition to the data of the vehicle flow in and out which was counted by the intersection detectors in step 10. Based on the vehicular flow, the vehicle queue was calculated in step 11 and the green phases' times were determined in step 12. In step 13, the total cycle time was calculated and based on the control system conditions and constraints, the green times are modified, and this was applied to the traffic signal in steps 14 and 15.

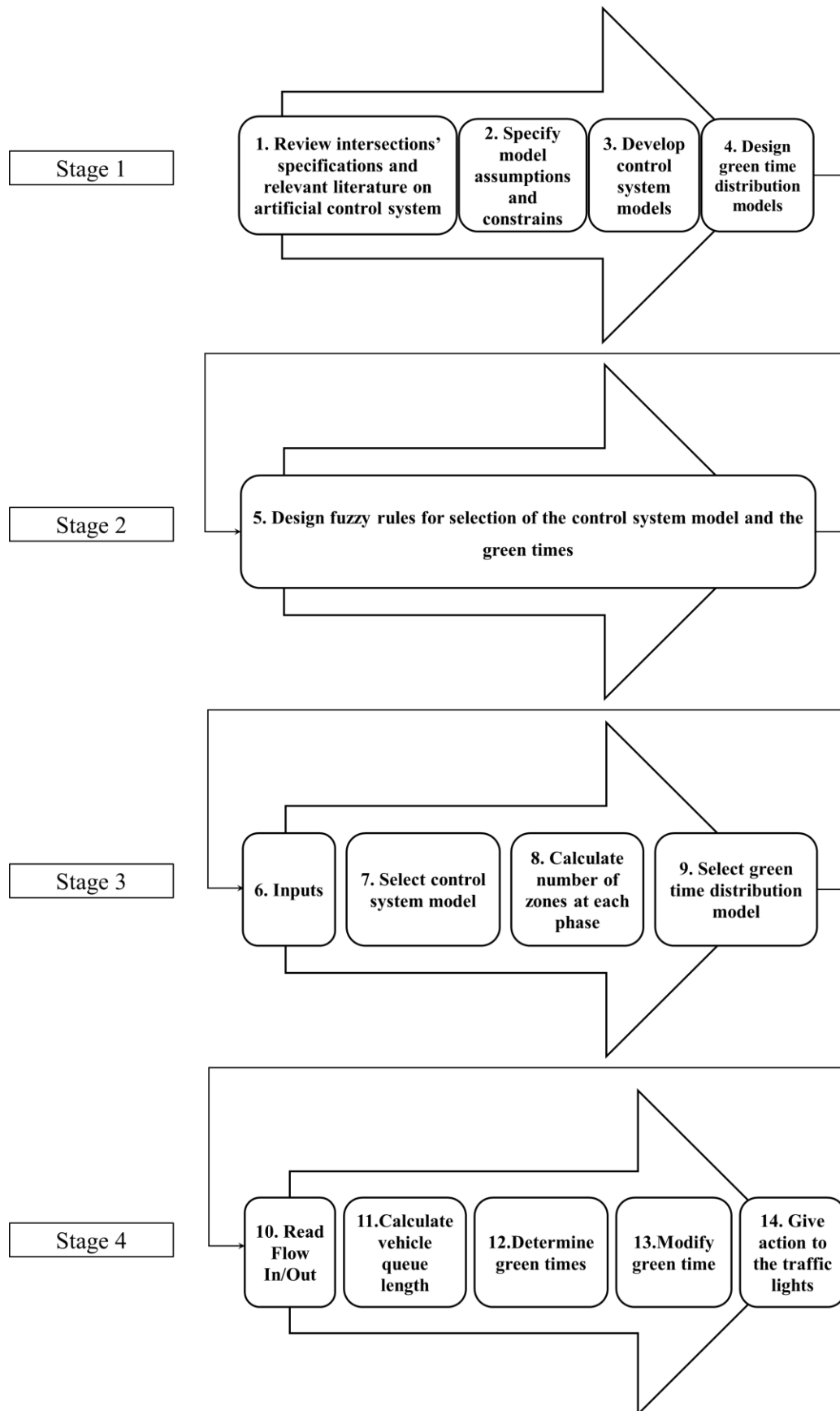


Figure (3)

Developed Control System Stages and Steps

1.8. Structure of The Study

This research consists of seven chapters, in addition to the list of references and appendices as follow:

Chapter 1: It describes the research problem, objectives, the questions to be answered, research significance and the methodology that was used.

Chapter 2: It reviews the artificial traffic control systems and the literature related to fuzzy logic.

Chapter 3: It reviews intersection geometry and layout, intersection network, control devices, timing parameters, artificial control systems and the determination of control system performance. This chapter presents an introduction to the theoretical and field studies, research population, and sample, existing intersection control system in Kuwait, proposed intersection control system and applied study.

Chapter 4: This chapter presents the description of the developed control system, starting with the overall construction and processes, a procedure of developing the green time distribution, designing the fuzzy rules and finally presents the way to run the developed control system.

Chapter 5: It discusses the validation of the developed control system using the data of the existing traffic system.

Chapter 6: This chapter presents the results and compares performance of the developed control system and the existing one.

Chapter 7: Conclusions, recommendation and further research.

1.9. Definition of Terms

Adaptive control system: Traffic adaptive control systems feature sufficient surveillance capability to provide a detailed profile of traffic approaching an intersection (Gordon, 2005).

Approach delay: Is defined as stopped-time delay along with time loss due to deceleration from the approach speed to a stop-time and the time loss due to acceleration back to the desired speed (Mathew, 2014).

Average stopped-time delay: Is defined as the average stopped delay for all vehicles during a specified period (Mathew, 2014).

Average vehicle delay: It is defined as the time delay (seconds) per vehicle for a specified time interval (TRUM, 2015).

Control delay: It is the delay caused by a traffic signal. Control delay approximates to time-in-queue delay plus the acceleration-deceleration delays. Delay measured can be stated for a single vehicle, as an average for all vehicles over a specified period, or as an aggregate total value for all vehicles over a specified period. The aggregate delay is measured in total vehicle-seconds, vehicle-minutes, or vehicle-hours for all vehicles in the specified time interval (TRUM, 2015).

Cycle time: Is the time in seconds that a signal takes to complete one full cycle of indications. Cycle time is defined as the time interval between the starting of green for one phase till the next time the green starts (RDM, 2015).

Freeways: Are arterial highways with full control of access having the capacity for high speed and high-volume traffic movements over long traffic movements, over long distances, in an efficient and safe manner (RDM, 2015).

Fuzzy control systems: Fuzzy control strategies come from experience and experimental observations rather than from mathematical models and, are therefore, linguistic validations are much faster accomplished. Fuzzy control strategies involve many inputs, most of which are relevant only for some special conditions. Such inputs are activated only when the related condition prevails (Simoës, 2016).

Green time: Is defined as the duration of the green indication for a given movement at a signalized intersection (Gordon, 2005).

Intersection capacity: Is defined as the maximum rate at which vehicles can pass through the intersection under prevailing conditions (NCHRP, 2008).

Intersection demand: Is defined as the volume of traffic at an intersection, approach, or movement (NCHRP, 2008).

Intersection geometry and layout: Is defined as being primarily composed of the alignment of the legs; width of traffic lanes, bicycle lanes, crosswalks, sidewalks on each phase, number of lanes, median and street side elements; and the method of treating and channelization of turning movements (Bochne, 2010).

Intersection phase: Is defined as the part of the signal cycle which is allocated to any combination of traffic movements which is receiving the right-of-way simultaneously during one or more intervals (Gordon, 2005).

Level of service: Is defined as a qualitative measure describing operational conditions within a traffic stream, based on service measures such as speed and travel time, freedom to maneuver, traffic interruptions, comfort, and convenience (Dne, 2012).

Lost time: Is defined as the time during which the intersection was not effectively used by any movement, or the amount of time in a cycle

which was effectively lost to the traffic movement in the phase because of starting delay (Davara, 2016).

Overflow delay: Is defined as the additional delay that occurs when the capacity of an individual phase, or series of phases, is less than the demand or arrival flow rate (Mathew, 2014).

Queue length: Is defined as the physical space that vehicles occupy, while waiting to proceed through an intersection (NCHRP, 2008).

Stopped delay: It is the time while a vehicle waiting in a queue to pass through the intersection. It begins when the vehicle was fully stopped and ends when the vehicle began to accelerate (Mathew, 2014).

Traffic intersection: Is defined as an area where two or more streets join or cross each other at-grade. It includes the areas needed for various mode of travel: pedestrian, bicycle, motor vehicle, and transit. It includes the adjacent sidewalks and pedestrian curb cut ramps. The intersection is defined as encompassing all alterations to the otherwise typical cross-sections of the intersecting streets (MassHighway, 2006).

Travel delay: Is defined as the difference between the actual time taken and the driver's expected travel time through the intersection (Mathew, 2014).

Chapter Two

Literature Review

2.1. Artificial Control Systems

2.2. Fuzzy Systems for Traffic Signals

2.3. Example of Existing Systems (SCATS and SCOOT)

2.3. Commentary on Literature Review

Chapter Two

Literature Review

2.1. Artificial Control Systems

The artificial intelligent concept combines the objective knowledge, formula and equations, and the subjective knowledge, linguistic information, to assist solving traffic problems. Fuzzy and neural are the most famous artificial traffic control systems and both are used to improve the traffic situation and to increase traffic capacity. One difference between the two methods is that the membership functions of a fuzzy classifier are initialized in a state close to the correct solution while a neural network is initialized in a random state. Thus, the training of the computer to optimize the classifier is much faster with a fuzzy than that with a neural network classifier. The problem with a fuzzy system is that this system struggles to deal with too many features, membership functions, and rules. Neural networks are highly suited for large amounts of features and classes. In this study, the fuzzy system was used to develop the traffic control system, this is due to its ability to process various data, vague and uncertain inputs of the system, and provide results that are suitable for decision making. Fuzzy logic can incorporate human knowledge and experience to respond quickly in unknown environments, adapt conditions and an ability to involve decisions with incomplete information, complex equations, and non-linear processes. It allows for the manipulation of linguistic data (large, medium, and small) and imprecise, as a useful tool in the design of the intelligent traffic control system.

Fuzzy control systems come from experience and experiments rather than from mathematical models and, therefore, linguistic validations are much faster accomplished. Fuzzy control strategies involve many inputs,

most of which are relevant only for some special conditions. Such inputs are activated only when the related condition prevails (Simoes, 2016) and a fuzzy control system can be a powerful tool. Its advantage is, it can deal with complex problems of traffic signal control in a straightforward way that provides an intelligent green phase time response based on dynamic traffic load inputs. A fuzzy control system is proposed to overcome the ineffectiveness of expected traffic controllers, which have a fixed cycle time, regardless of dynamic traffic load. This system can be validated in hardware, software, or a combination of both.

The fuzzy logic control system consists of three components; fuzzification, fuzzy control decisions block, rule matrix and fuzzy inference engine, and defuzzification (Figure 4).

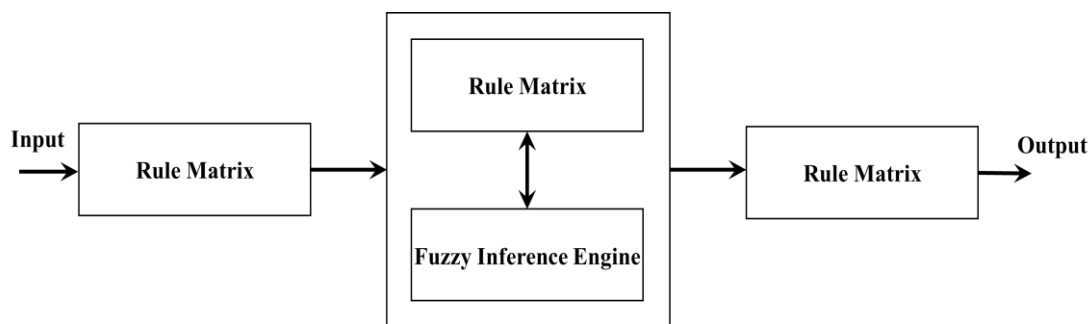


Figure (4)

Fuzzy Logic Control System Components

Fuzzification is a component where the fuzzy logic process starts sending input parameters to a fuzzy system based on the type of output result that will be calculated. These input parameters are fuzzified by using pre-defined input membership functions $\mu(x)$. There are several types of the membership function, but the simplest and widely used is a triangular shape membership (Figure 5).

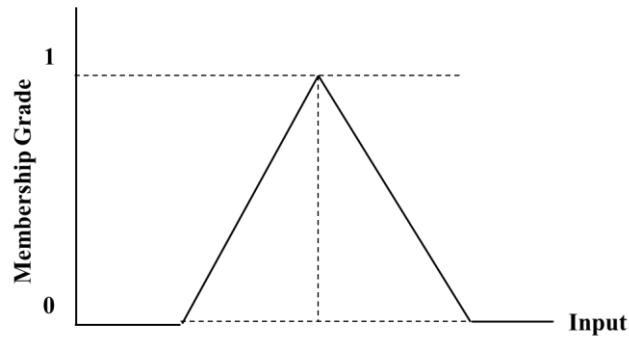


Figure (5)

Triangular Membership Function

The x-axis of the membership represents a chosen input variable, and y-axis presents quantification of the grade of membership of the input variables. For each input parameter, there is one related membership function. Fuzzy membership function must vary between zero (0) which means that the input variable is not a member of the fuzzy set and one (1) which means that the input variable is fully a member of the fuzzy set (Zhao, 2002). The membership functions give the inputs and effective rules a value and assists in weighing these values. These weighting factors determine the degree of membership each active rule has, by calculating the logical product of the membership weights for each active rule, a set of fuzzy output response magnitudes are produced.

The fuzzy control system decisions block is a component where the fuzzy control system uses fuzzy equivalents of logical AND, OR and NOT operations to build up fuzzy logic rules. It consists of rule matrix and fuzzy inference mechanisms. Rule matrix is used to describe the fuzzy sets in the form of a conditional statement, where a single fuzzy can be written as: if x is A then y is Z. A is a condition that should be satisfied, and Z is a consequence that can be indirect. If the rule has multi parts; then fuzzy operators are used to combine more than one input: AND = min, OR = max and NOT = additive complement. The fuzzy inference mechanism is used

to allow mapping a given input to an output using fuzzy logic. It uses membership functions, logical operations, and if-then rules.

Defuzzification is the last component in the fuzzy logic control system, where one single value that summarizes the fuzzy set is defined. The most common defuzzification techniques are as follows: centroid, provides center of the area under the curve of membership function, bisector, uses a vertical line that divides an area under the curve into two equal areas, mean of maximum, uses the average value of the combined membership function outputs, and largest of maximum, uses the maximum value of the combined membership function outputs(Figure 6).

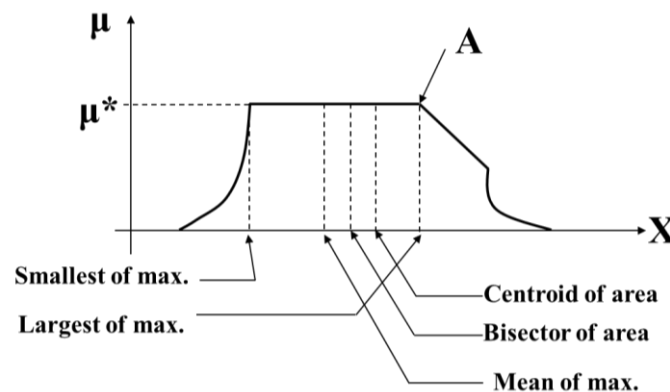


Figure (6)

Graphical Demonstration of Defuzzification Methods

2.2. Fuzzy Systems for Traffic Signals

Some researchers have developed fuzzy control systems, which are a powerful processing tool to deal with the complex problems of traffic signal control in a straightforward manner. The fuzzy control system provides an intelligent green phase time response based on dynamic traffic load inputs. The fuzzy control system can be used to model an expert's thinking in situations where the development of a mathematical model can

be very difficult. On the other hand, fuzzy logic allows for efficient use of defective information to reduce the complexity of control systems and can be implemented in hardware, software, or a combination of both. The following literature review presents some researchers that have developed fuzzy control systems to improve intersection management.

Madhavan and Cai (2007) proposed a fuzzy traffic control system to control flows under normal and unexpected traffic situations for a simply isolated intersection with four phases and three lanes at each phase with three vehicle movement strategy. The developed system receives information from sensors that are placed at incoming and outgoing lanes to make optimal decisions and to minimize the delay. A simulator has been developed using MATLAB with a fuzzy logic toolbox to evaluate the performance of the fuzzy system under different conditions. The fuzzy system showed better performance in normal conditions and had a similar performance in normal conditions with an existing control system.

Whereas, Vonglao (2007) proposed a fuzzy logic system to calculate the finest green time for each intersection phase for four intersections with three types (simple with three approaches, four approaches, and roundabout with three approaches) in a network at each cycle based on the traffic density. Mixed models with maximum likelihood estimation and the Bayesian inference were used to estimate traffic intensity. Algorithm based on Expectation Maximization algorithm, Markov Chain, Monte Carlo algorithm, queuing generation and fuzzy logic was established to calculate the green phase time by using Fortran language as a computer program. The cost function was calculated by a queuing system to evaluate the efficiency of the traffic controller. The results showed that the traffic signal timing was longer than the predictable controller traffic signal timing.

Thus, the developed control system was more efficient than a predicted controller.

Fahmy (2007) proposed a fuzzy logic control system for a roundabout with four approaches' intersection to extend or terminate the signal phase and to select the sequence of next phases based on the flow that was detected at the input of the fuzzy controllers and was converted into fuzzy values. A comparison between the performance of the fuzzy control system and the existing control system had been done. The performance analysis showed that the total waiting time in the developed control system was low compared when with the actual system.

Abbas et al. (2009) developed a fuzzy logic control algorithm to control traffic signals for traffic on oversaturated isolated simple intersections with the integration of right and left turns. The developed control system was used to decide whether to extend the current green time or terminate it based on a set of fuzzy rules and real-time traffic information. It also controlled the continuous and safe flow of emergency vehicles by extending the green phase time.

Rahman and Ratrout (2009) presented a comparison between a fuzzy logic controller network for a simple isolated intersection with four phases using traditional traffic control system. The result showed that the traffic performance of the fuzzy controller had better performance than traditional traffic signal controls, specifically during heavy or uneven traffic volume conditions.

Zarandi and Rezapour (2009) proposed a fuzzy signal control system for the T- isolated intersection with two-way streets and left turn lanes. The proposed system consisted of fuzzy phase selector and fuzzy green phase extender which helped in choosing decisions based on the fuzzy rules and real-time traffic information. The phase selector worked on the sequence

level and was used to determine the next green phase, while the green extender belonged to the green extension level of this multi-level signal control system and used to decide whether to extend or terminate the current green phase. The performance of the proposed system was evaluated by using simulation methods. The result of comparing the FSCS system with pre-timed control system showed significant improvement over pre-timed control strategy.

Andrade et al. (2010) designed a fuzzy control system for both isolated and arterial network intersections to control the green phase time and the average cycle time for each intersection. Furthermore, the authors studied the impact of controlling the isolated intersection on the intersections network without adding any special requirements to that type of operation. Three traffic performance, namely, average delay per vehicle, the percentage of stops, and some stops per vehicle were evaluated and used to measure the developed control system performance.

Soh et al. (2010) developed a fuzzy control system for an isolated simple signalized intersection, with four phases that have two lanes in each phase, based on the waiting time and vehicle queue at the green phase time and the vehicle queue at other intersection phases. This system was developed using MATLAB software based on M/M/1 queuing theory to control traffic signal timing and phases' sequence and to reduce waiting time, traffic delay, and queue length. A comparison between the developed control system and the tradition method showed that the developed system had a higher performance in controlling the flow.

Askerzade and Mahmud (2011) developed a fuzzy logic traffic control system to compute the optimal extension time to be added to the fixed control time for simply isolated intersection with four phases, concerning the situation of its backward and forward closest intersections.

The fuzzy logic toolbox in the MATLAB was used to simulate the developed control system.

Barzegar (2011) developed an artificial intelligent fuzzy control system for selected isolated intersections with only two directions. They were connected to the main road to minimize the stop time based on vehicle congestion, which has a small processor giving time for passing vehicles in each intersection phase and processing them either to change the traffic situation or not. CPN tool and C+ programming language were used to measure the developed control system performance.

Mehan (2011) proposed fuzzy traffic control system for a four phases simple intersection. Traffic density and vehicle queue obtained using image-processing techniques were used as control system inputs. So, the green, yellow and red times were adjusted as per the actual situation to improve the capacity and reduce the intersection delay. The fuzzifier, the fuzzy rule base formulated by human experts, the fuzzy inference engine and the defuzzifier, are components of the proposed system.

Ma et al. (2012) proposed a multi-phase fuzzy control system of four phases simple intersection. They implemented the integration of the multi-phase control and incorporated genetic algorithm into a fuzzy control design to optimize fuzzy membership functions based on traffic condition at different times. The proposed control system was flexible and could be applied to different traffic states.

Zang et al. (2012) developed an artificial intelligent fuzzy control algorithm system for a multi-phase simple signalized intersection. The developed control system helped in making full use of green time through optimizing green extension time and phase sequences by having two units, one was for optimizing green extension time of the current phase, and the other for choosing the sequence of the next phase based on the vehicle

queue. The proposed control system was evaluated by a simulation based on an actual traffic data that implemented under different traffic conditions.

Kuang and Xu (2012) proposed a transit-priority fuzzy neural network control system for simple four phases isolated intersection to reduce traffic delays. The proposed system was divided into two states, the special transit-priority which signified the absolute priority, and the normal transit-priority which reflected the relative priority. The developed control system increased the green time of a special phase that has a red signal and has a special vehicle's arrival. Once the special vehicle had passed through, the selection of the following phase will be based on the normal-transit-priority.

Mwangi et al. (2012) proposed a fuzzy logic control system, to control traffic signal timing and phase sequence to ensure smooth flow, to decrease delays, and to increase the capacity of the isolated roundabout intersection. The developed control system decided whether to extend or to terminate the current green phase, besides selecting the appropriate phase sequence based on the traffic data that was collected from upstream and downstream detectors. The effectiveness of the fuzzy controller that controlled the flow was tested by MATLAB software.

Zade and Dandekar (2012) developed a fuzzy inference traffic control system to control the traffic green time based on traffic density and flow rate. The developed control system reflected two parts of a traffic signal control, the observation of an on-going traffic situation around the intersection, and the control of the traffic signals in a manner appropriate to the observed situation. The system has been developed in SIMULINK environment of MATLAB tool which has reached the suitable results for traffic signal control.

Letia and Cuibus (2012) developed a fuzzy control system with the aim of getting the optimal control decisions to improve the control performance for fixed order intersection phases and fixed offsets between intersections in the network. Ranked styles were chosen to reduce the number of logic rules for different methods. The genetic method was used to obtain the fuzzy rules that would extend green phase time. The control rule sets, the simulations result, and their comparison were given for some methods.

Hou et al. (2012) developed a fuzzy traffic control system with full countdown function to solve the randomness problem and to control the green time by predicting the traffic data for a simple four phases intersection. The developed system provided a time distribution by studying and analyzing the flow through a mathematical statistic. A simulation of the developed system showed that the fuzzy system improved the controller performance and reduced the waiting time during a saturation situation.

Royani et al. (2013) applied a fuzzy neural network on a real-time traffic signal at an isolated simple four phases intersection with expert knowledge to improve the traffic control of fluctuating traffic volumes in oversaturated and unusual load condition, also, to improve the vehicular throughput and minimize delays. A genetic algorithm was applied to adjust the developed control system parameters by the learning process.

Khan and Lai (2013) used a fuzzy logic and image processing technique to propose an artificial intelligent traffic signal controller. A fuzzy logic control had been implemented on two traffic signals situated at a T-junction to provide the characteristic of intelligence to the system. The process was linked to the fuzzy logic controller to generate a unique output

for each input pattern by using the image process and fuzzy logic toolboxes of MATLAB to control the traffic lights.

Zhou et al. (2013) proposed an adaptive traffic control system for a simple four phases intersection, in which the sequence of traffic signals could be adjusted dynamically by the real-time traffic data and the traffic signal length by using wireless sensors.

Pour et al. (2013) introduced a multi-objective algorithm model to optimize the timing of traffic signal of an individual two-phase intersection with T-type, which minimizes the total traffic queue and pedestrian delays. A fuzzy traffic signal controller was used to optimize the control of fluctuating traffic volumes in oversaturated or unusual load conditions. Furthermore, fuzzy theory was used to consider the uncertainty in the real world and the entrance and exit rates of an intersection. Moreover, authors introduced a new defuzzification method to solve traffic problem and for more accurate calculation. Eventually, the performance of the introduced defuzzification method was compared with the centroid point defuzzification method by using ANOVA, it is the weight relative deviation measure.

Stotsko et al. (2013) developed and implemented a fuzzy algorithm traffic control system for a simple isolated intersection based on the existing traffic conditions by MATLAB software. The simulation results showed that the developed fuzzy algorithm is reduced the average and maximal vehicle queue before the intersection owing to the adaptation of control system parameters to traffic volumes.

Ng et al. (2013) reviewed and summarized the artificial intelligent systems methods which included computational intelligence, agent-based, and Petri nets, and they discussed the feasibility of these control and artificial intelligent systems.

Chao and Chen (2014) proposed a traffic control system based on radio frequency identification detection and ZigBee wireless network communication technology for network intersections. They designed an extension algorithm. Sensors were used to analyze the traffic information and to control the flow. The developed control system can perform remote transmission and reduce traffic accidents. Furthermore, it can effectively control the flow while reducing delay time and maintaining the smooth flow of traffic.

Alam and Pandey (2014 (a)) designed an artificial intelligent traffic signal system for isolated T- intersection and a 3-way intersection with a free left turn using a fuzzy logic, that is available with MATLAB and based on congestion estimation that is measured by sensors placed in each lane. The software was developed to simulate the situation of traffic and to analyze the controller efficiency based on waiting time, density and cost. The results showed that the fuzzy system performance was better than the fixed time or actuated control systems.

Alam and Pandey (2014 (b)) developed an advanced traffic control system for simple isolated intersection with four phases using fuzzy logic to extend green time. The developed system is performed according to linguistic rules. MATLAB was used to simulate the situation of an isolated intersection based on estimating congestion. Simulation results indicated that advanced traffic signal system had the potential to improve traffic in the intersection. It also showed that the system could reduce traffic congestion and avoid lost green time.

Kulkarni et al. (2014) designed an adaptive control system based on a new traffic infrastructure using wireless sensor network and dynamics techniques to control the flow sequences for simple isolated intersection with four phases and networks. Simulation system had been proposed to

measure the developed system performance based on the waiting time and average vehicle queue on the single intersection and thus, in turn, efficient network flow control on multiple intersections.

Mahesh et al. (2014) designed and simulated an artificial intelligent traffic signal controller based on the Neuro-fuzzy method by using MATLAB on field programmable gate array to provide variation in green cycle intervals based on the heavy traffic loads, which changed at every lane in a four phases intersection control. This controller had the capability to reduce delays at the intersection.

Yan (2014) proposed a two-stage traffic signal control method based on traffic urgency degree according to two-stage fuzzy inference on single four phases simple intersection. The traffic urgency evaluation module was used to calculate traffic urgency degree for all red phases at the first stage, in addition, to select large traffic urgency as the next phase to switch. At the second stage, green delay of the existing green phase was determined by fuzzy inference based on the number of vehicles of current green phase and next green phase. The average vehicle delay was used to evaluate the performance of the fuzzy signal controller. Simulation and comparisons are performed with the pre-timed controller and fuzzy logic controller without considering the urgency of red phase.

Sayyed et al. (2014) designed an artificial intelligent traffic signal controller by having specific functions with hardware interface and fuzzy rules for four phases simple intersection. The first part of the program consisted of data collection, sorting, calculation of percentage and to use them for automatic evaluation of signal time. The second part is a web application that was designed to provide traffic alerts for road users and take measures to avoid congestion. This system aimed to save a large amount of waiting hours caused by traffic gridlocks.

Jha and Shukla (2014) developed a traffic model and traffic controller using MATLAB software based on queuing theory model for a multi-phase's intersection with two lanes in each phase. The developed controller was based on the waiting time and vehicle queues at present green phase and vehicles queues at the other lanes. The developed controller is simple to construct using SIMULINK model, fuzzy inference system method, sim event toolbox and fuzzy toolbox in MATLAB. The fuzzy logic traffic controller had emergency vehicle alert sensors, which detected emergency vehicle movement, and gave maximum priority to pass the preferred signal.

Sandhu et al. (2015) implemented an intelligent-agent traffic model to control the amount of time a signal runs green based on vehicle density for the simple four phases intersection. The developed model smoothed the flow and reduced unnecessary delays.

Caselli et al. (2015) developed a swarm-based traffic signals control system where each intersection controller makes independent decisions to improve the traffic performance of the network intersections. The control method is divided into macroscopic and microscopic control levels that react to the congestion length and the traffic density, and acts on the choice of the signal program or the development of the frame signal program. The simulation results showed that the proposed approach performance is like the fully actuated one and the system performance does not degrade depending on the percentage of detectable vehicles.

Yasar and Rashid (2015) developed an artificial intelligent dynamic traffic signal control system with the support of artificial neural networks algorithm for a simple four phases intersection. A program has been developed using a popular programming platform to calculate drive orders for traffic signals. Road traffic simulation software has been used to verify

the application output. The decision-making algorithm has been designed to respond to certain traffic situations.

Mittal et al. (2015) proposed an innovative algorithm to measure the arterial performance by tracing the traffic density on the road to maximize traffic amount and minimize average waiting time at a simple isolated intersection. The advantage of the developed system was that travel time errors could be self-corrected with the signal status data by matching differences between current and updated images, and then deciding on the timings of traffic signals. The efficiency of proposed method was evaluated by using MATLAB, JAVA and LabVIEW software. The proposed algorithm can do better decision-making to manipulate the timings of traffic signals, and it was effective in terms of improving the moving time and reducing waiting time for the control of the traffic signals to reduce road congestion.

Wen et al. (2015) proposed an artificial intelligent traffic signal control system based on fuzzy logic controller and non-dominated sorting-based genetic algorithm. The fuzzy logic system was used to model nonlinear systems, and it was implemented to optimize both the fuzzy rules and the membership function parameters, as it can optimize multiple objects simultaneously when compared with other evolutionary algorithms. The proposed method was applied to a six-intersections traffic network, different traffic scenarios were simulated and compared with each other and the results revealed that the proposed control system was characterized by better performance than the other methods.

Shah et al. (2015) proposed a traffic control system using wireless sensor network to monitor and measure the vehicle number and road speed in real time for a simple four phases intersections. The control system was developed to eliminate the phase time when vehicles are passing across,

and to reduce waiting times. The simulation process showed a high performance of the developed control system.

Jina et al. (2016) introduced a fuzzy artificial intelligent traffic signal control system for an isolated four phases simple intersection. The developed control system was programmed with a capability to receive messages from the signal controller during real-time operations. Results showed that the developed control system has the potential to improve traffic mobility due to its ability in generating flexible phase structures and making timing decisions. A microscopic traffic simulation framework was developed to evaluate the developed control system.

2.3. Example of Existing Systems (SCATS and SCOOT)

Advanced traffic control systems have been recognized as advanced technology used in large cities in the developed and the developing countries to ease traffic congestion using real time data. The Sydney Coordinated Adaptive Traffic System (SCATS) and Split Cycle Offset Optimization Technique (SCOOT) are the most widely deployed adaptive traffic control systems worldwide. Under the SCATS, the timing of the signals is administrated by a computer-based control logic. The system can modify signal timings on a cycle-by-cycle basis using traffic flow information collected through the detector at the stop-line of the intersection. The system uses to minimize stops, minimize delay and maximize throughput. SCOOT is a cyclic, parametric, centralized, traffic-responsive signal control system. The main philosophy of the SCOOT traffic signal control system is to react to changes in observed average traffic demands by making frequent, but small, adjustments to the signal cycle time, green allocation, and offset of every controlled intersection. It

responds automatically to traffic fluctuations. It continuously measures traffic volumes on all approaches of the various intersections within a network and changes the signal timings to minimize a Performance Index (PI), which is a composite measure of delay, queue length and stops in the network.

Wang et al. (2012) proposed C-means clustering algorithm to evaluate the importance of intersections in traffic network and to determine the key intersections based on three indexes instead of just on traffic counts in traditional methods. In addition, the improved network community discovery method is used to give more reasonable evidence in traffic control subarea division. A hardware-in-loop simulation environment composed of regional traffic control system, microsimulation software and signal controller hardware are built to test the effectiveness of network analysis approach. Both the traditional method and proposed approach are conducted by SCOOT system and VISSIM simulation software to evaluate traffic operation performance indexes, for example, travel time, stop times, delay and average vehicle speed based on real traffic data. Simulation results showed that the proposed network analysis approach improved the traffic control system operation performance effectively.

Christian et al. (2013) installed SCATS on 4000 traffic signal-controlled sites on the road network to demonstrate the indicative travel, environmental and economic operational value that the SCATS intelligent transport system offers to individual road customers. These sites include instrumented: intersections, roundabouts and motorway ramps. The analysis covers 24 hours of a key arterial corridor on the North Shore of Sydney, Australia. The study compared a base scenario demonstrating SCATS to a contrary scenario. Performance metrics analyzed include: travel time, stops and pollution effects. The results indicated that across the

network for 24 hours there was an overall benefit for all performance metrics. Improvements were shown in travel time and stops cross individual road customers and road customers grouped by trip. Results showed that SCATS deliver road customers broad traffic performance improvements in both magnitude and reliability across the road network and across their differing characteristic trips through that network.

Koorey et al. (2015) investigated the scope for reducing trip time variability associated with incidents by using micro-simulation (S-Paramics) to model incident detection and response in a part of the network. The effect of blockages on the motorway or an adjacent arterial road were evaluated with and without mitigation by modifying the SCATS arterial road signal coordination plan, using variable message signing and allowing motorway traffic to use the hard-shoulder. From the results, it was found that the reductions in the variability of trip times, as a result of implementing mitigation options, were much larger than the reductions in mean trip times.

Shyamu and Raviraj (2017) designed looks of the net of Things (LoT) based intelligent transportation systems to integrate an adaptive system as Split Cycle Offset Optimization Technique (SCOOT) and Secured automotive communication. The looks of the net of Things (LoT) provides a replacement trend for intelligent traffic development. This analysis proposes to use the LoT, agent and alternative technologies to boost traffic conditions, relieve the traffic pressure and to minimize the sum of the average queues in the area. Through collected period traffic information, the system will acknowledge current traffic operation, traffic flow conditions and might predict the longer-term traffic flow. The system could issue some latest period traffic info that helps drivers selecting optimum routes by monitoring and managing moving vehicles. The system

continuously measures traffic volumes on all approaches of intersections in the network and changes the signal timings to minimize a Performance Index (PI) which is a composite measure of delay, queue length and stops in the network using the SCOOT control system and secured automotive system. The simulations results showed that the planned traffic system supported some important following features using SCOOT and Secured Automotive Communications. In addition, the system improves the flow of vehicles throughout town.

2.4. Commentary on Literature Review

This chapter covers the application of artificial intelligence (fuzzy) to control and manage traffic systems. It has been observed that the implementation of fuzzy systems in terms of controlling transportation facilities has a substantial impact on traffic levels. Although traffic control systems still have some limitations, future research has highlighted the promise for smart traffic control systems. Researchers are investigating methods to overcome these limitations to make the control systems completely efficient. From the previous review, the following conclusions can be made: Traffic fuzzy systems have different patterns, which are often recurrent; improving flow rate, forecasting traffic capacity, controlling phase selection, and controlling signal timing; Most of the researchers have used Mamdani type inference and are reliant on historical data to compare between the proposed and existing systems; many researchers work at the control of an isolated intersection with fuzzy control method (Madhavan and Cai (2007), Abbas et al. (2009), Zarandi and Rezapour (2009), Andrade et al. (2010), Soh et al. (2010)); however, there has been considerably less research on simple isolated intersections (Askerzade and

Mahmud (2011), and Mehan (2011);or on a roundabout intersection (Fahmy (2007), and Mwangi et al. (2012)).

Furthermore, some of researchers have focused on T-intersections (Vonglao (2007), Zarandi and Rezapour (2009), and Zang et al. (2012)) or two-way intersections (Zarandi and Rezapour (2009), and Zaied and Alothman (2011)). Regardless of the intersection type few researchers have applied fuzzy logic system to the coordinated control of arterial or area traffic.

The results showed that the traffic performance of Fuzzy Logic Traffic Control Systems has better performance than traditional traffic signal controls, specifically during heavy and uneven traffic.

Adaptive control systems such as SCOOT and SCATS are a flexible, powerful, expandable and yield unprecedented monitoring and management possibilities for traffic control systems. They are used to determine the cycle lengths, offsets, splits, and to measure the performance. SCOOT and SCATS are popular in advanced countries, but such systems cannot cope up with some situations without adaptation to the traffic scenario.

The expected benefit from SCATS comes from its ability to constantly modify signal timing patterns to most effectively accommodate changing traffic conditions. The reductions in the variability of trip times, as a result of implementing SCATS models are larger than the reductions in mean trip times. While the potential benefits from this control structure may be significant, the main criticisms of SCATS are: it lacks user-friendly interface features to support day-to-day operations and programming tasks; the error messages are not easy to translate and do not provide the opportunity for corrective actions by system operators; and it is very costly.

SCOOT has three optimization procedures by which it adjusts signal timings: split optimizer, cycle time optimizer and offset optimizer. SCOOT systems can be linked to other traffic management and control systems such as: variable message signs, emergency green wave routes, fault identification and management, diversions, fixed time plan, green confirmation and manual control. The main limitations of SCOOT are inability to handle closely spaced signals due to its detection configuration requirements, interface is difficult to handle and primarily designed to react to long-term, slow variations in traffic demand, and not to short-term random fluctuations.

Both SCOOT and SCATS have limitations as mentioned earlier, which led to develop perception towards designing a new controlling system that controls green and cycle times in the absent of the offset, flexible, powerful, expandable that can be apply to all traffic scenarios with less cost. Furthermore, it supports day-to-day operations and programming tasks. To be more specific, the proposed system can control intersections with short and medium distances and does not highly affected by detectors locations.

Chapter Three

Intersection Review and Existing Control System

3.1. Background

3.2. Intersection Review

3.3. Existing Traffic Control System in Kuwait

3.4. Research Population

3.5. Sample Data

Chapter Three

Intersection Review and Existing Control System

3.1. Background

Intersections are controlled by a traffic signal system which assigns the right of the way to one vehicle movement or several non-conflicting vehicle movements at any one time. The right of way is assigned by turning on a green signal for an effective green time and ended with yellow time and red clearance time followed by the display of a red time. The control system specifies the duration of the green phases time either by fixed plans or an adaptive operation based on the actuated traffic situation. The control system developed during this research is based on intersection geometries and specifications, where an artificial system is designed to run the developed control system based on the system assumptions and constraints. This chapter presents the intersections geometry, layout, network types, in addition to existing traffic control devices and systems.

3.2. Intersection Review

Intersection geometry and layout is mainly composed of the arrangement of the intersection phases; width of traffic lanes, bicycle lanes, crosswalks, and sidewalks on each phase number of lanes, median and street side elements; and the method of treating and channelization of turning movements (Bochne, 2010). Each intersection is defined by a name where there are different ways to label and name the intersection based on the traffic system for each country. Additionally, each country has a specific strategy when designing timing plans and control systems that are

affected by intersection phases and phasing, intersection types, and intersections road types.

3.2.1. Intersection geometry and layout

Intersections are defined as consisting of a different number of phases with different intersected angle between these phases; the most common traffic intersection consists of four phases with 90° intersected angles. Traffic intersection complexity increases as the number of phases increases. Intersection phasing is the order and sequence of intersection phases, South, North, East, and West to be served with three vehicle movements; Straight through, right, left and U-turn. Where the vehicle movement can be either a single movement or a combination of different vehicle movements of different intersection phases that occur at the same time.

Intersections with four phases are categorized based on their lane number, and intersection shape, where the most common types are; simple, flared, skewed (channelized), and roundabout intersections. At a simple intersection, the number of lanes at all phases are constant and this type is suitable for the locations where turning lanes are not needed. The flared intersection is an intersection where the turn lane has an expanded cross section to increase capacity at high traffic volume locations, and safety at a higher speed. Skewed (channelized) intersections are an intersection where the channelized islands are used to outline right turn and it is used to support the right turn lanes. The roundabout is another type of intersection, that is a channelized intersection with one-way flow circulating a central island.

The intersection is formed by intersecting two types of roads, where these roads are classified by their functions, speed and the service they provide. The main road function is to provide mobility and access when

roads with higher classifications are providing greater mobility. The intersection roads types are freeway, arterial, and collector roads. The freeway road is a full control of access road that has the capacity for high speed (~120 km/hr) and high traffic volume movements over very long traffic movements and long distances in an efficient and safe way (RDM, 2015). The arterial road is a main road of the city which has been constructed to deliver traffic from collector roads to freeways and to deliver between the city centers at a high level of services. Designing arterial roads varies from country to country and from city to city, where they can be arranged in circles or a grid. Arterials roads are classified into major arterial, which is the road with the high flow at high speed of 80 km/hr and high traffic volumes for long distance. Minor arterial is a road with a medium flow at the medium speed of 50 km/hr and medium traffic volumes over a long distance (RDM, 2015). A collector is a road that provides a low to medium vehicular capacity and is constructed to move traffic from local roads to the arterial road with an average speed of 42 km/hr (Layton, 2012).

A set of intersections are placed in a series to form a network, with specific distance lengths between them, based on the intersection roads type. The distance length between the freeway intersections ranges between 1600 m and 3200 m and, the distance between arterial intersections is not less than 1600 m. When arterial intersections intersect with collector intersections, then the distance length should not be less than 800 m (Layton, 2012).

3.2.2. Intersection network

An intersection network is a set of roadways that are connected at nodes in several ways and can be characterized by these nodal connections. Nodes receive inputs and then process them to obtain an output. The connections determine the information of the flow between nodes and the

interactions that lead to a global behavior of the network. There are two types of traffic network; Arterial network and grid network. The arterial network is one of a series of head-to-head signalized intersections along an arterial roadway. The arterial network consists of one arterial road and several local streets which have an intersection with the arterial as shown in Figure 7.

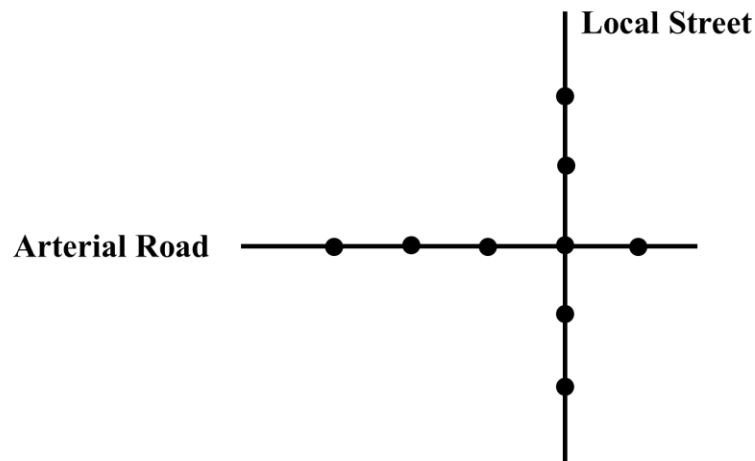


Figure (7)

Arterial Network

The grid network is composed of arterial roads that cross several parallel arterials at varying distances in the city (Chen, 2007) (Figure 8). Each node in this network relates to two neighbors along one or more dimensions.

The entire network is often timed together to ensure consistent behavior between intersections since the intersections in grid networks are either crossing arterials or a series of intersecting roads with similar function and traffic volumes.

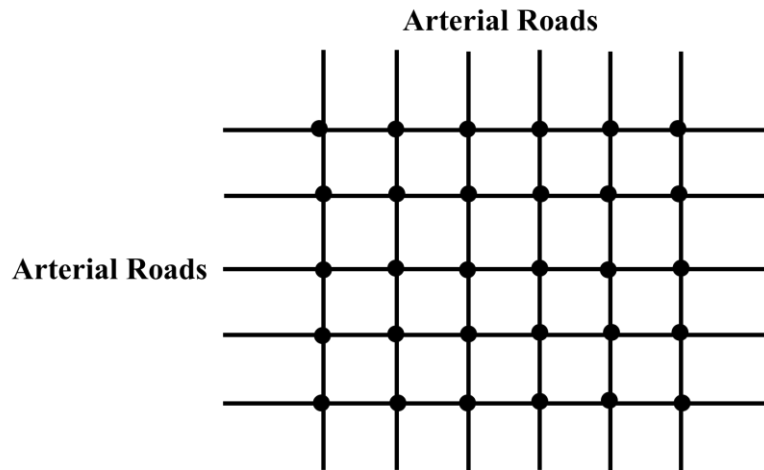


Figure (8)

Grid Network

3.2.3. Intersection control devices

To manage vehicular movement through an intersection, a control system device is used to determine the priorities of right-of-way by providing suitable green time to reach the driver's expectations, and this time is updated based on the traffic demand and flow. The control system can adjust timing parameters based on historical and real-time data which is being received from the detectors to improve intersectional efficiency. The detector is a device used to ensure that the traffic queue is served in each phase and to run a safe end of the green interval by sending the traffic data to the control system. The control system specifies the green times and give the action to the traffic signal.

Loop detector is the most reliable, efficient, cheapest, and widely used detector with three different types; Stop-line detector, queue detector, and gridlock detector. The stop-line detector is mostly a loop detector that is placed 4 m from the stop line, and it is used to measure the flow that exits from the intersection phase, a queue detector is a detector that is placed based on the road speed (Table 2) to measure the length of the vehicle

queue. A gridlock detector is a detector that is placed at the entrance of the intersection phase to measure the flow as it enters the phase.

Table (2)

Location of Queue Detectors Based on the Road Speed (MTDD, 2005)

Road Speed (km/hr)	Queue Detector placement (m)
40	77
56	77
64	86
72	100
80	108
88	118

3.2.4. Traffic signal timing parameters

Designing the traffic control plans is depend on several traffic signal timing parameters such as cycle time, green time, yellow and red clearance time. The cycle time is the time in seconds that it takes a signal to complete one full cycle of indications (Bonneson, 2009). It indicates the time interval between the start of green time for one approach till the next green time starts (RDM, 2015). It is used to maintain a steady operation between following intersections where shorter cycle times cause less delay time and shorter vehicle queues than longer cycle times. Several methods are used to determine the cycle time, and some of these methods specify the cycle time based on the intersection geometry as mentioned in Federal Highway Administration manual where the cycle time of the small intersections should not exceed 120 seconds, and for busy intersections are operating at 160 or 180 seconds. However, a large intersection with high speed, the cycle time could be 210 seconds (Federal Highway Administration). The green phase time is the duration of the green signal of a phase at a signalized intersection that is based on the effective green time and is the actual time that a vehicle requires to cross the intersection (Gordon, 2005).

It considers the green lost time when an intersection is not effectively using the green time by any phase.

As with cycle times, the minimum and maximum green times are determined based on the intersection road type and speed. If the green time is too long, then there is an unnecessary time delay at the intersection, and if it is too short, then it will upset driver expectation and safety (Bonneson, 2009). Minimum and maximum green time setting ranges are listed in Table 3.

Table (3)
Minimum and Maximum Green Times Based on the Road Type and Speed (MUTCD, 2009)

Road Type	Minimum Green Time Range (second)	Maximum Green Time Range (second)
Major Arterial (Road speed limit exceeds 64 km/hr)	9 to 15	50 to 70
Major Arterial (Road speed limit is 64 km/hr)	6 to 15	40 to 60
Minor Arterial	4 to 10	30 to 50
Collector	2 to 10	20 to 40

The yellow and red clearance times are used to provide safe movement between traffic signal phases. Yellow time is used to caution drivers to expect a change in the right-of-way, and it is counted from the green time. Red clearance time is used to provide additional time following the yellow time to clear the intersection before operating the next phase. These yellow and red clearance times are specified based on road speed and the intersections width (Table 4).

Table (4)**Yellow and Red Clearance Times Duration for a Road Speed and Intersection Width (MUTCD, 2009)**

Road Speed (km/hr)	Yellow Time (second)	Width of Intersection (meter)					
		15	21	27	33.5	39.5	46
		Red Clearance Interval (second)					
40	3	1.9	2.5	3	3.5	4.1	4.6
48	3.2	1.6	2.0	2.5	3.0	3.4	3.9
56	3.6	1.4	1.8	2.1	2.5	2.9	3.3
64	3.9	1.2	1.5	1.9	2.2	2.6	2.9
72	4.3	1.1	1.4	1.7	2.0	2.3	2.6
80	4.7	1.0	1.2	1.5	1.8	2.0	2.3
88	5	0.9	1.1	1.4	1.6	1.9	2.1
96	5.4	0.8	1.0	1.2	1.5	2.1	2.3

3.2.5. Signal control system

There are different types of the traffic control systems which are used to specify the cycle and green times of the intersection; Fixed-time control system (pre-timed) where the traffic signal operates without detectors and the timing and phasing do not vary from one cycle to another cycle. Fixed time control systems are used for isolated intersection where the phases sequence and the green times are provided for every phase during traffic cycles for some periods regardless of the number of the vehicles in the sequence and the congestion situation. The actuated control system is another type that adjusts the green time based on the real-time traffic demand measurements obtained from detectors (Messer, 1996); while the operation controllers respond to the fluctuations of the flows in the network. The adaptive control system is a control system type where the signal parameters and phase sequences are adjusted in real time based on the current traffic conditions, demand, and capacity. The control system

requires general investigation, historically in the form of detectors, and a communications infrastructure to be in place.

3.2.6. Artificial control systems

Fuzzy and neural control systems are the most popular artificial traffic control systems. Both are extensively used to determine the transfer function between a feature space and a given class and are subsequently automatically adapted by the computer to optimize performance.

3.2.7. Control system performance measures

A traffic control system analysis is used to develop signal timing plans and to fully understand the situation at an intersection. Any tools used in methods of traffic operation analysis should be calibrated and validated to ensure reliable results. The data collected which is subsequently used by the control system should be accurate and updated to be used by the intersection analysis. The performance measures the traffic control system and provides a basic understanding of whether congestion, reliability, and other aspects of the transportation system performance are getting better or worse. This performance is measured by different factors such as; saturation flow rate, volume-to-capacity ratio, level of service, delay time and queue length (Dne, 2012).

The saturation flow rate is defined as the equivalent hourly rate at which previously queued vehicles can cross the phase under main conditions if the green signal is always available and no lost times are experienced (Waldon, 2012). Based on the Highway Capacity Manual, the ideal saturation flow rate is equal to 1,900 veh. /hr. / lane (HCM, 2010).

The capacity (c) is defined as the maximum sustainable flow rate at which vehicles can pass through a given point in an hour under prevailing conditions (Brian, 2013). The traffic volumes (v) is the total number of

vehicles passing a selected point in one hour (Mathew, 2014). The volume to capacity ratio (v/c) is the degree of saturation, represents the sufficiency of an intersection to accommodate the vehicular demand (HCM, 2010). If $v/c < 1.0$; then the intersection is under saturated condition and the operation is constant, however, when v/c is > 1.0 , then the intersection can be in an oversaturated situation. The level of service is a qualitative measure describing operational conditions within a traffic stream, based on service measures such as road speed and travel time, freedom to maneuver, traffic interruptions, comfort, and convenience (Dne, 2012). It defines control delay as that given in Table 5 and is scaled from A to F, where level A is the best and F is the worst for the driver.

Table (5)

Level of Service for Signalized Intersections (Waldon, 2012)

Level of Service	Average Delay/vehicle (second)	Description
A	≤ 10	Most vehicles do not stop at all. Most arrive during the green phase. Little or no delay
B	> 10 to 20	More vehicles stop than for LOS A. Still good progression through lights. Short traffic delays.
C	> 20 to 35	Significant numbers of vehicles stop, though many passes through without stopping.
D	> 35 to 55	Many vehicles stop. Individual signal cycle failures are noticeable. Progression is intermittent.
E	> 55 to 80	Considered to be the limit of acceptable delay. Individual cycle failures are frequent; progression is poor.
F	> 80	Extreme and unacceptable traffic delays.

The delay time was one of the traffic control system performance measures which has been defined as the additional travel time experienced

by a driver, passenger, bicyclist, or pedestrian beyond that what is required to travel at the desired speed (HCM, 2010). It is an important performance measure because it allows for a comparison between performances of intersections under different operating conditions. Delay has different forms as; stopped delay, is the time a vehicle has stopped in the queue while waiting to pass through the intersection or until the time that vehicle started moving. Delay begins when the vehicle has fully stopped and ends when the vehicle begins to accelerate. The average stopped-time delay is another form of delay it is the average for all vehicles during a specified time. Approach delay is the delay which includes stopped-time delay but adds the time lost due to deceleration from the road speed to a stop and the loss of time as a result of re-accelerating back to the desired speed. The travel delay is the difference between the driver's expected travel time through the intersection and the actual time taken. Total delay is the total time from a vehicle joining the intersection queue to its discharge across the stop line on departure (Mathew, 2014).

Finally, control delay is the delay caused by a control device, either a traffic signal or a stop sign. It is approximately equal to total delay plus the acceleration-deceleration delay component. Delay measures can be stated for a single vehicle, as an average for all vehicles over a specified time, or as an aggregate total value for all vehicles over a specified time. The aggregate delay is measured in total vehicle-seconds, vehicle-minutes, or vehicle-hours for all vehicles in the specified time interval. The average individual delay is stated regarding seconds per vehicle for a specified time interval (Mathew, 2014).

In 1966, Webster and Cobb (Webster, 1966) developed a model to estimate the three control delay parts. It is now over a half-century since they developed the model, but their model is still used as a basis for the

development of other delay models because the factors of this model are available and easy to calculate. The three control delay parts are: Uniform delay, is the delay based on an assumption of uniform vehicle arrivals and a steady flow with no separate cycle failures which means that the number of vehicles that discharged during a green interval is greater than the number of arrivals per cycle.

Random overflow delay is defined as the additional delay which occurs when arrivals at an intersection are greater than capacity. Some of the signal's phases fail to dissipate the intersection where some vehicles not being served at the end of green intervals, which means that they must wait for at least another cycle to depart the intersection.

Continuous overflow delay is the additional delay that occurs when traffic demand exceeds capacity. In that case, every green phase time fails for a significant period, and the remaining vehicles queuing continues to grow over time. In oversaturated conditions, the delay time depends on the length of time, consequently the delay continues to grow and queue length builds-up continuously. This will lead to overflow delay, beside the uniform delay. The vehicles arriving during the analysis period will experience an additional delay because they will be joining an existing queue (Mathew, 2014).

An important traffic control system performance measure is the queue length that is used to inform the traffic signal control system. It is a measurement of the length of time vehicles are waiting when proceeding through an intersection. The vehicles arrive at an intersection during the red time and create queues that are dissipated during the green time at the rate that corresponds to the difference between the rates at which vehicles leave the queue at the front and the rate which vehicles join the queue at its tail end. Under saturated intersections, the time required to dissipate the

queue that has formed during a previous red interval is less than the green time duration. But, in the case of over-saturation intersection, the green time during each cycle is insufficient to dissipate the queue that forms during the previous red interval. In that case, there is growing vehicle residual that remains vehicles at the end of each cycle.

3.3. Existing Traffic Control System in Kuwait

The signal control system strategies used in Kuwait to control the flow and vehicle movements are either fixed time or semi-actuated signal control systems. The fixed time control system is used in all intersections throughout the day in peak periods. Whereas, the semi-actuated control systems are used only during non-peak periods to adjust the green phases time continuously. The order and the sequence of the phases are fixed during the fixed time control system. It may vary under certain situations within the actuated control system.

The most common type of intersection in Kuwait is a four phases intersection that is separated by directional roads into two separate subsystems, the North-South and the East-West road, where each road has three vehicle movements: straight through, left, and right. The vehicle movements can pass through four basic stages in the North-South direction, either by phase three vehicle movements together or by a combination of two phases vehicle movements. All possible vehicle movements in a four phases intersection are highlighted in Figure 9.

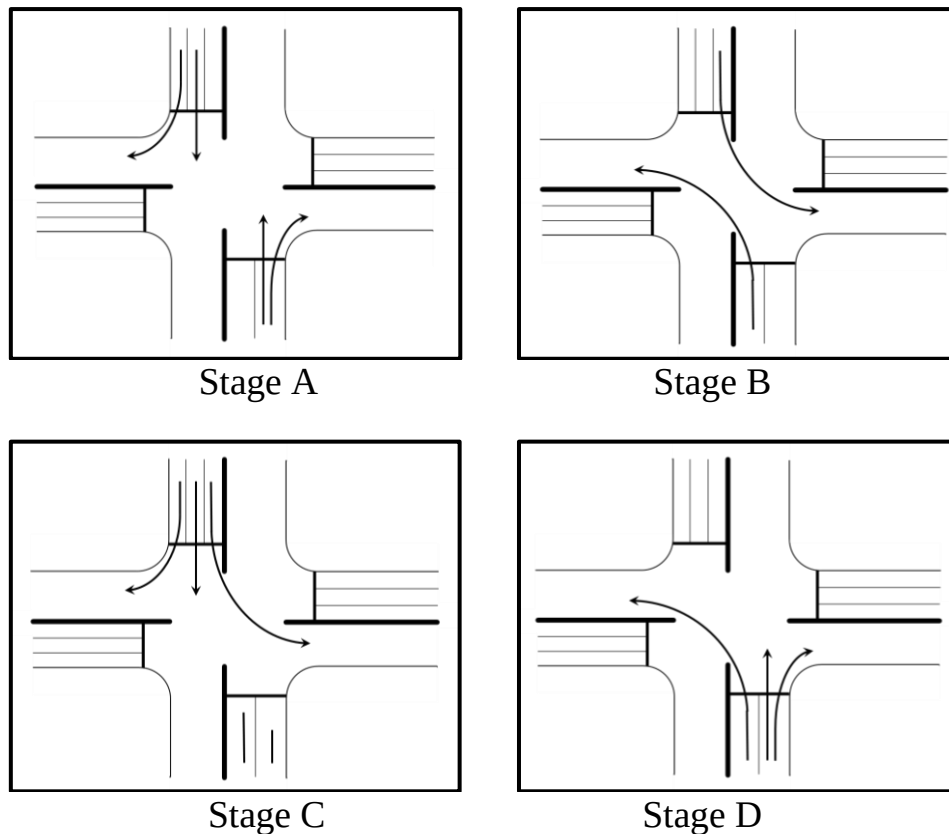


Figure (9)

Vehicle Movements in Four Phases Intersection in Kuwait

The vehicle movements at Stage A are allowable straight through, with a right turn entering the intersection from North and South directions. At Stage B, the vehicle movements are allowable for left turn entering the intersection from North and South directions. However, vehicle movements at Stage C, are allowed for straight through and left and right turns only from the North direction. Finally, at Stage D, the vehicle movements are allowable for straight through, and left and right turns only from the South direction.

The existing traffic control system for the selected sites depends on the data collected from three loop detectors (d) that are fixed on the roadway surface in different locations. First detector (d1) is placed 8 to 12 meters away from the stop-line, the second detector (d2) is placed 24 meters away from the stop-line, and third detector (d3) is placed 35 m away

from the stop-line (Figure 10). The average vehicle length (V_l) (head to head) is equal to 7 m.

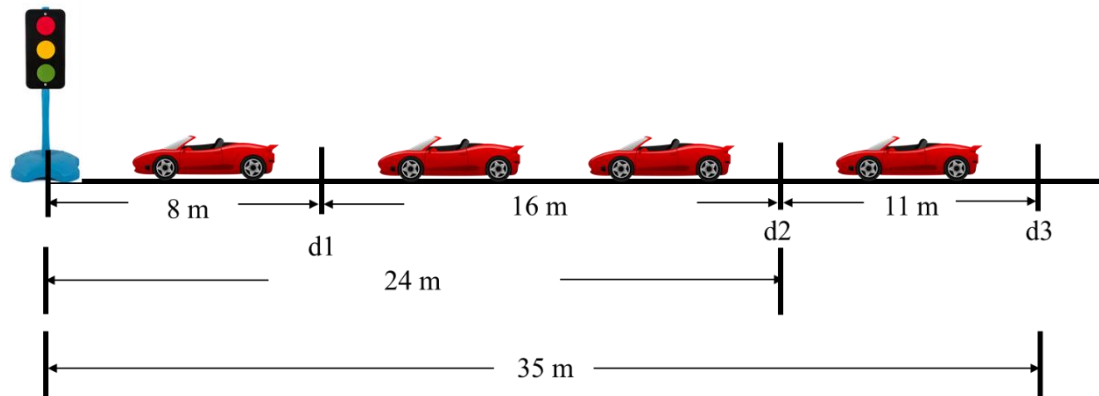


Figure (10)

Detectors Locations in the Existing Control System in Kuwait

The detected zone is the area between d1 and d3 detectors, which means that the system knows how many vehicles are approaching the stop line. The traffic signal timing plans are generated in Kuwait by using a Synchro program, where each intersection has its timing and phasing strategy. Synchro measures the control system delay time by implementing the percentile delay method. The percentile delay calculation looks at different levels of traffic arrivals so that actuated signals can be evaluated under varying traffic loads. This allows for the percentile delay method to capture and rationally model the non-linear behavior of actuated signals (www.synchro.com). A Synchro system measures control delay, queue delay, delay per vehicle, and the total delay for all directions of the intersection. The block diagram for the existing system structure in Kuwait is shown in Figure 11.

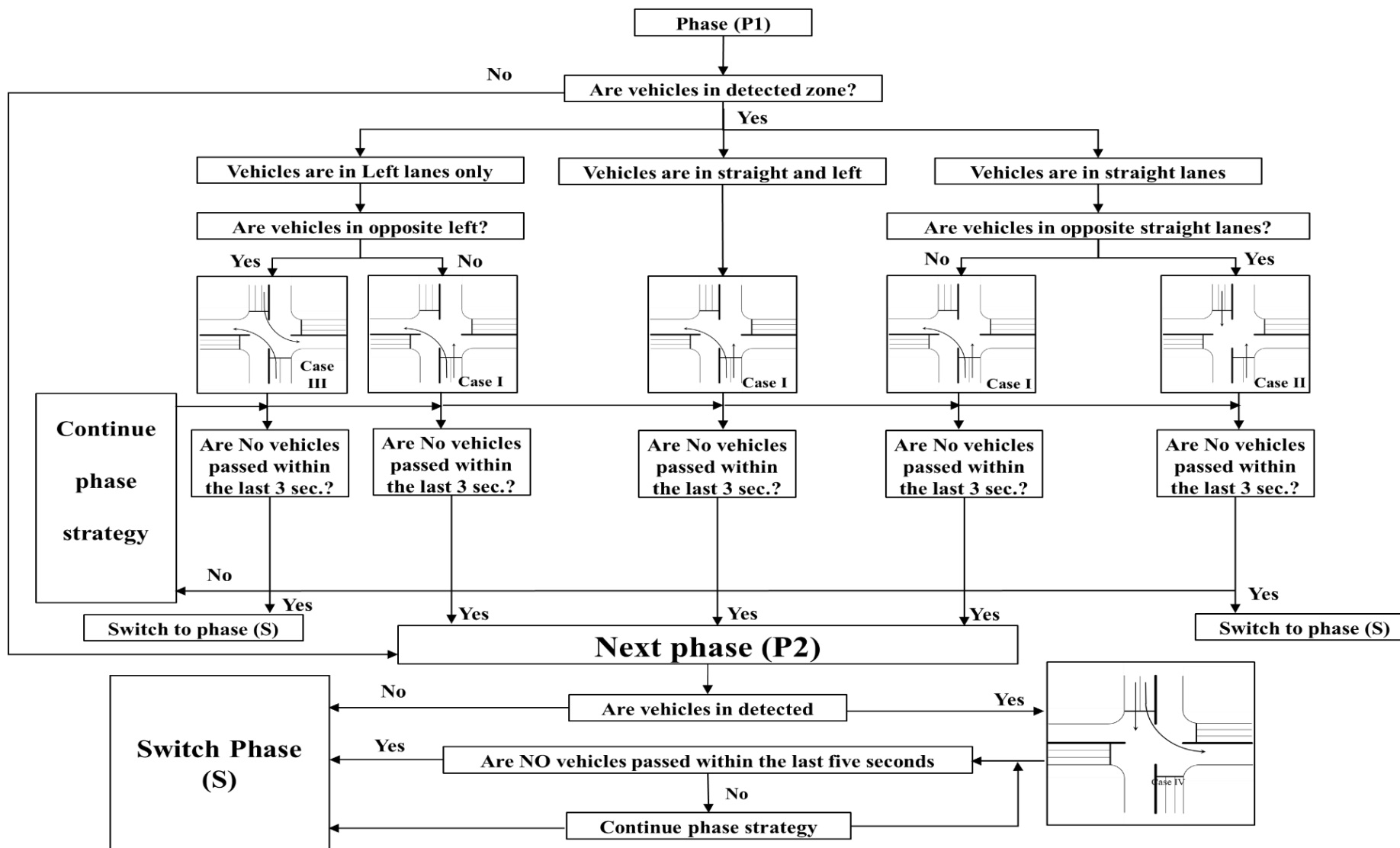


Figure (11)
Existing Traffic System Structure in Kuwait

3.4. Research Population

The State of Kuwait consists of six governorates (Figure 12) namely, Al Asimah, Hawally, Al Ahmadi, Al Farwaniyah, Al Jahra, Mubarak Al-Kabeer. The areas of these governorates are presented in Table 6.



Figure (12)

The Governorates of Kuwait (Karageorgi, 2013)

Table (6)

The Areas of the Governorates in Kuwait (KPACI, 2015)

Governorate	Area (km²)	Population (2015)
Al Asimah	175	544,156
Hawally	85	911,996
Al Ahmadi	5,120	854,366
Al Farwaniyah	204	1,122,638
Al Jahra	12,750	507,793
Mubarak Al-Kabeer	104	237,648

The control system is applied on Al Asimah and Hawally populations due to the following reasons: Al Asimah governorate is considered the most important governorate in Kuwait as it includes the presidency, government centers, and most of the banks and stock market are located in it. Furthermore, it includes historic buildings and museums. Whereas Hawally governorate is located near to Al Asimah, and it is the most crowded governorate because it is the center of schools, markets, and malls. Additionally, Hawally governorate has many places of entertainment and many important roads pass through the Al Asimah governorate. Al Asimah has 1% of the total area of Kuwait and Hawally has 0.5% (Figure 13).

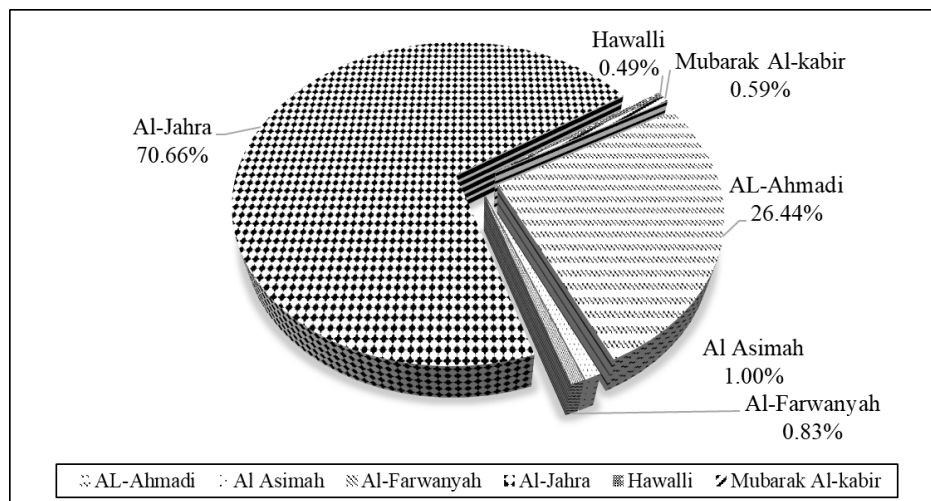


Figure (13)

Kuwait Governorates Areas (KPACI, 2015)

Using data from 2015, Al Asimah has 13%, and Hawally has 22% of the total population of Kuwait, respectively (Figure 14).

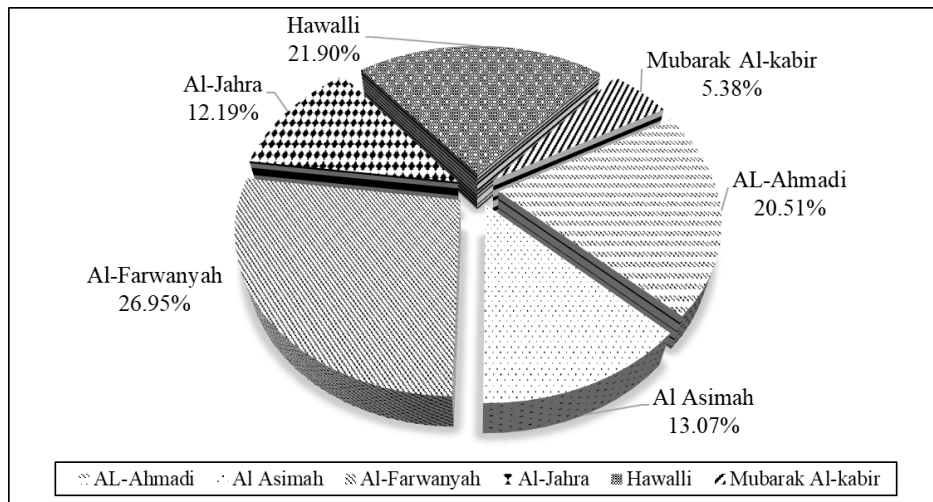


Figure (14)

Kuwait Population in The Governorates - 2015 (KPACI, 2015)

The Hawalli governorate has the highest ratio between the population and the governorate area (45%), and Al Asimah has the third highest ratio (13%) (Figure 15); which indicates that these governorates are crowded when compared with the majority of the other governorates.

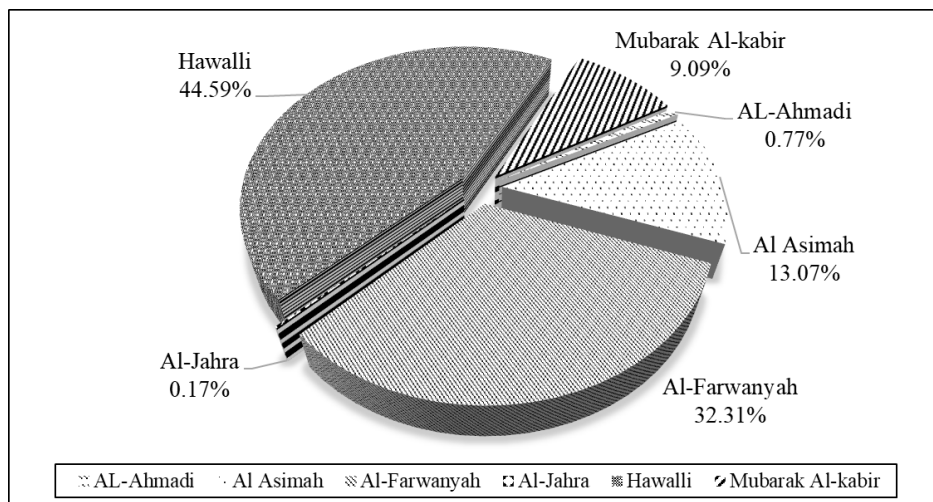


Figure (15)

Ratio Between Governorates Population and Areas - 2015 (KPACI, 2015)

Most of the schools are centralized in Hawalli governorates, where the ratio between the number of students to the governorate area is highest (34%) when compared with other governorates (Figure 16).

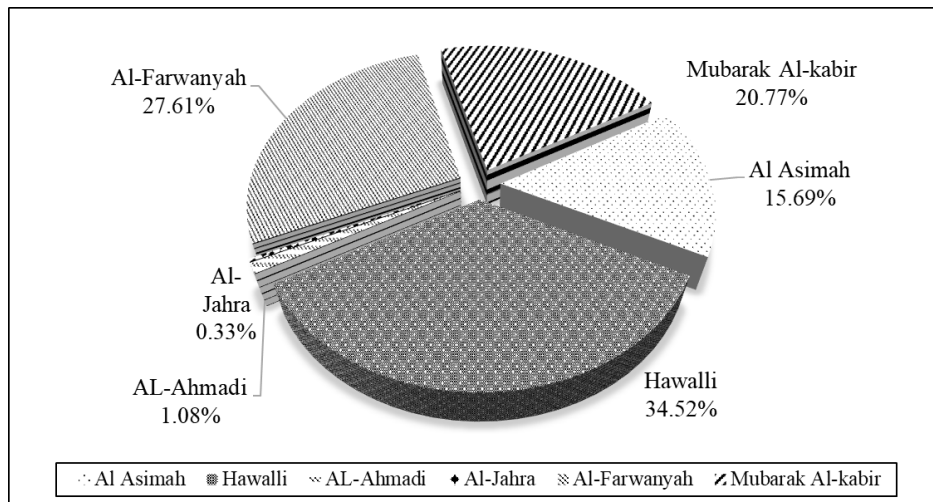


Figure (16)

Ratio Between Number of Students to the Governorates Areas - 2015 (KPACI, 2015)

In addition, Hawally governorate has the highest ratio (40%) between driving licenses and governorates when compared with other governorates (Figure 17).

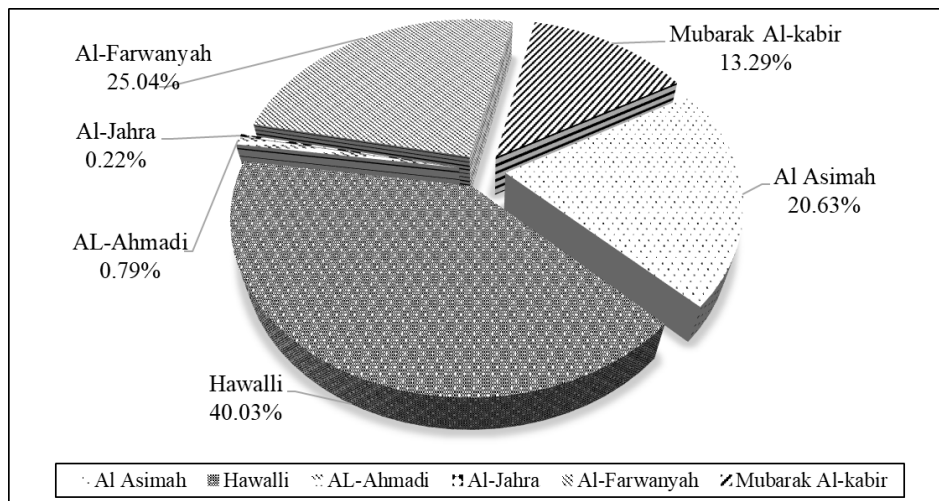


Figure (17)

Ratio Between Driving Licenses and Governorate Areas - 2015 (KPACI, 2015)

From above, the traffic movement in Hawally governorate is high, which strongly supports the hypothesis that this governorate suffers from

traffic congestion and that will affect the traffic in Al Asimah governorate that neighbors it.

Al Asimah and Hawally governorates are located in the center of Kuwait. Where, these governorates are surrounded from the South by Forth Ring Road, from North by Alshuhada street, from the East by Istiqlal street and from the West by Riyadh street. There are several roads in between these boundaries, which intersect and form a grid network (Figure 18). Figure 18 highlights the fact that these intersections are concentrated mainly in Al Asimah and Hawally governorates with short roads.

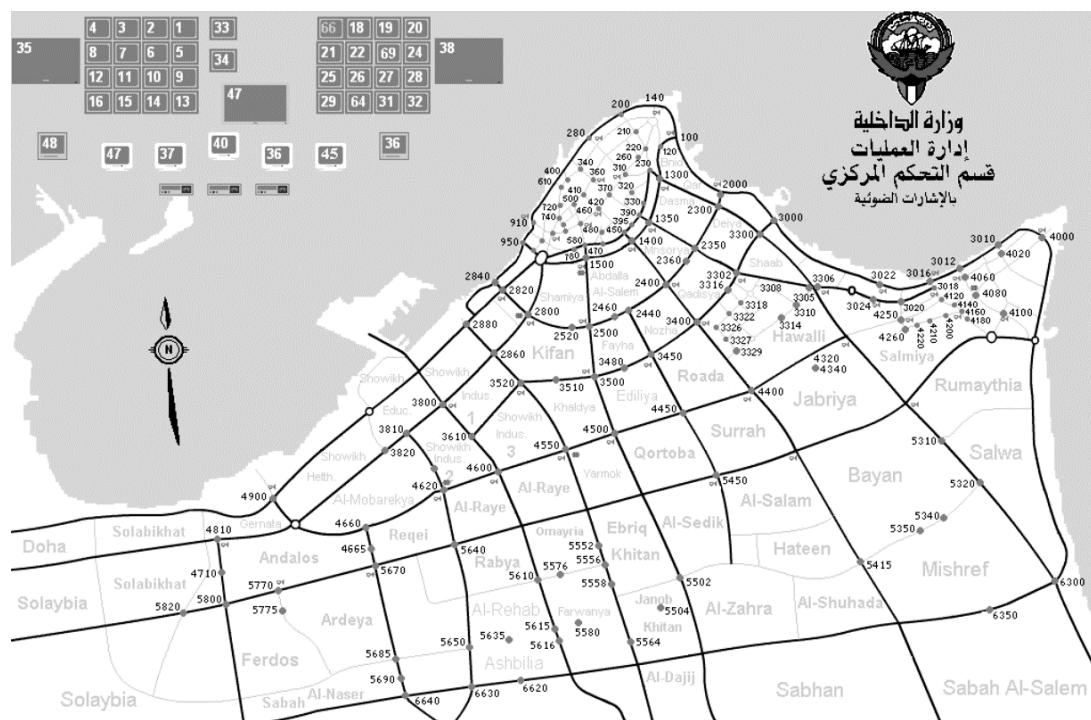


Figure (18)

Al Asimah and Hawally Intersections Numbers' and Boundaries
(MOI, 2013)

3.5. Sample Data

Actual data is needed to validate the control system. The traffic data of Al Asimah and Hawally at thirteen intersections were collected by the General Traffic Department in the Ministry of Interior to select intersections that will be controlled in the simulation process.

Historical flow data for the specified intersections was collected by the Ministry of Interior. Flow data was collected by using the stop-line detector to count the number of vehicles exiting the intersection through the green time. The historical flow data will be elaborated in chapter 6 to be used for validation and analysis.

Vehicle flow data for the twelve months in 2016 was gathered and categorized by their situation, school months, occasional months, and vacation months. By calculating the traffic capacity of the intersections through these months, the traffic capacity was characterized in terms of heavy traffic flow. January was determined to be the most congested month. Analyzing the data gathered during January, it revealed that Monday 11th was the most congested day. Therefore, vehicle data for this day is further analyzed. Four periods were specified as being the peak period, where each period length is 15 minutes. Data collection and analysis will be explained in Chapter 5.

Data was also collected and used for running the control system RE. This data consisted of the intersection geometries and their corresponding timing plans for the specified periods. These included the following characteristics: number of lanes at each phase, green times and timing plans of five intersections. The intersections geometries for the five specified intersections and their time control strategies are as follow:

3.5.1. Intersection No.1400 (X, Y1)

The geometry and number of lanes of intersection No.1400 are shown in Figure 19, and the timing control strategies' durations for one week are presented in Table 7.

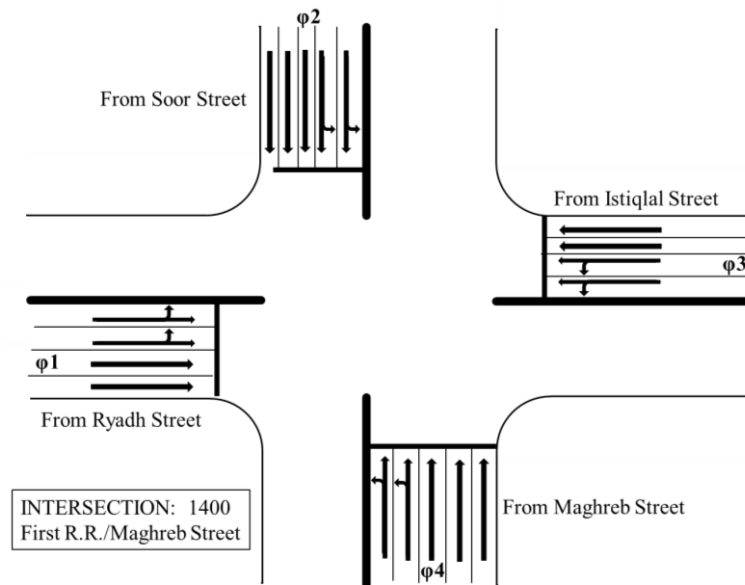


Figure (19)

The Geometry of Intersection No. 1400 (MOI, 2013)

Table (7)

Time Control Strategies of Intersection No. 1400 (MOI, 2013)

Time of Day	Day of Week	Plan No.	Phase 1, TW' (sec.)	Phase 2, TN' (sec.)	Phase 3, TE' (sec.)	Phase 4, TS' (sec.)	Cycle Length (sec.)
06:30 - 08:30	SMTWT	1	25	17	35	168	245
08:30 - 9:30	SMTWT	8	29	22	29	165	245
9:30 - 11:30	SMTWT	4	25	50	35	110	220
11:30 - 14:00	SMTWT	3	25	66	45	54	190
14:00 - 15:00	SMTWT	7	20	69	44	37	170
15:00 - 16:00	SMTWTS	2	22	48	40	60	170
16:00 - 18:00	SMTWTFS	9	25	45	40	65	175
18:00 - 06:30	SMTWTFS	5	25	48	37	60	170

3.5.2. Intersection No. 2350 (X1, Y)

The geometry and number of lanes of intersection No. 2350 are shown in Figure 20, and the timing control strategies' durations for one week are presented in Table 8.

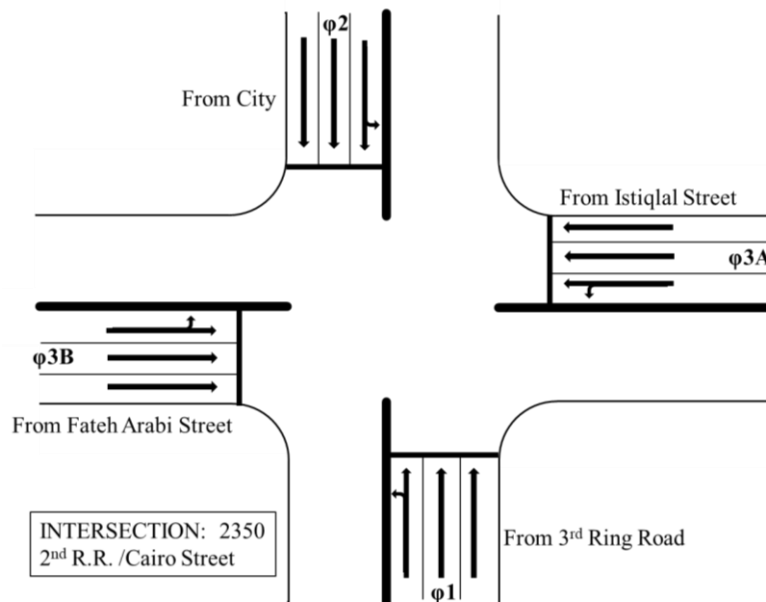


Figure (20)

The Geometry of Intersection No. 2350 (MOI, 2013)

Table (8)

Time Control Strategies of Intersection No. 2350 (MOI, 2013)

Time of Day	Day of Week	Plan No.	Phase 1, TS' (sec.)	Phase 2, TN' (sec.)	Phase 3, TE' (sec.)	Phase 4, TW' (sec.)	Cycle Length (sec.)
06:30 - 09:00	SMTWT	1	70	30	90	90	190
09:00 - 12:00	SMTWT	3	45	40	75	75	160
12:00 - 15:30	SMTWT	2	40	45	105	105	190
15:30 - 17:00	SMTWT	9	45	50	85	85	180
17:00 - 00:00	SMTWTFS	8	45	50	95	95	190
00:00 - 06:30	SMTWTFS	Actuation	70	65	105	105	240

3.5.3. Intersection No. 2400 (X, Y)

The geometry and number of lanes of intersection No. 2400 are shown in Figure 21, and the timing control strategies' durations for one week are presented in Table 9.

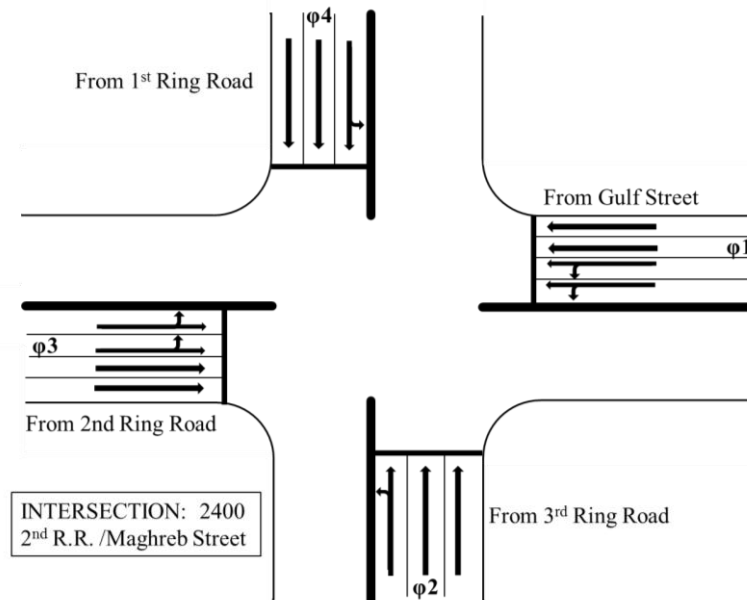


Figure (21)

The Geometry of Intersection No. 2400 (MOI, 2013)

Table (9)

Time Control Strategies of Intersection No. 2400 (MOI, 2013)

Time of Day	Day of Week	Plan No.	Phase 1, TE' (sec.)	Phase 2, TS' (sec.)	Phase 3, TW' (sec.)	Phase 4, TN' (sec.)	Cycle Length (sec.)
06:30 - 09:00	SMTWT	1	80	40	45	25	190
09:00 - 12:00	SMTWT	3	54	23	59	24	160
12:00 - 15:30	SMTWT	2	71	31	66	22	190
15:30 - 17:30	SMTWT	9	54	23	59	24	160
17:30 - 00:00	SMTWT	4	72	28	72	18	190

3.5.4. Intersection No. 2500 (X-1, Y)

The geometry and number of lanes of intersection No. 2500 are shown in Figure 22, and the timing control strategies' durations for one week are presented in Table 10.

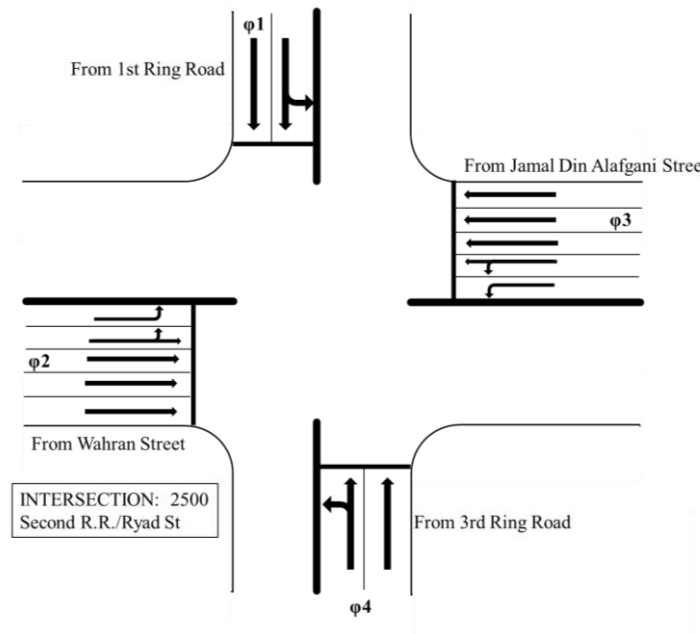


Figure (22)

The Geometry of Intersection No. 2500 (MOI, 2013)

Table (10)

Time Control Strategies of Intersection No. 2500 (MOI, 2013)

Time of Day	Day of Week	Plan No.	Phase 1, TN' (sec.)	Phase 2, TW' (sec.)	Phase 3, TE' (sec.)	Phase 4, TS' (sec.)	Cycle Length (sec.)
06:30 - 09:00	SMTWT	1	15	20	90	65	190
09:00 - 11:00	SMTWT	3	20	31	49	60	160
11:00 - 12:00	SMTWT	4	20	36	49	55	160
12:00 - 13:00	SMTWT	5	20	60	60	50	190
13:00 - 15:30	SMTWT	2	29	70	45	46	190
15:30 - 19:00	SMTWT	9	22	47	46	45	160
19:00 - 00:00	SMTWTFS	8	23	41	51	65	180
00:00 - 06:30	SMTWTFS	Actuation	50	80	100	75	305

3.5.5. Intersection No. 3400 (X, Y-1)

The geometry and number of lanes of intersection No. 3400 are shown in Figure 23, and the timing control strategies' durations for one week are presented in Table 11.

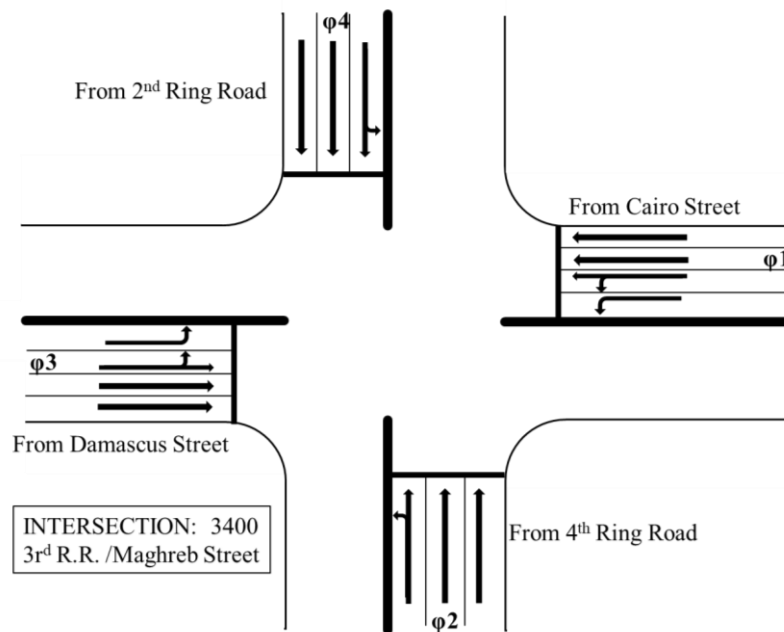


Figure (23)

The Geometry of Intersection No. 3400 (MOI, 2013)

Table (11)

Time Control Strategies of Intersection No. 3400 (MOI, 2013)

Time of Day	Day of Week	Plan No.	phase 1, TE' (sec.)	phase 2, TS' (sec.)	phase 3, TW' (sec.)	phase 4, TN' (sec.)	Cycle Length (sec.)
06:30 - 09:00	SSMTWTF	1	66	83	27	14	190
09:00 - 12:00	SSMTWTF	3	50	58	42	30	180
12:00 - 13:15	SSMTWTF	2	35	57	40	28	160
13:15 - 14:15	SSMTWTF	8	35	52	40	33	160
14:15 - 15:30	SSMTWTF	9	50	60	40	30	180
15:30 - 16:30	SSMTWTF	6	42	64	46	28	180
16:30 - 21:00	SSMTWTF	4	58	52	45	25	190
21:00 - 23:00	SSMTWTF	7	60	58	42	30	190
23:00 - 06:30	SSMTWTF	Actuation	80	70	70	40	

Chapter Four

Development of Traffic Control System

4.1. Introduction

4.2. Control System Development

4.3. Stage 1: Design of the Green Time Distribution Models

4.4. Stage 2: Design of Fuzzy Rules for Signal Timings

4.5. Stage 3: Initialization of the Control System

4.6. Stage 4: Execution of the Developed Control System

4.7. Reporting of Outputs

Chapter Four

Development of Traffic Control System

4.1. Introduction

System design is the process of defining the assumptions, components, modules, interfaces, and data for a system to satisfy specified requirements (Whitten, 2007). Traffic system design ensures that vehicles can pass safely with or without minimal delay. The control system development concepts, design steps, mathematical calculations and probabilities of the decision has on the traffic signal timing are shown and explained in this chapter.

Fuzzy logic is introduced and applied to a wide range of traffic control tasks. The main benefit of a fuzzy logic is the opportunity to help in making decisions. To build a fuzzy system, an understanding of the process and principles underlying the system operation is essential in determining the system inputs and outputs.

4.2. Control System Development

A control system is developed as a dynamic system which uses a fuzzy expert system that is a precise analytical tool. This section presents the design of the developed control system using fuzzy rules as building tools.

4.2.1. Control system design

The control system consists of four stages. Each stage is designed through several steps. Figure 24 shows the design stages and Figure 25 shows the corresponding steps for each stage. Stage 1: covers the design

of the green time distribution models. This is carried out in steps 1 to 4. Stage 2: covers the design of the fuzzy rules for selection of signal timings (step 5). Stage 3: initializes the control system through steps 6 to 9. Stage 4: execute the developed control system through steps 10 to 15. At stage 1, intersections' geometries and specifications are reviewed and studied to specify the control system constraints and assumptions. Seven control systems are designed based on the type of the road; collector, major and minor arterial, and the combination between them. Each intersection is surrounded by four intersections of different distances at each phase where each distance is divided into several zones. Based on the combinations of these number of zones, eighty-one green time distribution models are designed. The green times are distributed for each zone based on the on intersections' characteristics. At stage 2, sets of fuzzy rules are designed where in the first set the intersection road type is used as inputs to select the actual control system, and in the second set the number of zones at each intersection phase is used as inputs to select the actual green time distribution model. A simulation software is designed by applying the fuzzy rules in the visual basic and computer-based program (Excel) to run the developed control system for the validation process (Attached CD). At stage 3, the control system starts running by using intersections' geometries as inputs to select the actual control system. The control system calculates the number of zones at each intersection phase in order to select the green time distribution model. At stage 4, detectors send the traffic flow data to the control system to calculate the vehicle queue at each phase. Based on the queue length, the control system determines the green time and the intersection maximum cycle time. Hence, the total cycle time is calculated and compared with the specified cycle time. At the same stage, the control system modifies the green time and gives action to the traffic light.

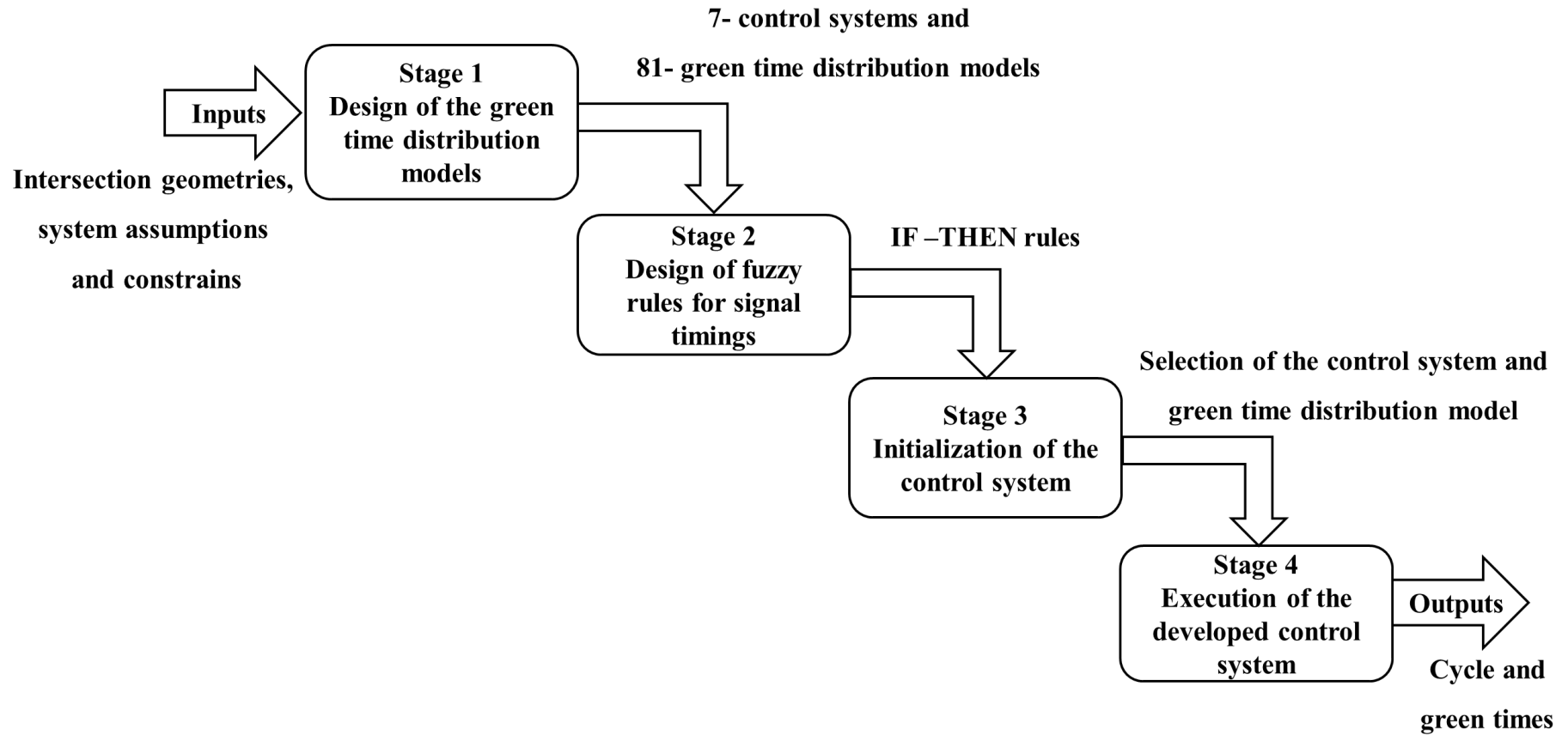


Figure (24)

Stages of Designing the Developed Control System

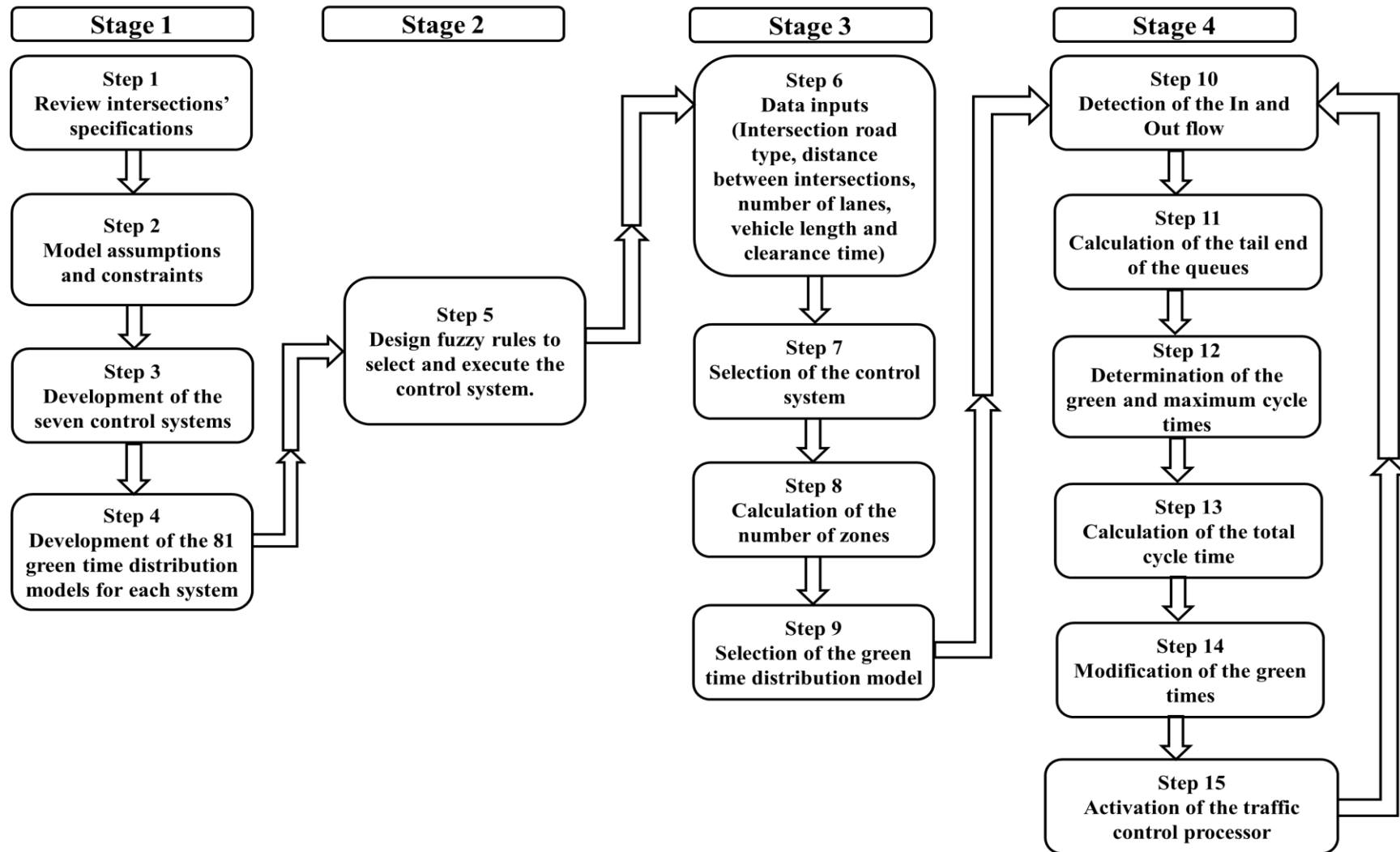


Figure (25)

Steps of Developing the Intersection Control System

4.2.2. Fuzzy system tool

To build-up a proposed fuzzy system either to build-up a system from scratch using a primary programming language or use a fuzzy logic development shell. In this work, Microsoft Excel and the Visual Basic were used to design the proposed control system to facilitate the selection of the green time distribution plan. The excel language is easy to use when building fuzzy rules. The proposed fuzzy rules define different cases and different scenarios in the form of "IF-THEN" statements.

4.3. Stage 1: Design of the Green Time Distribution Models

Stage 1 consists of 4 steps as shown in Figure 26. The intersections' geometries and specifications are handled in stage 1 as inputs. The green time distribution models are the outputs from this stage.

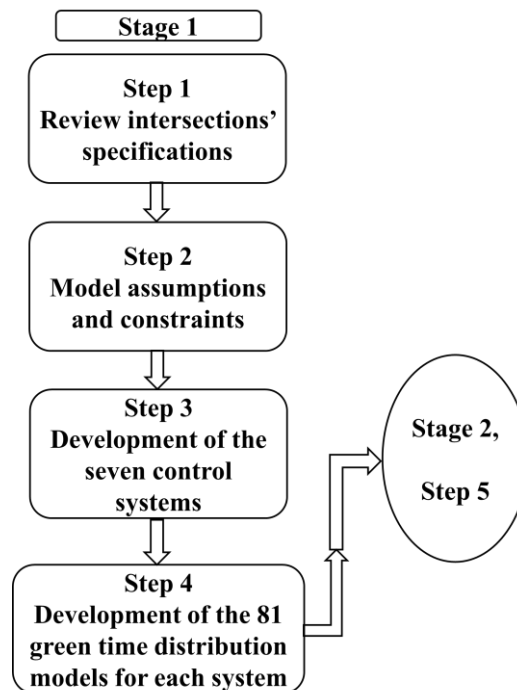


Figure (26)

Schematic of Designing the Green Time Distribution Models

4.3.1. Step 1: Intersections' specifications

The intersections' specifications are studied to develop the control system constraints and assumptions. These intersections specifications' are: the intersections types (simple, flared and roundabout), the road types (collector, major and minor arterials), the road speed, the vehicle movement strategies (straight through, left, and right movements), the traffic devices, and the control systems (fixed, actuated, and artificial system (Chapter 2)). The adaptive control system is developed for the simple intersection with four perpendicular phases with three vehicles movements. These intersections are formed by the combination between any of the collector, minor and major arterial roads where these roads are the main roads connecting the inner roads by the highways. In addition, the green time is designed based on the roads' type and speed to control the traffic lights.

4.3.2. Step 2: Model assumptions and constraints

A list of system assumptions and constraints are specified at this step to design the proposed control system based on a review of the data during step 1. The control system is designed for unsynchronized simple intersections with four perpendicular phases labeled as: S' (vehicles moving from South to North), N' (vehicles moving from North to South), E' (vehicle moving from East to West), and W' (vehicles moving from West to East). Each phase consists of three movements of vehicles; straight through, left turn, and right turn (S_T , L, and R) (Figure 27).

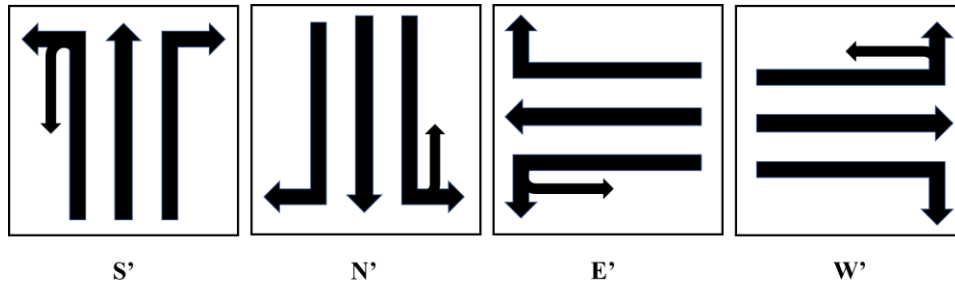


Figure (27)

Assumed Vehicle Movements Strategy

The intersections, as mentioned earlier, are formed by the combination of any of the following phasing roads within a grid network collector, major arterial and minor arterial roads. The grid network is divided into horizontal and vertical arterials. Each intersection is labeled by a coordination code (X_i, Y_j) as in departure and latitude shown in Figure 28.

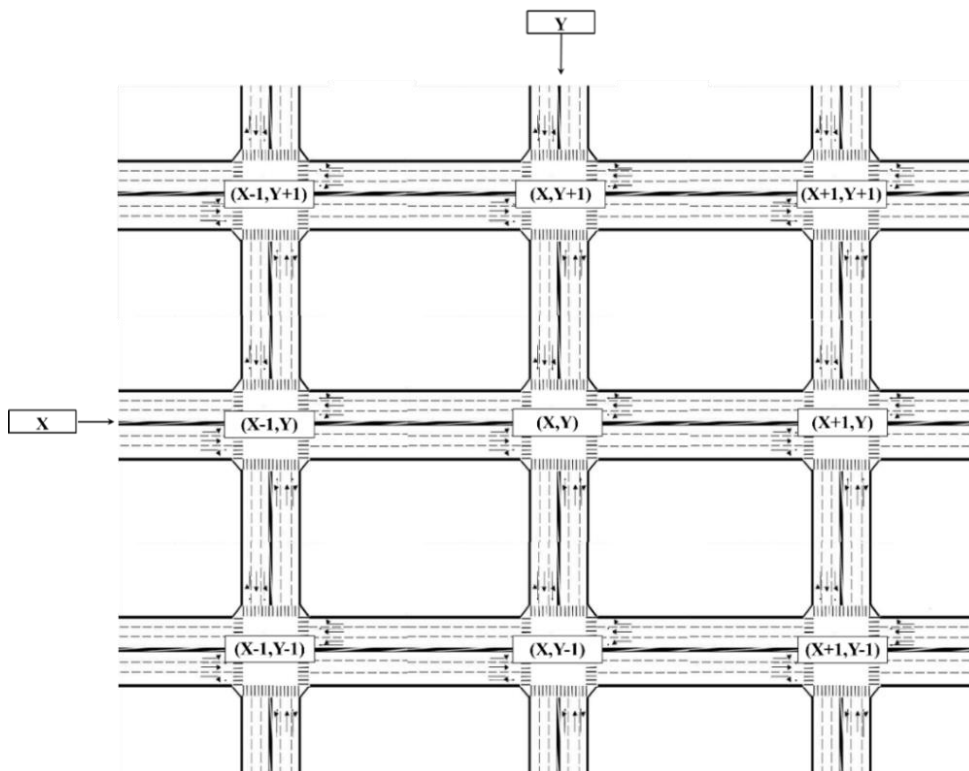


Figure (28)

Schematic Example of Grid Network Intersection with Coordination Codes

Furthermore, the control system is designed for all traffic conditions (under saturation, saturation, and over-saturation) but, emergency situations (vehicle accidents, ambulances in service, drivers' behavior and nature crises, etc.) are excluded during the process of developing the control system.

As an assumption, the system is developed based on the flow arrivals and departures in a deterministic, uniform and distributed equally on the phases' lanes. Moreover, vehicle acceleration and deceleration are not factored into the model calculation. The traffic flow is counted by two detectors; stop-line (ds) and gridlock (dg) detectors that are placed at the intersection phase (Figure 29).

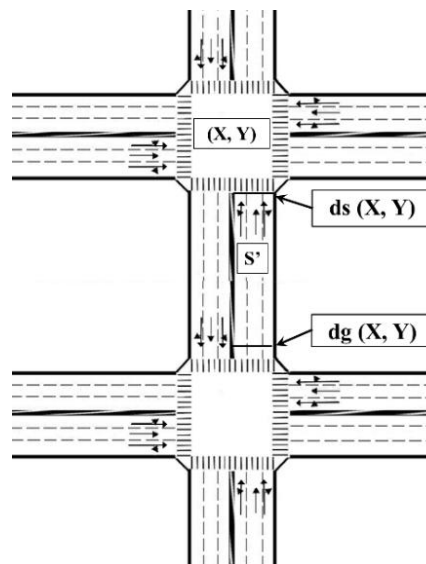


Figure (29)

Two Detectors Placed at Intersection to Read the Traffic Flow

The distance between the intersections is labeled by (L_d) in meters. The maximum distance is labeled by $(L_d)_{max}$ and the minimum distance is labeled by $(L_d)_{min}$. The distance between two intersections was divided into several zones. Each zone is labeled by (Z) where the minimum allowable intersection distance is labeled by zone unit $(Z)_{unit}$ and the last interval at the zone is labeled by critical zone interval $(Z)_{critical}$.

By analyzing the intersections' geometries that was covered in Chapter 3 Section 3.2.1, a set of the system constraints were specified in designing the control system process. Based on the major arterials specifications, the maximum distance was specified by $(L_d)_{\max} = 2400$ meters and based on the collector roads specifications, the minimum distance was specified by $(L_d)_{\min} = 800$ meters which means that as a system constraint, the distance between intersection was $800 \text{ m} \leq L_d \leq 2400 \text{ m}$. The minimum distance was assigned as a zonal unit and labeled by $(Z)_{\text{unit}} = 800 \text{ m}$.

The intersection cycle time was labeled as (T_{cycle}) in seconds which is the time for a cycle to be completed. The maximum cycle time was labeled as $(T_{\text{cycle}})_{\max}$ and the minimum cycle time is labeled as $(T_{\text{cycle}})_{\min}$. As mentioned earlier in Chapter 3 Section 3.2.4, the maximum cycle time for the collector road was specified as $(T_{\text{cycle}})_{\max} = 120 \text{ sec}$. The maximum cycle time for major arterial was specified as $(T_{\text{cycle}})_{\max} = 210 \text{ sec}$. and for minor arterial was specified as $(T_{\text{cycle}})_{\max} = 180 \text{ sec}$.

The phase green time is labeled by (T_{ϕ}) in seconds where ϕ is assigned as an intersection phase. The minimum green time was labeled as $(T_{\phi})_{\min}$ and the maximum green time was labeled as $(T_{\phi})_{\max}$. The minimum and maximum green time ranges for the collector, major arterial and minor arterials roads are presented in Table 3. The maximal green time of the minimum green time range (maximum of minimum range) of an intersection phase was assigned as a default green time and labeled as $(T_{\phi})_{\text{default}}$. The red clearance time was labeled as (T_c) and it is specified based on the road type and speed (Table 4). The summation of the green time of the four phases plus their corresponding clearance time was assigned as a total cycle time and was labeled as $(T)_{\text{total}}$. Sets of detectors are used in developing the control system namely, queue detector and

gridlock detector. The queue detector was labeled as (d_q) and its location was based on the road type (Table 2). The gridlock detector was labeled as (d_g) and was placed at the phase's entrances.

As a summary, the timing parameters (maximum cycle time, minimum and maximum green time and the queue detector locations) for each road type are presented in Table 12.

Table (12)

Intersections' Roads Specifications and Timing Limits

Specification	Collector Road	Major Arterial Road	Minor Arterial Road
Maximum cycle time ($T_{\text{cycle}}_{\text{max}}$ (sec.))	120	210	180
Minimum green time range, (T_{ϕ}) _{min} (sec.)	$6 \leq T_{\phi\text{min}} \leq 10$	$9 \leq T_{\phi\text{min}} \leq 15$	$6 \leq T_{\phi\text{min}} \leq 10$
Maximum green time range, (T_{ϕ}) _{max} (sec.)	$20 \leq T_{\phi\text{max}} \leq 40$	$50 \leq T_{\phi\text{max}} \leq 70$	$30 \leq T_{\phi\text{max}} \leq 50$
Queue detector location (d_q) (m)	77	108	77

Some of the development constraints are specified in designing the control system are as follow: green time (T_{ϕ}) should not be less than the default time (T_{ϕ})_{default} unless the green time (T_{ϕ}) was equal to the minimum green time (T_{ϕ})_{min}. The total time (T_{Total}) should not exceed the maximum cycle time ($T_{\text{cycle}}_{\text{max}}$). In addition, when there were no vehicles passing over the queue detector (d_q) during the minimum green time (T_{ϕ})_{min}, then the next phase traffic signal will not take over unless the minimum green time ends for a safety incident.

4.3.3. Step 3: Development of seven control systems

Control systems were developed for intersections which are formed by either one type of road as collector, major arterial or minor arterial roads, or by a combination between two road types as collector with minor

arterial, minor arterial with collector, major arterial with minor arterial roads, or minor arterial with major arterial roads. Based on these road types and their feasible combinations, seven control system models were designed (Table 13). The developed control systems were named by the types of intersection road. When the intersection roads are the same type, then the control system was named by this road type. Control system 1 was named as a collector, system 2 named as a major arterial, and system 3 named as a minor arterial. When both intersection roads are arterial, but one is major and the other is minor then, the control system was named as system 4, as an arterial mix 1, or by system 5 as arterial mix 2. However, when the intersection roads were a collector and minor arterial, then the control system was named system 6 by mix-1 (minor arterial and collector) or system 7 by mix-2 (collector and minor arterial).

Table (13)

Seven Control Systems Developed by the Intersections Road Types Combinations

Control System		Intersections' Road Types			
No.	Name	S'	N'	E'	W'
1	Collector	Collector	Collector	Collector	Collector
2	Major Arterial	Major Arterial	Major Arterial	Major Arterial	Major Arterial
3	Minor Arterial	Minor Arterial	Minor Arterial	Minor Arterial	Minor Arterial
4	Arterial Mix1 (Major + Minor)	Major Arterial	Major Arterial	Minor Arterial	Minor Arterial
5	Arterial Mix2 (Minor + Major)	Minor Arterial	Minor Arterial	Major Arterial	Major Arterial
6	Mix1 (Minor arterial + Collector)	Minor Arterial	Minor Arterial	Collector	Collector
7	Mix2 (Collector + Minor arterial)	Collector	Collector	Minor Arterial	Minor Arterial

4.3.4. Step 4: Development of the eighty-one green time distribution models

For each developed control system (Table 13), eighty-one green time distribution models were developed and tabled. As a system constraint, the distance between intersections was set at $800 \text{ m} \leq L_d \leq 2400 \text{ m}$, and the zone unit was set as $Z_{\text{unit}} = 800 \text{ m}$. Each distance was divided into several number of zones. The number of zones at the intersection phase was labeled (Z_ϕ), and it was calculated by dividing the distance over the zone unit. Number of zones equal to 1, 2, or 3 ($Z_\phi = \frac{800}{800} = 1$, $\frac{1600}{800} = 2$, or $\frac{2400}{800} = 3$). The green time distribution models were designed by combining these number of zones (1, 2, or 3) at each intersection, and are labeled by the zones' numbers, for example (1,1,1,1), (1,1,1,2), (1,1,1,3), ... etc. Based on the number of all possible arrangements of these zones in the four phases, eighty-one green time distribution models were developed for each control system. Thus, a zoning code (i, j, k, l) was used where i, j, k, and l represented the number of zones of an intersection with four phases. These models are provided with timing parameters, maximum cycle time, minimum green time, default time and maximum green time, that were specifically based on the designing rules of the system. These are discussed next.

As mentioned earlier, 7 control system were developed for intersections formed by either one type of road or by a combination between two types of roads. The maximum cycle time for the intersections with same road type was specified based on the intersection road specifications. As presented in Table 12, the maximum cycle times were specified as follow: maximum cycle time for the intersection formed by collector roads (Collector system) is $(T_{\text{cycle}})_{\text{collector}} = 120 \text{ sec.}$, for the intersection formed by major arterial roads (Major Arterial system) is

$(T_{\text{cycle}})_{\text{major-arterial}} = 210 \text{ sec.}$, and for the intersection formed by a minor arterial roads (Minor Arterial system) is $(T_{\text{cycle}})_{\text{minor-arterial}} = 180 \text{ sec.}$ However, the maximum cycle time for an intersection formed by two different road types is specified as an average of these two roads maximum cycle times as follow: the maximum cycle time for major arterial road = 210 sec. and the maximum cycle time for the minor arterial road = 180 sec., then the maximum cycle time for the intersection formed by major and minor arterials (Arterial Mix1 and Mix2 systems) is $(T_{\text{cycle}})_{\text{arterial-mix1, 2}} = \frac{210+180}{2} = 195 \text{ sec.}$ In addition, the maximum cycle time for minor arterial road = 180 sec. and the maximum cycle time for the collector road = 120 sec., then the maximum cycle time for the intersection formed by minor arterial and collector road (Mix1 and Mix2 systems) is $(T_{\text{cycle}})_{\text{mix1, 2}} = \frac{120+180}{2} = 150 \text{ sec.}$

As mentioned earlier, eighty-one green time distribution models were developed for each control system based on all possible arrangements of number of zones in the four phases of the intersection. The green time for each zone is specified as follow:

As presented in Table 12, the minimum green time range (sec.) for collector road is $6 \leq T_{\phi\text{min}} \leq 10$, for major arterial is $9 \leq T_{\phi\text{min}} \leq 15$, and for minor arterial is $6 \leq T_{\phi\text{min}} \leq 10$. The minimum green time value of the minimum green time range (minimum of minimum range) was assigned as a minimum green time $(T_{\phi})_{\text{min}}$ for the road type. The minimum green time for a phase with a collector road type is $(T_{\phi\text{min}})_{\text{collector}} = 6 \text{ sec.}$ for a phase with major arterial type $(T_{\phi\text{min}})_{\text{major-arterial}} = 9 \text{ sec.}$ and for a phase with a minor arterial type $(T_{\phi\text{min}})_{\text{minor-arterial}} = 6 \text{ sec.}$

The maximum time value of the minimum green time range (maximum of minimum range) was assigned as a default time $(T_{\phi})_{\text{default}}$ for

the road type. The default time for a phase with a collector road type was $(T_{\phi\text{default}})_{\text{collector}} = 10$ sec, for a phase with a major arterial type was $(T_{\phi\text{default}})_{\text{major-arterial}} = 15$ sec. and for a phase with a minor arterial was $(T_{\phi\text{default}})_{\text{minor-arterial}} = 10$ sec.

As presented in Table 12, the maximum green time range (sec.) for collector road is $20 \leq T_{\phi\text{max}} \leq 40$, for major arterial is $50 \leq T_{\phi\text{max}} \leq 70$, and for minor arterial is $30 \leq T_{\phi\text{max}} \leq 50$. The maximum green time for each phase was specified based on the number of zones as follows: the maximum green time $(T_{\phi})_{\text{max}}$ for a phase with $Z_{\phi} = 1$ is the minimum green time value of the maximum green time range (minimum of maximum range). The maximum green time $(T_{\phi})_{\text{max}}$ for a phase with $Z_{\phi} = 3$ is the maximum green time value of the maximum green time range (maximum of maximum range). However, the maximum green time $(T_{\phi})_{\text{max}}$ for a phase with $Z_{\phi} = 2$ is the average of the minimum of maximum range and maximum of maximum range of green time.

In other words, $(T_{\phi})_{\text{max}}$ selected value is dependent on the number of zones (Z_{ϕ}) in a specific phase. For example, for a collector control system, the $(T_{\phi})_{\text{max}} = 20$ sec. when $Z_{\phi} = 1$, and $(T_{\phi})_{\text{max}} = 40$ sec. when $Z_{\phi} = 3$, then $(T_{\phi})_{\text{max}} = \frac{20+40}{2} = 30$ sec. when $Z_{\phi} = 2$. These timing parameters; $(T_{\text{cycle}})_{\text{max}}$, $(T_{\phi})_{\text{min}}$, $(T_{\phi})_{\text{default}}$, d_q location and $(T_{\phi})_{\text{max}}$ for the seven control systems are presented in Table 14.

Timing parameters were specified for a specific number of zones. During actual situations, a vehicle queue may end at any location within these zones. The location of the vehicle queue at an intersection phase is labeled as $(Z_{q\phi})$. For higher accuracy, each zone is divided into intervals where each interval = $0.5 * Z_{\text{unit}} = 400$ m except the first and second intervals. The first interval was specified by the distance between the stop-line and the queue detector located at (d_q) . The second interval was

specified by the distance between the queue detector located at 400 m away from the stop-line detector. As presented in Table 2, the queue detector (d_q) location is specified based on the road type. It was positioned on collector and minor arterial roads at 77 m and on major arterial roads at 108 m from the stop-line.

Table (14)
Timing Parameters for the Seven Control Systems

Control System	Collector			Major Arterial			Minor Arterial			Arterial Mix 1			Arterial Mix 2			Mix 1			Mix 2		
Maximum cycle time (sec.), $(T_{\text{cycle}})_{\text{max}}$	120			210			180			195			195			150			150		
Two phases road type	Collector			Major Arterial			Minor Arterial			Major Arterial			Minor Arterial			Minor Arterial			Collector		
Minimum green time (sec.), $(T_{\phi})_{\text{min}}$	6			9			6			9			6			6			6		
Default time (sec.), $(T_{\phi})_{\text{default}}$	10			15			10			15			10			10			10		
Queue detector location (m), d_q	77			108			77			108			77			77			77		
Zone No., (Z_{ϕ})	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Maximum green time (sec.), $(T_{\phi})_{\text{max}}$	20	30	40	50	60	70	30	40	50	50	60	70	30	40	50	30	40	50	20	30	40
Two phases road type	Collector			Major Arterial			Minor Arterial			Minor Arterial			Major Arterial			Collector			Minor Arterial		
Minimum green time (sec.)	6			9			6			6			9			6			6		
Default time (sec.)	10			15			10			10			15			10			10		
Queue detector location (m)	77			108			77			77			108			77			77		
Zone No. (Z)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Maximum green time (sec.)	20	30	40	50	60	70	30	40	50	30	40	50	50	60	70	20	30	40	30	40	50

The green time for each interval was calculated based on the ratio between the interval length and the whole length (I_z) as in Eq. 1.

$$I_z = \text{Interval length} / L_d \quad \text{Eq. 1}$$

Firstly, when number of zones (Z_ϕ) was set for zones 1, 2, or 3. For each number of zones several intervals are formed. Each interval holds a different green time. When the number of zone (Z_ϕ) was equal to 1 ($L_d = 800$ m), then three intervals were formed within this phase. The green time (T_ϕ) for the first interval ($0 \text{ m} < \text{Interval 1} \leq dq \text{ (m)}$) was estimated by following Eq. 2. For the second interval ($dq \text{ m} < \text{Interval 2} \leq 400 \text{ m}$) was estimated by following Eq. 3, with an additional condition of T_ϕ not being less than $(T_\phi)_{\text{default}}$. For the third interval ($400 \text{ m} < \text{Interval 3} \leq 800 \text{ m}$) was estimated by following Eq. 4, with further condition of T_ϕ not being less than $(T_\phi)_{\text{default}}$.

$$T_\phi = (T_\phi)_{\min} \quad \text{Eq. 2}$$

$$T_\phi = (T_\phi)_{\max} * I_z = (T_\phi)_{\max} * \frac{400}{800} = (T_\phi)_{\max} * 0.5 \quad \text{Eq. 3}$$

$$T_\phi = (T_\phi)_{\max} * I_z = (T_\phi)_{\max} * \frac{800}{800} = (T_\phi)_{\max} * 1 \quad \text{Eq. 4}$$

Secondly, when the number of zone (Z_ϕ) was set equal to 2 ($L_d = 1600$ m), then five intervals were formed within this distance. The green time (T_ϕ) for the first interval ($0 \text{ m} < \text{Interval 1} \leq dq \text{ (m)}$) was estimated by following Eq. 5. For the second interval ($dq \text{ m} < \text{Interval 2} \leq 400 \text{ m}$) was estimated by following Eq. 6, with an additional condition of T_ϕ not being less than $(T_\phi)_{\text{default}}$. For the third interval ($400 \text{ m} < \text{Interval 3} \leq 800 \text{ m}$) was estimated by following Eq. 7. Furthermore, green time (T_ϕ) for the fourth interval ($800 \text{ m} < \text{Interval 4} \leq 1200 \text{ m}$) was estimated by following Eq. 8. Finally, green time (T_ϕ) for the fifth interval ($1200 \text{ m} < \text{Interval 5} \leq 1600 \text{ m}$) was estimated by following Eq. 9.

$$T_{\phi} = (T_{\phi})_{\min} \quad \text{Eq. 5}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{400}{1600} = (T_{\phi})_{\max} * 0.25 \quad \text{Eq. 6}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{800}{1600} = (T_{\phi})_{\max} * 0.5 \quad \text{Eq. 7}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{1200}{1600} = (T_{\phi})_{\max} * 0.75 \quad \text{Eq. 8}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{1600}{1600} = (T_{\phi})_{\max} * 1 \quad \text{Eq. 9}$$

Thirdly, when the number of zones (Z_{ϕ}) was set equal to 3 ($L_d = 2400$ m), then seven intervals were formed in this distance. The green time (T_{ϕ}) for the first interval ($0 \text{ m} < \text{Interval } 1 \leq dq \text{ (m)}$) was estimated by following Eq. 10. For the second interval ($dq \text{ m} < \text{Interval } 2 \leq 400 \text{ m}$) was estimated by following Eq. 11, with an additional condition of T_{ϕ} not being less than $(T_{\phi})_{\text{default}}$. The green time (T_{ϕ}) for the third interval ($400 \text{ m} < \text{Interval } 3 \leq 800 \text{ m}$) was estimated by following Eq. 12. For the fourth interval ($800 \text{ m} < \text{Interval } 4 \leq 1200 \text{ m}$) was estimated by following Eq. 13. Furthermore, the green time (T_{ϕ}) for the fifth interval ($1200 \text{ m} < \text{Interval } 5 \leq 1600 \text{ m}$) was estimated by following Eq. 14. For the sixth interval ($1600 \text{ m} < \text{Interval } 6 \leq 2000 \text{ m}$) was estimated by following Eq. 15. Finally, the green time (T_{ϕ}) for the seventh interval ($2000 \text{ m} < \text{Interval } 7 \leq 2400 \text{ m}$) was estimated by following Eq. 16.

$$T_{\phi} = (T_{\phi})_{\min} \quad \text{Eq. 10}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{400}{2400} = (T_{\phi})_{\max} * 0.167 \quad \text{Eq. 11}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{800}{2400} = (T_{\phi})_{\max} * 0.33 \quad \text{Eq. 12}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{1200}{2400} = (T_{\phi})_{\max} * 0.5 \quad \text{Eq. 13}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{1600}{2400} = (T_{\phi})_{\max} * 0.67 \quad \text{Eq. 14}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{2000}{2400} = (T_{\phi})_{\max} * 0.83 \quad \text{Eq. 15}$$

$$T_{\phi} = (T_{\phi})_{\max} * I_z = (T_{\phi})_{\max} * \frac{2400}{2400} = (T_{\phi})_{\max} * 1 \quad \text{Eq. 16}$$

Example 4.1: Green time distribution for four phases intersection:

This example describes the green time distribution process for an intersection with four phases (S', N', E', and W'). All are collector roads. Given the distances between the intersection and surrounded intersections as follow: the distance from South is 800 m, from North is 800 m, from East is 2400 m, and from West is 1600 m. Steps of designing the green time distribution models are as follow:

The control system is defined based on the intersection road type. This mean that the control system of this intersection is defined as a collector control system.

The green time distribution model is defined and labeled based on the number of zones. Number of zones at each phase is calculated by dividing the distance over the zone unit (800 m). This mean that the number of zones for this intersection phases are $Z_{S'}= 1$, $Z_{N'}= 1$, $Z_{E'}= 3$, and $Z_{W'}= 2$. The green time distribution model is labeled by 1132 ($Z_{S'}$, $Z_{N'}$, $Z_{E'}$, $Z_{W'}$).

Each zone is divided into several intervals based on the number of zones. This mean that there are 3 intervals through South and North phases ($0 \text{ m} < Z_{qS'} \leq d_q$, $d_q < Z_{qS'} \leq 400 \text{ m}$, $400 \text{ m} < Z_{qS'} \leq 800 \text{ m}$). There are 7 intervals through the East phase ($0 \text{ m} < Z_{qE'} \leq d_q$, $d_q < Z_{qE'} \leq 400 \text{ m}$, $400 \text{ m} < Z_{qE'} \leq 800 \text{ m}$, $800 \text{ m} < Z_{qE'} \leq 1200 \text{ m}$, $1200 \text{ m} < Z_{qE'} \leq 1600 \text{ m}$, $1600 \text{ m} < Z_{qE'} \leq 2000 \text{ m}$, $2000 \text{ m} < Z_{qE'} \leq 2400 \text{ m}$). Finally, there are 5 intervals through the West phase ($0 < Z_{qW'} \leq d_q$, $d_q < Z_{qW'} \leq 400 \text{ m}$, $400 \text{ m} < Z_{qW'} \leq 800 \text{ m}$, $800 \text{ m} < Z_{qW'} \leq 1200 \text{ m}$, $1200 \text{ m} < Z_{qW'} \leq 1600 \text{ m}$).

The green time control system is filled by the timing parameters based on the intersection road types specifications and timing design conditions (Table 14) as follow: the queue detectors were located 77 m from the stop-line for each phase. The minimum green time $(T_{\phi})_{\min} = 6$ sec. The default time $(T_{\phi})_{\text{default}} = 10$ sec. The maximum green time for South and North phases with $Z_{\phi} = 1$ was assigned as $(T_{S'})_{\max} = (T_{N'})_{\max} = 20$ sec. For East phase with $Z_{\phi} = 3$ was assigned as $(T_{E'})_{\max} = 40$ sec. For West phase with $Z_{\phi} = 2$ was assigned as the average of $(T_{\phi})_{\max}$ when $Z_{\phi} = 1$ and $Z_{\phi} = 3$ as $(T_{\phi})_{\max} = \frac{20 + 40}{2} = 30$ sec. The maximum green times were determined for the last interval are presented in Table 15.

Table (15)

Maximum Green Time for a Model 1132

Phase (ϕ)	S'	N'	E'	W'
Z_{ϕ} No.	1	1	3	2
$(T_{\phi})_{\max}$ (sec.)	20	20	40	30
$(T_{\phi})_{\min}$ (sec.)	6	6	6	6
$(T_{\phi})_{\text{default}}$ (sec.)	10	10	10	10
dq (m)	77	77	77	77
$Z_{q\phi}$ (m)	$0 < Z_{qS'} \leq dq$	$0 < Z_{qN'} \leq dq$	$0 < Z_{qE'} \leq dq$	$0 < Z_{qW'} \leq dq$
T_{ϕ} (sec.)				
$Z_{q\phi}$ (m)	$dq < Z_{qS'} \leq 400$	$dq < Z_{qN'} \leq 400$	$dq < Z_{qE'} \leq 400$	$dq < Z_{qW'} \leq 400$
T_{ϕ} (sec.)				
$Z_{q\phi}$ (m)	$400 < Z_{qS'} \leq 800$	$400 < Z_{qN'} \leq 800$	$400 < Z_{qE'} \leq 800$	$400 < Z_{qW'} \leq 800$
T_{ϕ} (sec.)	20	20		
$Z_{q\phi}$ (m)			$800 < Z_{qE'} \leq 1200$	$800 < Z_{qW'} \leq 1200$
T_{ϕ} (sec.)				
$Z_{q\phi}$ (m)			$1200 < Z_{qE'} \leq 1600$	$1200 < Z_{qW'} \leq 1600$
T_{ϕ} (sec.)				30
$Z_{q\phi}$ (m)			$1600 < Z_{qE'} \leq 2000$	
T_{ϕ} (sec.)				
$Z_{q\phi}$ (m)			$2000 < Z_{qE'} \leq 2400$	
T_{ϕ} (sec.)			40	

The green time (T_{ϕ}) for each interval was calculated based on the number of zones (Z_{ϕ}) and I_z ratio. The maximum green time for South and

North phases with $Z_\phi = 1$ was equal to $T_{S'\max} = T_{N'\max} = 20$ sec. As mentioned previously, there are 3 intervals in these phases, and the green time for each interval on these phases were estimated as follow: the green time for the first interval was equal to the minimum time (Eq. 2) as $T_{S'} = T_{N'} = 6$ sec. For the second interval, the green time was estimated by following Eq.3 and was equal to $T_{S'} = T_{N'} = (T_\phi)_{\max} * I_z = 20 * \frac{400}{800} = 20 * 0.5 = 10$ sec. For the third interval, the green time was estimated by either specifying the maximum green time or by following Eq.4 and it was equal to $T_{S'} = T_{N'} = (T_\phi)_{\max} * I_z = 20 * \frac{800}{800} = 20 * 1 = 20$ sec. The results from previous calculations are presented in Table 16.

Table (16)

**Green time Distribution for Intervals on South and North Phases
with $Z_\phi = 1$**

Phase (ϕ)	S'	N'
Z_ϕ No.	1	1
$(T_\phi)_{\max}$ (sec.)	20	20
$(T_\phi)_{\min}$ (sec.)	6	6
$(T_\phi)_{\text{default}}$ (sec.)	10	10
dq (m)	77	77
$Z_{q\phi}$ (m)	$0 < Z_{qS'} \leq dq$	$0 < Z_{qN'} \leq dq$
T_ϕ (sec.)	6	6
$Z_{q\phi}$ (m)	$dq < Z_{qS'} \leq 400$	$dq < Z_{qN'} \leq 400$
T_ϕ (sec.)	10	10
$Z_{q\phi}$ (m)	$400 < Z_{qS'} \leq 800$	$400 < Z_{qN'} \leq 800$
T_ϕ (sec.)	20	20

The maximum green time for East phase with $Z_\phi = 3$ was equal to $T_{E'\max} = 40$ sec. As mentioned previously, there are 7 intervals in this phase, and the green time for each interval on this phase were estimated with a system constraint that the green time should not be less than the default time $(T_\phi)_{\text{default}}$ unless it was the minimum time $(T_\phi)_{\min}$ as follow: the green time for the first interval was estimated by following Eq. 10 and it was equal to $(T_{E'})_{\min} = 6$ sec. For the second interval, the green time was equal

to the default time as $T_{E'} = T_{E'_{\text{default}}} = 10$ sec. The green time for the third interval was estimated by following Eq. 12 and was equal to the $T_{E'} = T_{E'_{\text{Max}}} * I_z = 40 * \frac{800}{2400} = 40 * 0.33 = 13.3$ sec. For the fourth interval, the green time was estimated by following Eq. 13 and was equal to $T_{E'} = T_{E'_{\text{max}}} * I_z = 40 * \frac{1200}{2400} = 40 * 0.5 = 20$ sec. The green phase time for the fifth interval was estimated by following Eq.14 and was equal to $T_{E'} = T_{E'_{\text{max}}} * I_z = 40 * \frac{1600}{2400} = 40 * 0.67 = 26.7$ sec. Furthermore, for the sixth interval, the green time was estimated by following Eq. 15 and was equal to $T_{E'} = T_{E'_{\text{max}}} * I_z = 40 * \frac{2000}{2400} = 40 * 0.83 = 33.3$ sec. The green time for the seventh interval was estimated by following Eq. 16 and was equal to the maximum green time as $T_{E'} = T_{E'_{\text{max}}} * I_z = 40 * \frac{2400}{2400} = 40 * 1 = 40$ sec. These green phase times are presented in Table 17.

Table (17)

Green Time Distribution for Intervals on East Phase with $Z_\phi = 3$

Phase (ϕ)	E'
Z_ϕ No.	3
$(T_\phi)_{\text{max}}$ (sec.)	40
$(T_\phi)_{\text{min}}$ (sec.)	6
$(T_\phi)_{\text{default}}$ (sec.)	10
dq (m)	77
$Z_{q\phi}$ (m)	$0 < Z_{qE'} \leq dq$
T_ϕ (sec.)	6
$Z_{q\phi}$ (m)	$Dq < Z_{qE'} \leq 400$
T_ϕ (sec.)	10
$Z_{q\phi}$ (m)	$400 < Z_{qE'} \leq 800$
T_ϕ (sec.)	13.3
$Z_{q\phi}$ (m)	$800 < Z_{qE'} \leq 1200$
T_ϕ (sec.)	20
$Z_{q\phi}$ (m)	$1200 < Z_{qE'} \leq 1600$
T_ϕ (sec.)	26.7
$Z_{q\phi}$ (m)	$1600 < Z_{qE'} \leq 2000$
T_ϕ (sec.)	33.3
$Z_{q\phi}$ (m)	$2000 < Z_{qE'} \leq 2400$
T_ϕ (sec.)	40

The maximum green time for West phase with $Z_\phi = 2$ was equal to $T_{W'_{\max}} = 30$ sec. As mentioned previously, there are 5 intervals in this phase, and the green time for each interval on this phase were estimated with a system constraint that the green phase time should not be less than the default time $(T_\phi)_{\text{default}}$ unless it was the minimum time $(T_\phi)_{\min.}$. The green time for the first interval was estimated by following Eq. 5 and was equal to $T_{W'} = (T_{W'})_{\min} = 6$ sec. For the second interval, the green time was equal to default time as $T_{W'} = (T_{W'})_{\text{default}} = 10$ sec. For the third interval, the green time was estimated by following Eq. 7 and was equal to $T_{W'} = (T_{W'})_{\max} * I_z = 30 * \frac{800}{1600} = 30 * 0.5 = 15$ sec. For the fourth interval, the green time was estimated by following Eq. 8 and was equal to $T_{W'} = (T_{W'})_{\max} * I_z = 30 * \frac{1200}{1600} = 30 * 0.75 = 22.5$ sec. The green time for fifth interval was estimated by following Eq. 9 and was equal to $T_{W'} = (T_{W'})_{\max} * I_z = 30 * \frac{1600}{1600} = 30 * 1 = 30$ sec. The green phase times for phase W' are presented in Table 18.

Table (18)

Green time Distribution for Intervals on East Phase with $Z_\phi = 2$

Phase (ϕ)	W'
Z_ϕ No.	2
$(T_\phi)_{\max}$ (sec.)	30
$(T_\phi)_{\min}$ (sec.)	6
$(T_\phi)_{\text{default}}$ (sec.)	10
dq (m)	77
$Z_{q\phi}$ (m)	$0 < Z_{qW'} \leq dq$
T_ϕ (sec.)	6
$Z_{q\phi}$ (m)	$dq < Z_{qW'} \leq 400$
T_ϕ (sec.)	10
$Z_{q\phi}$ (m)	$400 < Z_{qW'} \leq 800$
T_ϕ (sec.)	15
$Z_{q\phi}$ (m)	$800 < Z_{qW'} \leq 1200$
T_ϕ (sec.)	22.5
$Z_{q\phi}$ (m)	$1200 < Z_{qW'} \leq 1600$
T_ϕ (sec.)	30

These procedures were applied when developing the 81-green time distribution models for each of the seven control systems. The timing parameters for all intervals of all number of zones were established and arranged in the green time distribution models for the seven control system models. The green time distribution models for collector model are presented in Appendix (1), for major arterial model are presented in Appendix (2), for minor arterial model are presented in Appendix (3), for arterial mix1 are presented in Appendix (4), for arterial mix2 model are presented in Appendix (5), for mix1 model are presented in Appendix (6), and for mix2 model are presented in Appendix (7).

4.4. Stage 2: Design of Fuzzy Rules for Signal Timings

At Stage 2, i.e. step 5, the sets of fuzzy rules were designed to determine the signal timing through two processes (Figure 30). The first process was to select the actual green time distribution model (i, j, k, l). The second process was to execute the control system to determine the intersection timing parameters.

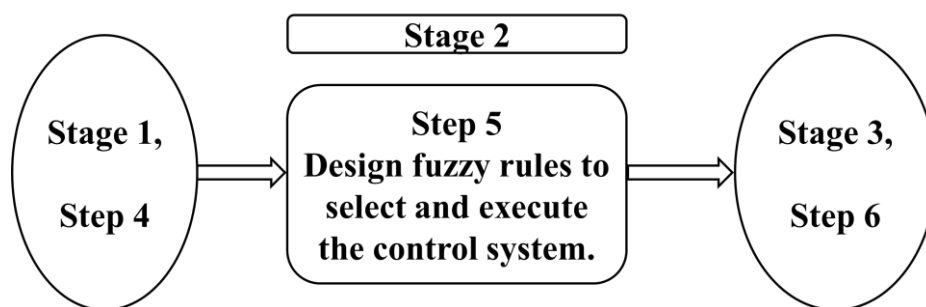


Figure (30)

Designing of Fuzzy Rules at Stage 2

The fuzzy rules for the selection process are designed in step 5A which is further subdivided into 5A.1 and 5A.2, as will be discussed next as “if and then” statements. The fuzzy rules for execution process of the developed control system are designed in step 5B, which in turn was subdivided into 5B.1 and 5B.2 (Figure 31).

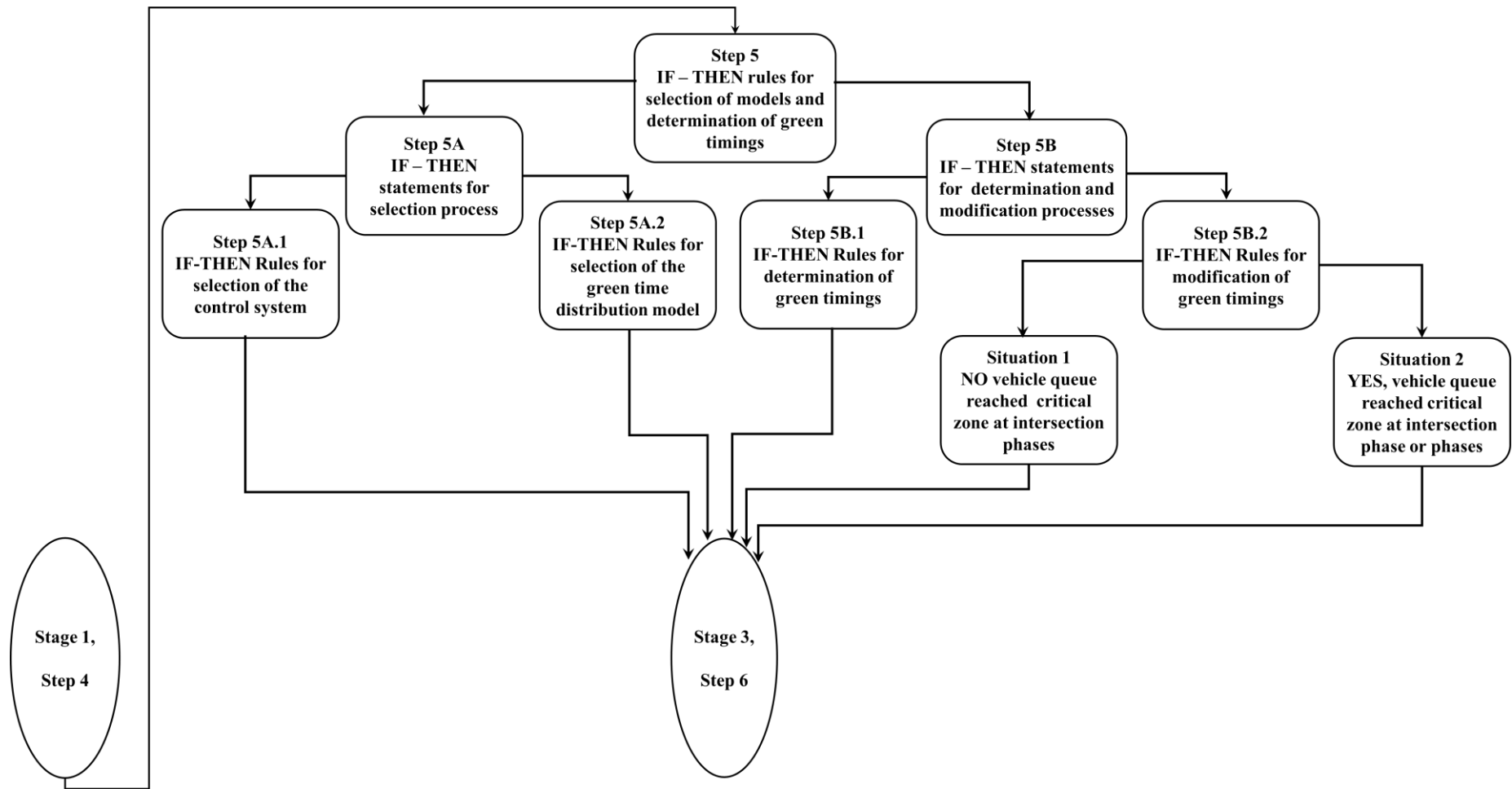


Figure (31)
Processes of Designing Fuzzy Rules

4.4.1. Step 5A: IF-THEN statements for selection process

The selection process specified the actual control system and green time distribution models based on the intersection geometries. A set of fuzzy rules were designed, in step 5A, 5A.1 to select the actual control system model. The fuzzy rules in the following step 5A.2 were designed to select the actual green time distribution model (Figure 32).

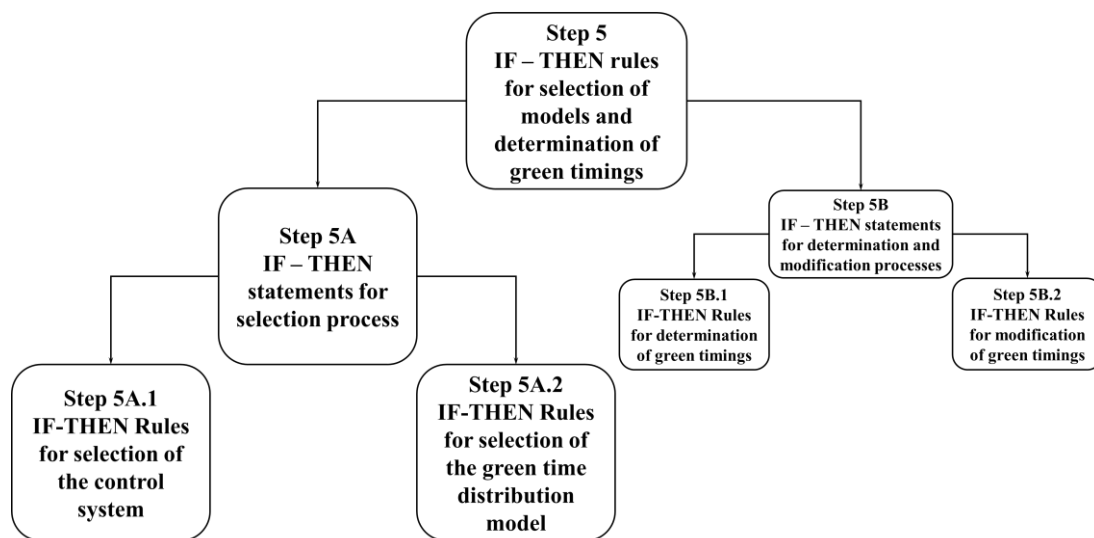


Figure (32)

Fuzzy Rules for Selection Process

i. Step 5A.1: IF-THEN rules for selection of the control system

A set of fuzzy rules were designed to select one out of the seven pre-designed control system models as in Table 13. As mentioned earlier, the intersection is formed by either the same type of roads or different ones. The fuzzy rules were designed by using the intersection roads types as a rule condition, and the control system model names as a result. The scheme of fuzzy rules is shown in Figure 33 and the set of the fuzzy rules are presented in Table 19.

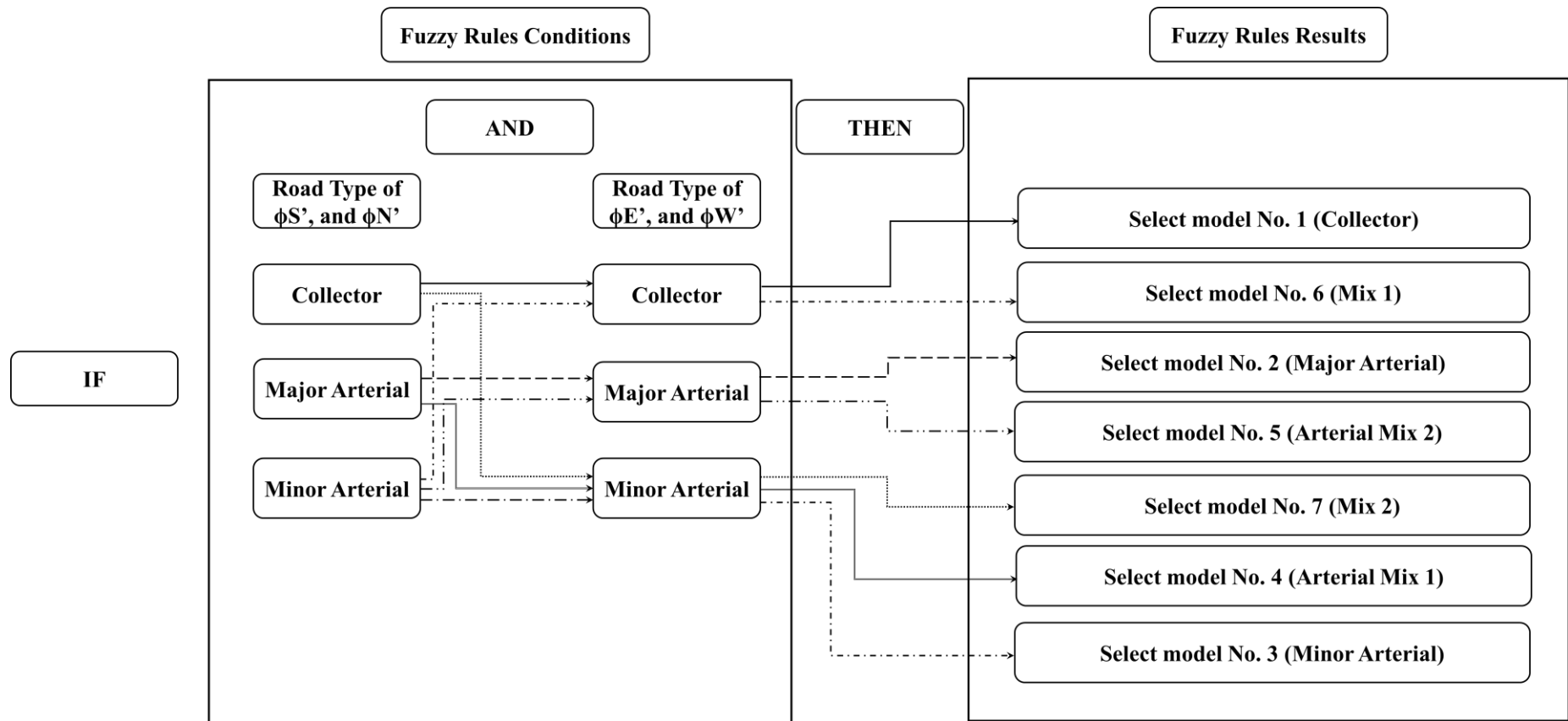


Figure (33)

Schematic of the Fuzzy Rules Design for Selection of the Control System

Table (19)

Fuzzy Rules for Selection of The Control System

IF the S' and N' are Collector roads and E' and W' are Collector roads, THEN select control system No. 1 (collector).
IF the S' and N' are Major Arterial roads and E' and W' are Major Arterial roads, THEN select control system No. 2 (major arterial).
IF the S' and N' are Minor Arterial roads and E' and W' are Minor Arterial roads, THEN select control system No. 3 (minor arterial).
IF the S' and N' are Major Arterial roads and E' and W' are Minor Arterial roads, THEN select control system No. 4 (arterial mix1).
IF the S' and N' are Minor Arterial roads and E' and W' are Major Arterial roads, THEN select control system No. 5 (arterial mix2).
IF the S' and N' are Minor Arterial roads and E' and W' are collector roads, THEN select control system No. 6 (mix1).
IF the S' and N' are Collector roads and E' and W' are Minor Arterial roads, THEN select control system No. 7 (mix2).

Example 4.2 explains the way of designing fuzzy rules for an intersection with the same type of road.

Example 4.2: If the South-North bounds of the intersection consisted of collector road type ($\phi_{S'}$, $\phi_{N'}$) and East-West bounds of a collector road type ($\phi_{E'}$, and $\phi_{W'}$), then the fuzzy rule was designed to select the control system model No. 1 (collector model) from Table 19 as follow:

- IF the road of $\phi_{S'}$ and $\phi_{N'}$ is collector AND IF the road of $\phi_{E'}$, and $\phi_{W'}$ is collector, THEN select model No. 1 (collector model).

ii. Step 5A.2: IF-THEN Rules for selection of the green time distribution model

A set of fuzzy rules were designed to select one out of the eighty-one pre-designed green time distribution models as in Appendices 1-7.

As mentioned earlier, the intersection is surrounded by intersections from four phases with different distances. The fuzzy rules were designed by using the number of zones at each phase as a rule condition, and the green

time distribution model (zoning code) as a result. The scheme of fuzzy rules is shown in Figure 34 and the set of the fuzzy rules are presented in Appendix (8).

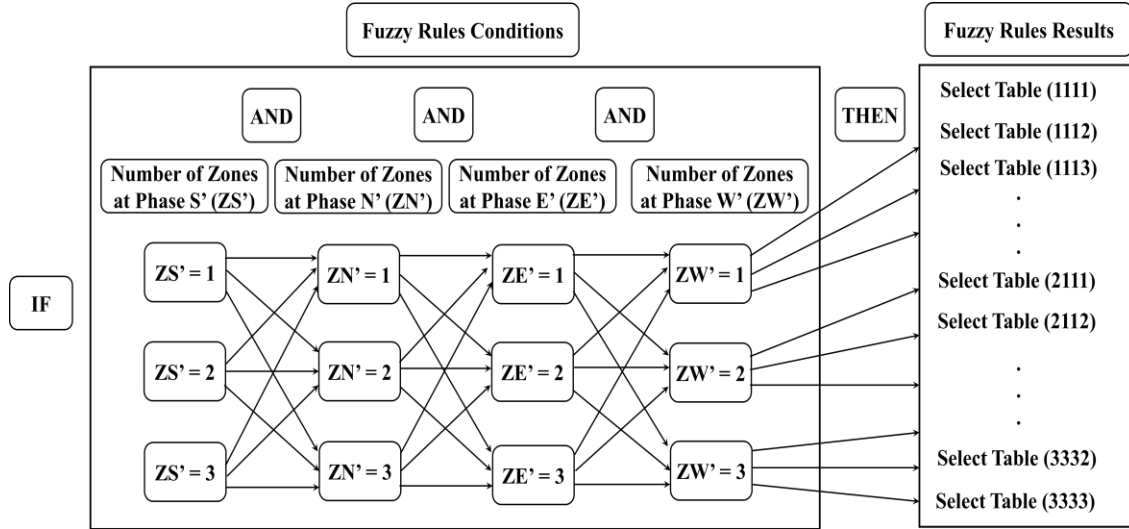


Figure (34)

Schematic of the Fuzzy Rules Design for Selection of the Green Time Distribution Model

Example 4.3 explains the method employed in designing these fuzzy rules.

Example 4.3:

If the numbers of zones of the various phases of the intersection mentioned in example 4.2, were, for example, $Z_{S'} = 1$, $Z_{N'} = 1$, $S_{E'} = 3$, and $S_{W'} = 2$, then the fuzzy rule was designed to select the (1132) green time distribution model (Appendix 1) as follow:

IF $Z_{S'} = 1$ AND $Z_{N'} = 1$ AND $Z_{E'} = 3$ AND $Z_{W'} = 2$, THEN select Table 3.8 (1132).

4.4.2. Step 5B: IF – THEN statements for green timings determination and modification processes

The execution process is the actual run process for the control system where the parameters for timing signals are specified by the determination and modification processes. A set of fuzzy rules are designed, in step 5B.1 to determine the green times from the green time distribution model based on the vehicle queue length along the specified phase. The fuzzy rules in the following step 5B.2 were designed to modify the selected green times according to the prevailing intersection conditions (Figure 35).

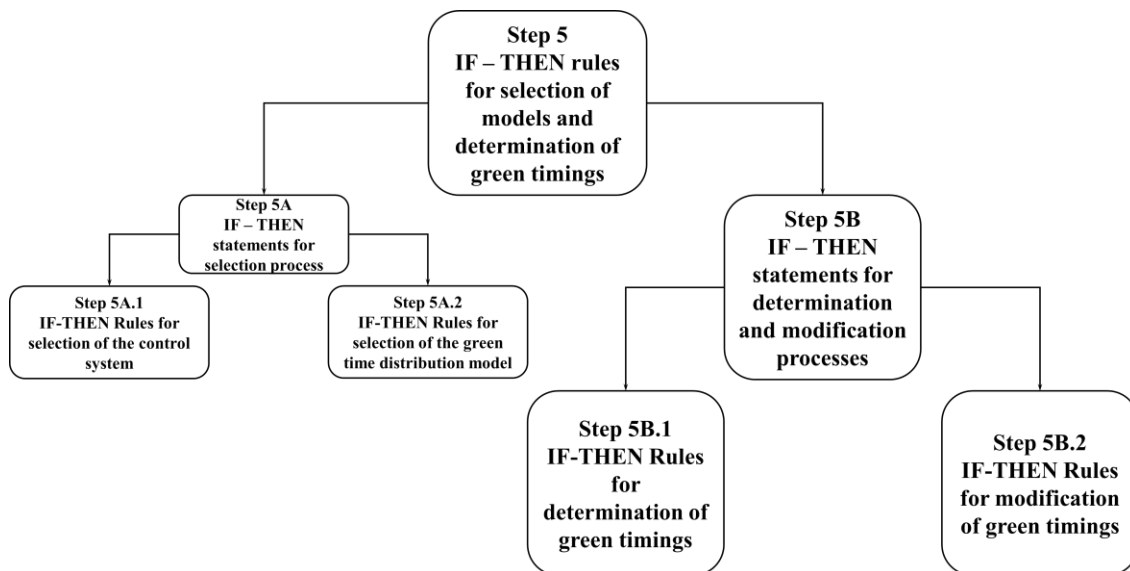


Figure (35)

Design Fuzzy Rules for Green Timings Determination and Modification Processes

i. Step 5B.1: IF-THEN Rules for determination of green timings

A set of fuzzy rules are designed to determine the green time for each phase based on the vehicle queue location at the intersection specified phase. The locations of the tail end of the vehicle queues along the different intersection phases (Z_{ϕ}) were considered as a set of fuzzy rule's conditions,

and consequently the green times (T_ϕ) will be the results. The queue length along the intersection phase will be calculated based on the traffic flow, and the green time will be determined from a set of pre-selected ones from green time distribution models (step 5A.2).

Example 4.4:

In example 4.2, the control system was specified by model No. 1 (collector system) for the intersection. In example 4.3, the green time distribution model for the control system model No. 1 was specified by Table (1132). The signal timings for the intersection, mentioned in examples 4.2 and 4.3, were presented in Table 20. In this example, the locations of the tail end of the vehicle queues along the various phases of the intersection ($Z_{q\phi}$) are considered for example to be as follows: $0 < Z_{qS'} \leq d_q$ (m); d_q (m) $< Z_{qN'} \leq 400$ m; 1600 m $< Z_{qE'} \leq 2000$ m; and 400 m $< Z_{qW'} \leq 800$ m. Table 20, specifies the following green times: $T_{S'} = (T_{S'})_{\min} = 6$ sec.; $T_{N'} = 10$ sec.; $T_{E'} = (T_{E'})_{\text{table}} = 33.3$ sec. and $T_{W'} = (T_{W'})_{\text{table}} = 15$ sec. In summary, the calculations of green times are explained earlier in step 4 Section 4.3.4. And the fuzzy rule is:

- IF $0 < Z_{qS'} \leq d_q$ (m) AND d_q (m) $< Z_{qN'} \leq 400$ m AND 1600 m $< Z_{qE'} \leq 2000$ m AND 400 m $< Z_{qW'} \leq 800$ m, THEN $T_{S'} = 6$ sec. AND $T_{N'} = 10$ sec. AND $T_{E'} = 33.3$ sec. AND $T_{W'} = 15$ sec.

Table (20)**Green Time Distribution for Model 1132**

Phase (ϕ)	S'	N'	E'	W'
Z_ϕ No.	1	1	3	2
$(T_\phi)_{\max}$ (sec.)	20	20	40	30
$(T_\phi)_{\min}$ (sec.)	6	6	6	6
$(T_\phi)_{\text{default}}$ (sec.)	10	10	10	10
d_q (m)	77	77	77	77
$Z_{q\phi}$ (m)	$0 < Z_{qS'} \leq d_q$	$0 < Z_{qN'} \leq d_q$	$0 < Z_{qE'} \leq d_q$	$0 < Z_{qW'} \leq d_q$
T_ϕ (sec.)	6	6	6	6
$Z_{q\phi}$ (m)	$d_q < Z_{qS'} \leq 400$	$d_q < Z_{qN'} \leq 400$	$d_q < Z_{qE'} \leq 400$	$d_q < Z_{qW'} \leq 400$
T_ϕ (sec.)	10	10	6.7	7.5
$Z_{q\phi}$ (m)	$400 < Z_{qS'} \leq 800$	$400 < Z_{qN'} \leq 800$	$400 < Z_{qE'} \leq 800$	$400 < Z_{qW'} \leq 800$
T_ϕ (sec.)	20	20	13.3	15
$Z_{q\phi}$ (m)			$800 < Z_{qE'} \leq 1200$	$800 < Z_{qW'} \leq 1200$
T_ϕ (sec.)			20	22.5
$Z_{q\phi}$ (m)			$1200 < Z_{qE'} \leq 1600$	$1200 < Z_{qW'} \leq 1600$
T_ϕ (sec.)			26.7	30
$Z_{q\phi}$ (m)			$1600 < Z_{qE'} \leq 2000$	
T_ϕ (sec.)			33.3	
$Z_{q\phi}$ (m)			$2000 < Z_{qE'} \leq 2400$	
T_ϕ (sec.)			40	

ii. Step 5B.2: IF-THEN Rules for modification of green timings

The green times determined in step 5B.1 for the normal situations where the vehicle queue length for the various phases, did not reach a critical zone interval $(Z)_{\text{critical}}$. Where the critical zone interval $(Z)_{\text{critical}}$ as defined earlier is the last interval in the intersection distance. In the modification process, the control system checks the conditions to change the determined green times if necessary. The control system checks the location of the end of the vehicle queues for the various phases to determine whether these queues did reach the first, second or critical zone interval or did not $(Z)_{\text{critical}}$. Then, the control system checks the relation between the total cycle time $(T)_{\text{total}}$ (i.e. the sum of

the determined green times and clearance times of the phases) and the maximum cycle time $(T)_{\text{Cycle}}$ as specified at the green time distribution models as $(T)_{\text{total}} < (T)_{\text{cycle}}$, $(T)_{\text{total}} = (T)_{\text{cycle}}$ and $(T)_{\text{total}} > (T)_{\text{cycle}}$. Based on the vehicles queues locations and the relation between $(T)_{\text{total}}$ and $(T)_{\text{cycle}}$, the control system deals with the situation by using the fuzzy rules that are designed in this step.

The fuzzy rules are designed to modify green times for two situations: situation 1 when there is NO vehicle queue reaching the critical zone; and situation 2 when YES there is a vehicle queue which has reached the critical zone (Figure 36).

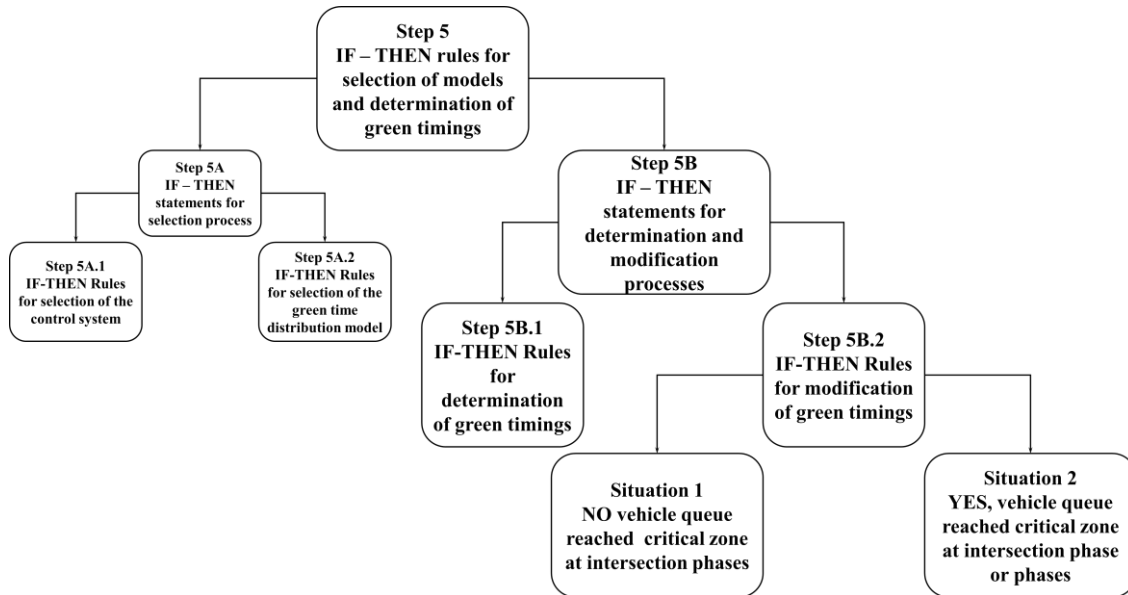


Figure (36)

Schematic of the Fuzzy Rules Design for the Green Timings Modification Process

The fuzzy rules for situation 1 and situation 2 are designed based on the number of phases their vehicle queues reached the critical zone at each intersection. For each situation, three sets of fuzzy rules are designed based on the relationship between the calculated total cycle time $((T)_{\text{total}})$ and the

maximum cycle time ($(T)_{\text{cycle}}$) as $(T)_{\text{total}} < (T)_{\text{cycle}}$; $(T)_{\text{total}} = (T)_{\text{cycle}}$; or $(T)_{\text{total}} > (T)_{\text{cycle}}$ as follow:

Situation 1: When there is NO vehicle queue (Z_q) reaching a critical zone interval ($Z)_{\text{critical}}$, then three sets of fuzzy rules are designed. These are explained next (Figure 37).

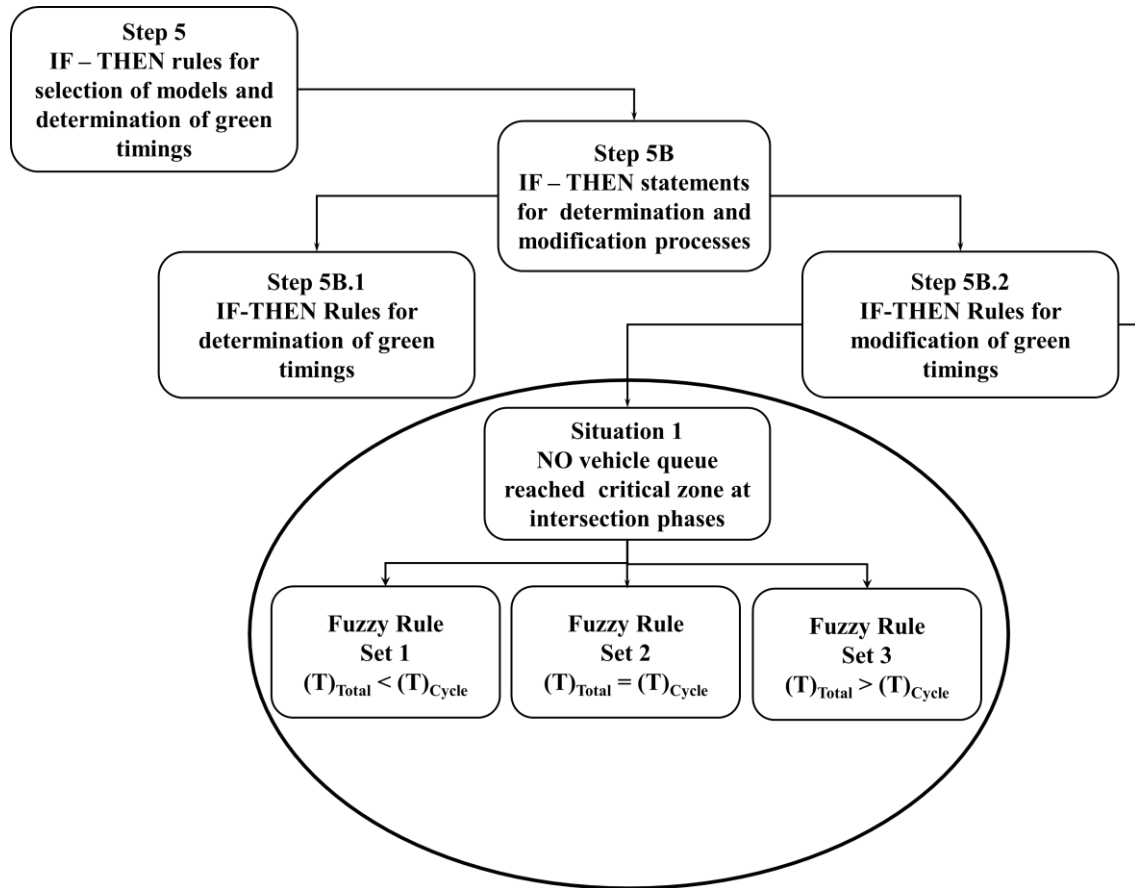


Figure (37)

Schematic of the Fuzzy Rules Design for Situation 1 of the Green Timings Modification Process

The fuzzy rules for situation 1 are designed where the vehicle queue locations in the intersection distance, number of phases that their vehicle queue (Z_q) reached the first or second intervals with green times equal $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), and the relationship between the calculated total cycle time $(T)_{\text{total}}$ and the specified maximum cycle time $(T)_{\text{cycle}}$ are used as the fuzzy

rule conditions. The green times (T_ϕ) after modification are the results of fuzzy rules.

Fuzzy rules to check the vehicle queue locations and the relation between $(T)_{\text{total}}$ and $(T)_{\text{cycle}}$ were designed as follow:

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) < (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) < (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) < (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) < (Z_{\phi 4})_{\text{critical}}$, THEN select fuzzy rules set 1.
- IF $(T)_{\text{total}} = (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) < (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) < (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) < (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) < (Z_{\phi 4})_{\text{critical}}$, THEN select fuzzy rules set 2.
- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) < (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) < (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) < (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) < (Z_{\phi 4})_{\text{critical}}$, THEN select fuzzy rules set 3.

Fuzzy rules set 1: when $(T)_{\text{total}} < (T)_{\text{cycle}}$ and no vehicles reached the critical zone $(Z_\phi)_{\text{critical}}$, then the green time (T_ϕ) was equal to the time that is determined by step 5B.1 (timings from green time distribution model). Fuzzy rules were designed as:

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$, AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{table}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{table}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$.

Fuzzy rules set 2: when $(T)_{\text{total}} = (T)_{\text{cycle}}$ and no vehicles reached the critical zone $(Z_\phi)_{\text{critical}}$ then the green time was (T_ϕ) equal to the time that was determined by step 5B.1. Fuzzy rules were designed as:

- IF $(T)_{\text{total}} = (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{table}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{table}}$

$$\text{AND } (T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}} \text{ AND } (T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} \text{ AND } (T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}.$$

Fuzzy rules set 3: when $(T)_{\text{total}} > (T)_{\text{cycle}}$ and no vehicles reached the critical zone $(Z_{\phi})_{\text{critical}}$, several fuzzy rules were designed for four situations. These situations are, when no phase had green time which equaled $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), when one phase had a green time equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), when two phases have green time which were equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), and when three phases have green time which were equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$) (Figure 38).

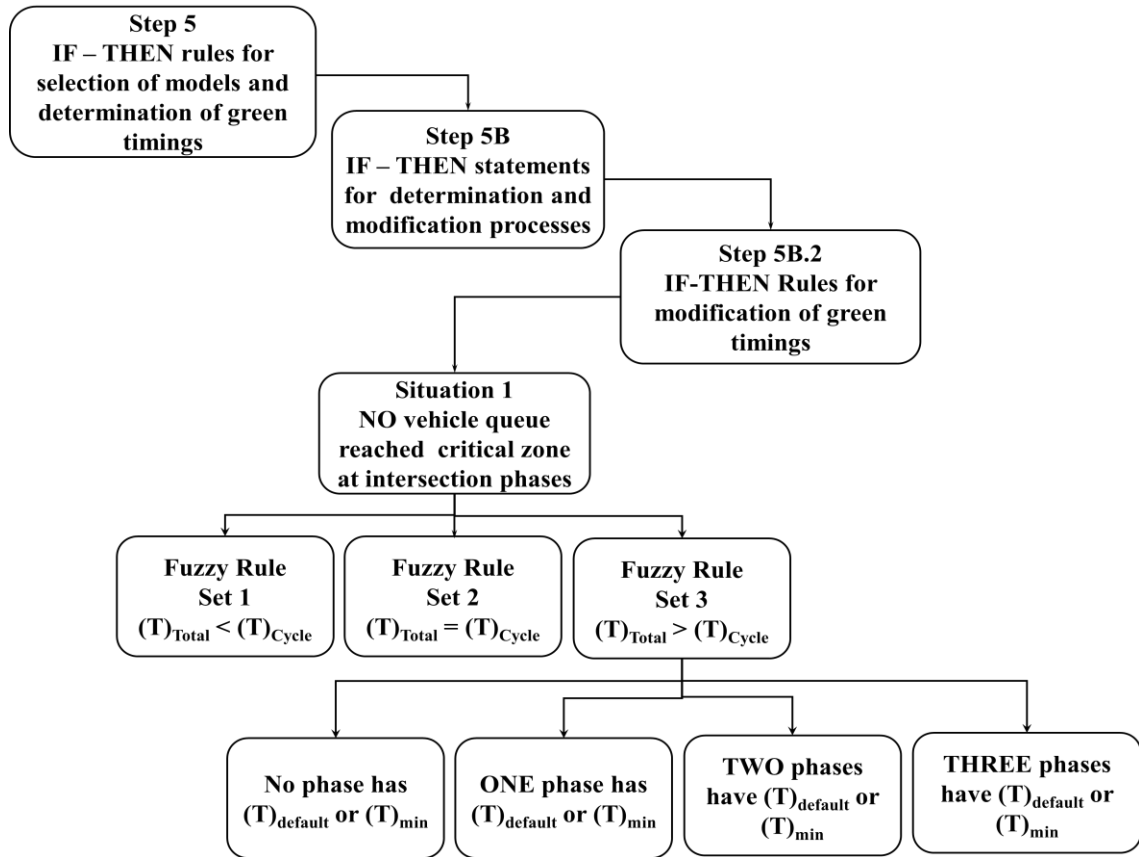


Figure (38)

Schematic of the Fuzzy Rules Design for Situation 1 When $(T)_{\text{total}} > (T)_{\text{cycle}}$

1. When $(T)_{\text{total}} > (T)_{\text{cycle}}$, no vehicles had reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there was no phase which had a green time equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), then the time difference between $(T)_{\text{total}}$ and $(T)_{\text{cycle}}$ was deducted from the determined green time equally with a condition that green time (T_{ϕ}) was not less than default time $(T_{\phi})_{\text{default}}$ unless the specified green time equals $(T_{\phi})_{\text{min}}$. Fuzzy rule was designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{table}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$.

If the green time of a phase $(T_{\phi})_{\text{modified}} < (T_{\phi})_{\text{default}}$, then the control system did more modifications for the green times considering that there is a phase (phases) has $(T_{\phi})_{\text{default}}$.

2. When $(T)_{\text{total}} > (T)_{\text{cycle}}$, had no vehicles which had reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there was one phase which had a green time equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), then the green time of this phase was equal to the $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), and the time difference between $(T)_{\text{total}}$ and $(T)_{\text{cycle}}$ was deducted from the other determined green times equally with a condition that (T_{ϕ}) should not be less than $(T_{\phi})_{\text{default}}$. That means, if the intersection phases (ϕ) have no vehicle queue which had reached the critical zone interval $(Z)_{\text{critical}}$, $(T)_{\text{total}} > (T)_{\text{cycle}}$ and $(Z_{\phi 1})$ at first interval then the control system modified $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{min}}$ (same as if $(T_{\phi 1}) = (T_{\phi})_{\text{default}}$) and the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the other three phases $(\phi 2, \phi 3, \phi 4)$ equally. Same when two or three phases have $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$). Fuzzy rules are designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{min}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{min}}$

AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 3$, AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 3$, AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 3$.

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{default}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{default}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 3$, AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 3$, AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 3$.

3. When $(T)_{\text{total}} > (T)_{\text{cycle}}$, no vehicles reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there are two phases which have green times equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), fuzzy rules were designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{min}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{min}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{min}}$, AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 2$, AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 2$.
- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{default}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$, THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{default}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{min}}$, AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 2$, AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}) / 2$.

4. When $(T)_{\text{total}} > (T)_{\text{cycle}}$, no vehicles reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there are three phases which have green times equal to $(T_{\phi})_{\text{min}}$ or $(T_{\phi})_{\text{default}}$, fuzzy rules were designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{min}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$, THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{min}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{min}}$, AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{min}}$, AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})$.
- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1}) = (T_{\phi 1})_{\text{default}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$, THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{default}}$

$$\text{AND } (T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{min}}, \text{ AND } (T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{min}}, \text{ AND } (T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}}).$$

When four phases have green times equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$), then there was no chance for $(T)_{\text{total}}$ to be greater than $(T)_{\text{cycle}}$.

Situation 2: When YES, there is a vehicle queue (Z_q) which had reached the critical zone $(Z_{\phi})_{\text{critical}}$, sets of fuzzy rules were designed for four cases based on the number of phases (one, two, three or four phases) that their vehicle queue (Z_q) had reached the critical zone interval $(Z)_{\text{critical}}$ as follow:

Case 1: when vehicle queue of one phase reached the critical zone

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) = (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) < (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) < (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) < (Z_{\phi 4})_{\text{critical}}$ THEN select fuzzy rules in case 1.

Case 2: when vehicle queue of two phases reached the critical zone

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) = (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) = (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) < (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) < (Z_{\phi 4})_{\text{critical}}$ THEN select fuzzy rules in case 2.

Case 3: when vehicle queue of three phases reached the critical zone

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) = (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) = (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) = (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) < (Z_{\phi 4})_{\text{critical}}$ THEN select fuzzy rules in case 3.

Case 4: when vehicle queue of four phases reached the critical zone

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(Z_{\phi 1}) = (Z_{\phi 1})_{\text{critical}}$ AND $(Z_{\phi 2}) = (Z_{\phi 2})_{\text{critical}}$ AND $(Z_{\phi 3}) = (Z_{\phi 3})_{\text{critical}}$ AND $(Z_{\phi 4}) = (Z_{\phi 4})_{\text{critical}}$ THEN select fuzzy rules in case 4.

For each case, three sets of fuzzy rules were designed based on the relation between $(T)_{\text{total}}$ and $(T)_{\text{cycle}}$ ($(T)_{\text{total}} < (T)_{\text{cycle}}$; $(T)_{\text{total}} = (T)_{\text{cycle}}$; and $(T)_{\text{total}} > (T)_{\text{cycle}}$) (Figure 39).

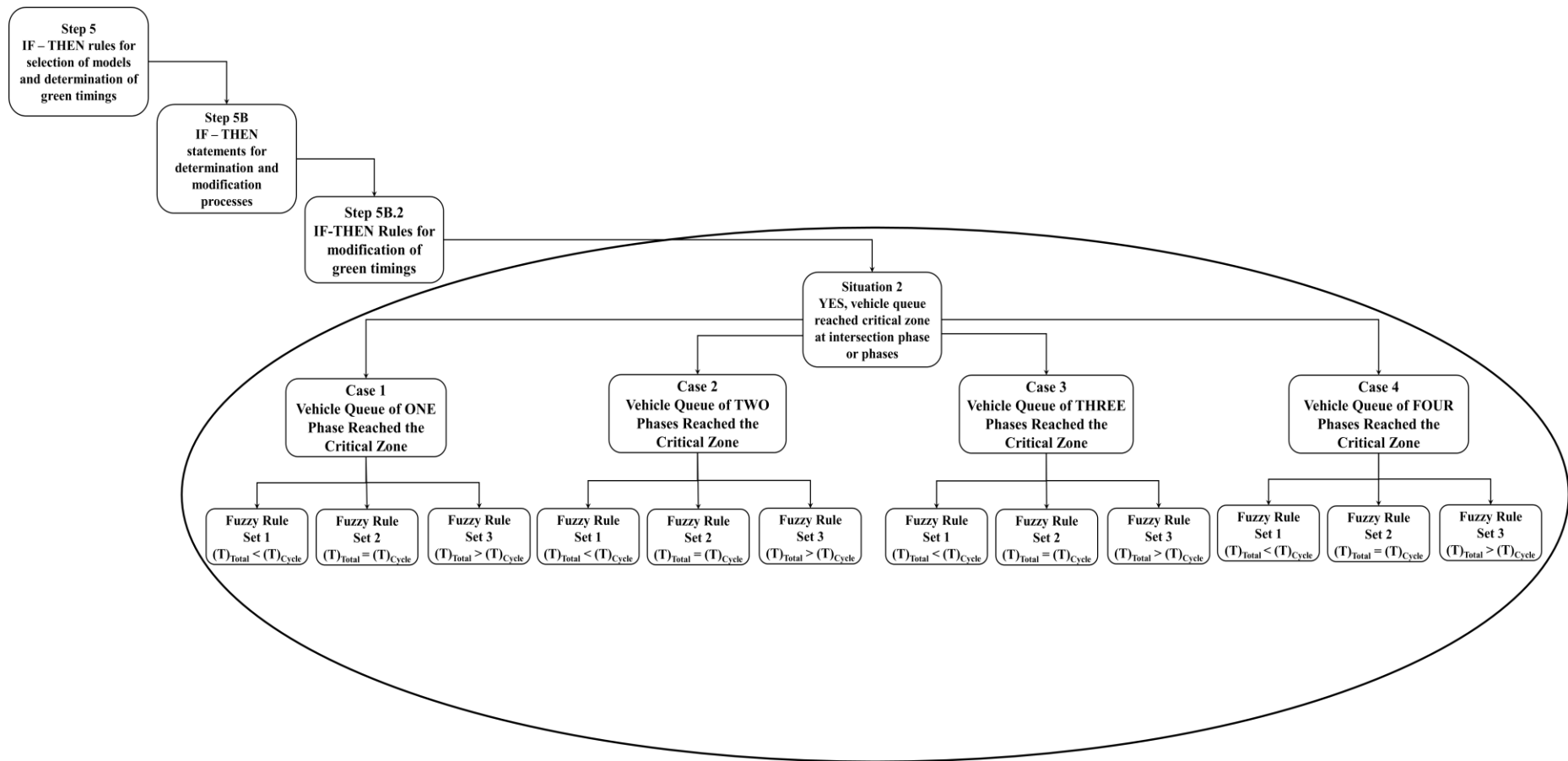


Figure (39)

Schematic of the Four Cases Formed for Situation 2

Number of phases that their vehicle queue reached the critical zone, vehicle queue locations in the intersection' distances, number of phases that their green times equaled $(T)_{\min}$ (or $(T)_{\text{default}}$), and the relationship between the calculated total cycle time $(T)_{\text{total}}$ and the specified maximum cycle time $(T)_{\text{cycle}}$ were used for the fuzzy rule conditions. Green times (T_{ϕ}) are the fuzzy rules results. As mentioned previously, four cases were designed based on the number of phases which had vehicle queues which had reached the critical zone.

The cases and the three sets of fuzzy rules were designed as follow:

Case 1: Three sets of fuzzy rules were designed when vehicle queues of ONE phase had reached the critical zone.

Fuzzy rule set 1: when $(T)_{\text{total}} < (T)_{\text{cycle}}$ and vehicle queue of one phase reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all other phases were specified as the green time in the green time distribution model, and the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was added to the green time of the phase with $(Z_{\phi})_{\text{critical}}$. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$

Fuzzy rule set 2: when $(T)_{\text{total}} = (T)_{\text{cycle}}$ and vehicle queue of one phase had reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all other phases was specified as the green time in the green time distribution model. The fuzzy rule was designed as:

- IF $(T)_{\text{total}} = (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$.

Fuzzy rules set 3: when $(T)_{\text{total}} > (T)_{\text{cycle}}$ and no vehicles had reached the critical zone $(Z_{\phi})_{\text{critical}}$, several fuzzy rules were designed for four subsets. These subsets are: when no phase had a green time equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$); when one phase had a green time equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$); when two phases have green times equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$); and when three phases have green times equal to $(T_{\phi})_{\text{min}}$ (or $(T_{\phi})_{\text{default}}$) (Figure 40).

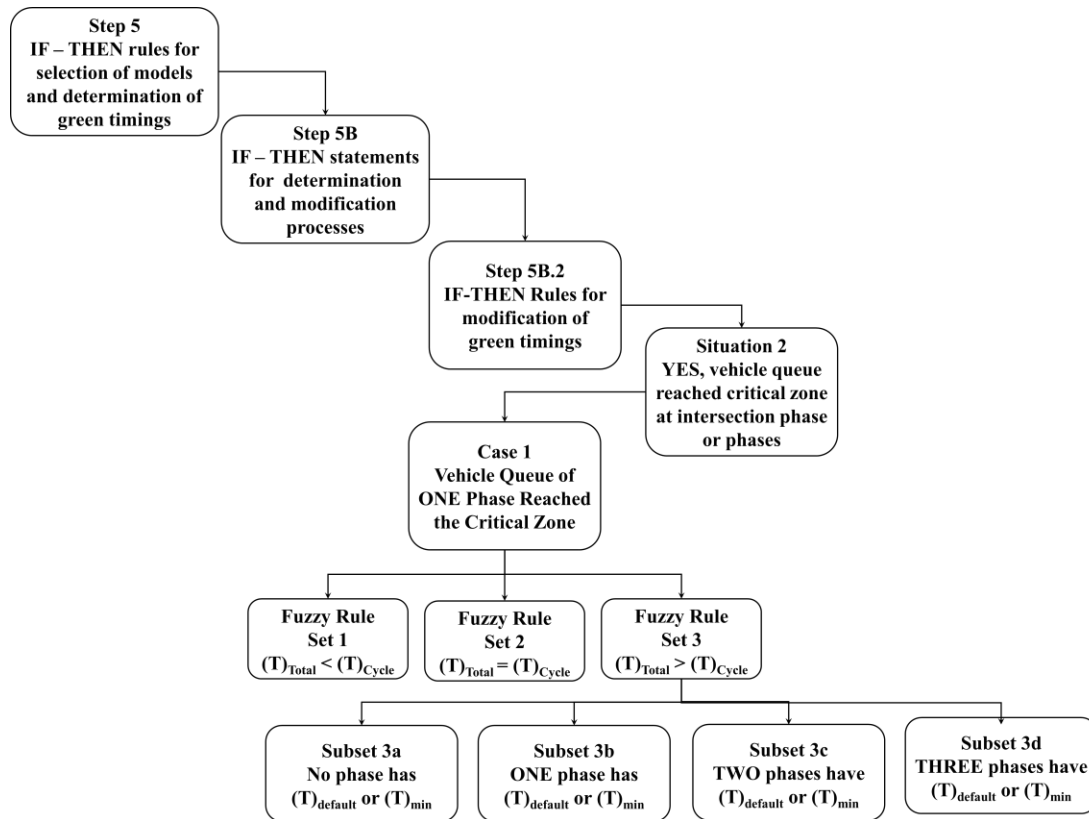


Figure (40)

Schematic of the Fuzzy Rules Design of Fuzzy Rules for Case 1 for Situation 2 When $(T)_{\text{total}} > (T)_{\text{cycle}}$

Subset 3a: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of one phase had reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there were no phase had a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then (T_{ϕ}) for the phase with $(Z)_{\text{critical}}$ was specified as the green time in the green time distribution model. The time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the other phases

specified green times equally with a consideration that $(T_{\phi})_{\text{modified}}$ should not be less than $(T_{\phi})_{\text{default}}$ unless the specified green time was equal to $(T_{\phi})_{\text{min}}$. The fuzzy rule was designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{table}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$.

Again, if the green time of a phase $(T_{\phi})_{\text{modified}} < (T_{\phi})_{\text{default}}$, then the control system did more modifications for the green times considering that there is a phase (phases) which was $(T_{\phi})_{\text{default}}$.

Subset 3b: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of one phase had reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there was one phase which had a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then (T_{ϕ}) for the phase with $(Z)_{\text{critical}}$ and the phase with $(T)_{\text{min}}$ (or $(T)_{\text{default}}$) are specified as the green time in the green time distribution model. The time differences between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the other phases specified green phases time equally with a condition that $(T_{\phi})_{\text{modified}}$ should not be less than $(T_{\phi})_{\text{default}}$ unless the specified green time equals $(T_{\phi})_{\text{min}}$. That means, when the vehicle queue reached the critical zone then the green time was at maximum $(T_{\phi})_{\text{max}}$. When the vehicle queue reached the first interval ($0 \leq Z_q < dq$), then the green time was equal to $(T_{\phi})_{\text{min}}$. (same as if the vehicle queue had reached second interval ($dq \leq Z_q < 400$ m), then the green time was equal to $(T)_{\text{default}}$). Since the $(T)_{\text{total}} > (T)_{\text{cycle}}$, the time difference was therefore deducted from the other phases, whose green times are neither $(T_{\phi})_{\text{max}}$ or $(T_{\phi})_{\text{min}}$ (or $(T)_{\text{default}}$), equally. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$.

Subset 3c: Same design process was applied $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of one phase reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there were two phases having green times which equaled $(T)_{\text{min}}$ (or $(T)_{\text{default}}$) as follow:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{correction}} = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3})_{\text{correction}} = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4})_{\text{correction}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})$.

Subset 3d: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of one phase reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there were three phases which have green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the green time of the phase that its vehicle queue reached the critical zone:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2}) = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{min}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{min}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{min}}$

Case 2: Three sets of fuzzy rules were designed when vehicle queues of TWO phases reached the critical zone.

Fuzzy rule set 1: when $(T)_{\text{total}} < (T)_{\text{cycle}}$ and vehicle queue of two phases reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all other phases are specified as the green time in the green time distribution model, and the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was added to the green time of

the two phases with $(Z_\phi)_{\text{critical}}$ equally. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$

Fuzzy rule set 2: when $(T)_{\text{total}} = (T)_{\text{cycle}}$ and vehicle queue of two phases reached the critical zone $(Z_\phi)_{\text{critical}}$, then the (T_ϕ) for all other phases are specified as the green time in the green time distribution model. The fuzzy rule was designed as:

- IF $(T)_{\text{total}} = (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$.

Fuzzy rule set 3: when $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of two phases reached the critical zone $(Z_\phi)_{\text{critical}}$, several fuzzy rules were designed for three subsets. These subsets are: when no phase has green time, which is equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$); when one phase has a green time which is equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$); and when two phases have green times which are equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$) (Figure 41).

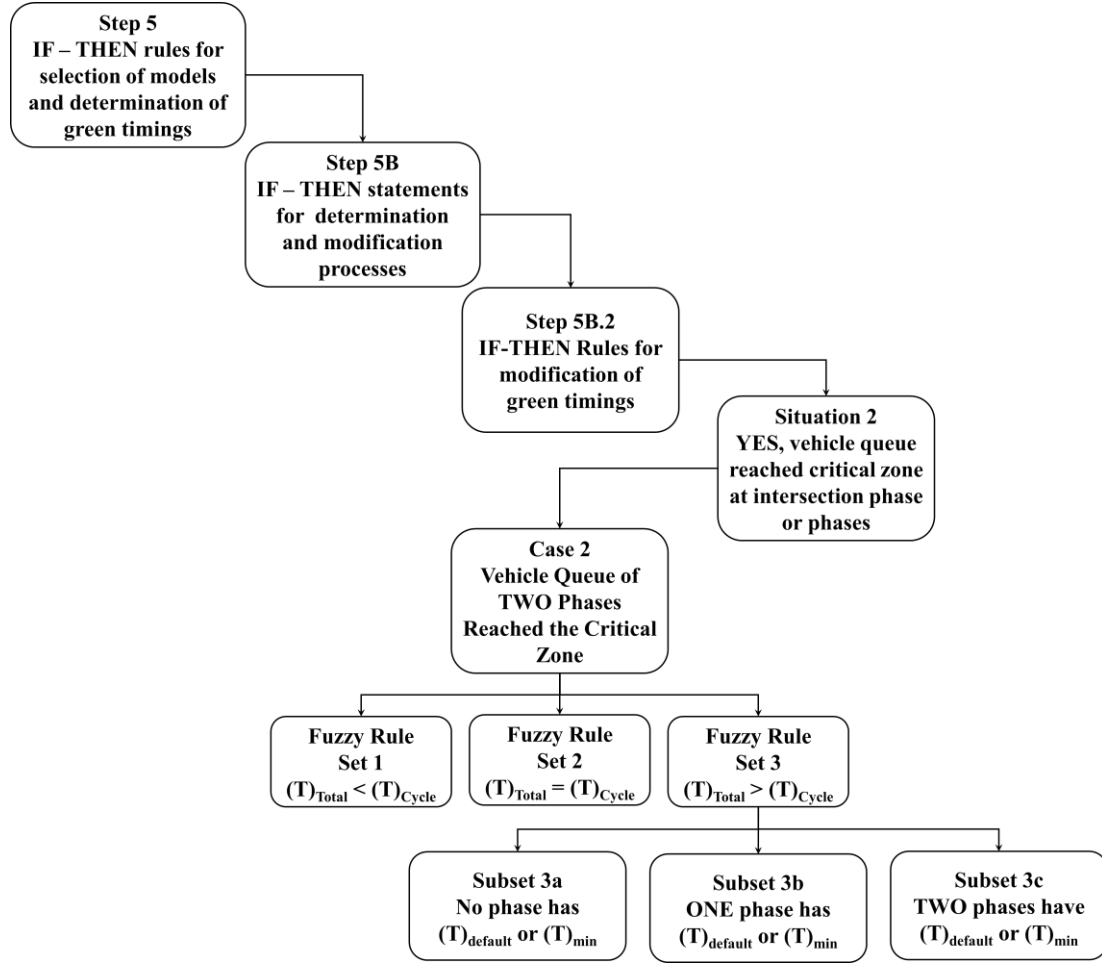


Figure (41)

**Schematic of the Fuzzy Rules Design of Fuzzy Rules for Case 2 for
Situation 2 When $(T)_{total} > (T)_{cycle}$**

Subset 3a: When $(T)_{total} > (T)_{cycle}$ and vehicle queue of two phases reached the critical zone $(Z_{\phi})_{critical}$ and there were no phases which had a green time equal to $(T)_{min}$ (or $(T)_{default}$), then (T_{ϕ}) for the phases with $(Z)_{critical}$ was specified as the green time in the green time distribution model. As a consequence, the time difference between $(T)_{cycle}$ and $(T)_{total}$ was deducted from the other two phases specified green times equally with a consideration that $(T_{\phi})_{modified}$ should not be less than $(T_{\phi})_{default}$ unless the specified green time was equal to $(T_{\phi})_{min}$. The fuzzy rule was designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{table}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$.

Again, if the green time of a phase $(T_{\phi})_{\text{modified}} < (T_{\phi})_{\text{default}}$, then the control system did more modifications for the green times with consideration that there was a phase (phases) which was $(T_{\phi})_{\text{default}}$.

Subset 3b: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of two phases reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there was one phase which had a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then (T_{ϕ}) for the phases with $(Z)_{\text{critical}}$ and the phase with $(T)_{\text{min}}$ (or $(T)_{\text{default}}$) were specified as the green time in the green time distribution model. The time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the last phase specified green phases time with a condition that $(T_{\phi})_{\text{modified}}$ should not be less than $(T_{\phi})_{\text{default}}$ unless the specified green time was equal to $(T_{\phi})_{\text{min}}$. That means, when the vehicle queue reached the critical zone then the green time is at the maximum $(T_{\phi})_{\text{max}}$. When the vehicle queue reached the first interval $(0 \leq Z_q < dq)$, then the green time was equal to $(T_{\phi})_{\text{min}}$. (same as if the vehicle queue reached second interval $(dq \leq Z_q < 400 \text{ m})$, then the green time was equal to $(T)_{\text{default}}$. Since $(T)_{\text{total}} > (T)_{\text{cycle}}$, time difference was deducted from the last phase where its green time was neither $(T_{\phi})_{\text{max}}$ or $(T_{\phi})_{\text{min}}$ (or $(T)_{\text{default}}$) equally. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})$.

Subset 3c: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of two phases reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there were two phases which had a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the green time of the phases for whose vehicle queue had reached the critical zone. The fuzzy rule for this situation was designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3}) = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{min}}$, THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/2$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{min}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{min}}$

Case 3: As previous cases, three sets of fuzzy rules were designed when vehicle queue of THREE phases had reached the critical zone.

Fuzzy rule set 1: when $(T)_{\text{total}} < (T)_{\text{cycle}}$ and vehicle queue of three phases reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all other phases was specified as the green time in the green time distribution model, and the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was added to the green time of the three phases with $(Z_{\phi})_{\text{critical}}$ equally. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{critical}} = (T_{\phi 3})_{\text{max}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$

Fuzzy rule set 2: when $(T)_{\text{total}} = (T)_{\text{cycle}}$ and vehicle queue of three phases had reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all other

phases were specified as the green time in the green time distribution model. The fuzzy rule was designed as:

- IF $(T)_{\text{total}} = (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{critical}} = (T_{\phi 3})_{\text{max}}$ AND $(T_{\phi 4}) = (T_{\phi 4})_{\text{table}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{max}}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}}$.

Fuzzy rule set 3: when $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of three phases had reached the critical zone $(Z_{\phi})_{\text{critical}}$, fuzzy rules were designed for two subsets. These subsets are: when no phase has a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$); and when one phase had a green time which was equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$) (Figure 42).

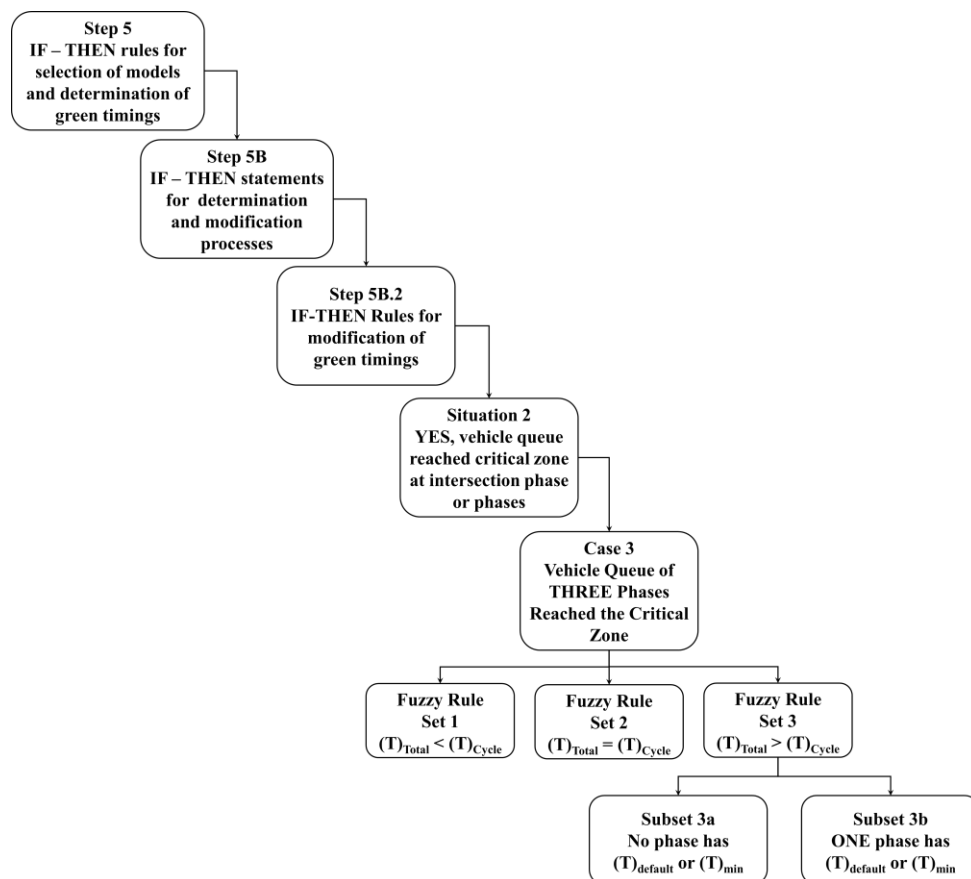


Figure (42)

**Schematic of the Fuzzy Rules Design of Fuzzy Rules for Case 3 for
Situation 2 When $(T)_{\text{total}} > (T)_{\text{cycle}}$**

Subset 3a: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of three phases had reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there was no phase which had a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then (T_{ϕ}) for the phases with $(Z)_{\text{critical}}$ and the phase with $(T)_{\text{min}}$ (or $(T)_{\text{default}}$) were specified as the green time in the green time distribution model. The time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the last phase specified green phases time with a condition that $(T_{\phi})_{\text{modified}}$ should not be less than $(T_{\phi})_{\text{default}}$ unless the specified green time was equal to $(T_{\phi})_{\text{min}}$. This indicates that when the vehicle queue reached the critical zone then the green time was as the maximum $(T_{\phi})_{\text{max}}$. When the vehicle queue reached the first interval ($0 \leq Zq < dq$), then the green time was equal to $(T_{\phi})_{\text{min}}$. (same as if the vehicle queue reached second interval ($dq \leq Zq < 400$ m), then the green time was equal to $(T)_{\text{default}}$). Since the $(T)_{\text{total}} > (T)_{\text{cycle}}$, then the time difference was deducted from the last phase where its green time was nether $(T_{\phi})_{\text{max}}$ or $(T_{\phi})_{\text{min}}$ (or $(T)_{\text{default}}$) equally. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi1})_{\text{critical}} = (T_{\phi1})_{\text{max}}$ AND $(T_{\phi2})_{\text{critical}} = (T_{\phi2})_{\text{max}}$ AND $(T_{\phi3})_{\text{critical}} = (T_{\phi3})_{\text{max}}$ AND $(T_{\phi4}) = (T_{\phi4})_{\text{table}}$; THEN $(T_{\phi1})_{\text{modified}} = (T_{\phi1})_{\text{max}}$ AND $(T_{\phi2})_{\text{modified}} = (T_{\phi2})_{\text{max}}$ AND $(T_{\phi3})_{\text{modified}} = (T_{\phi3})_{\text{max}}$ AND $(T_{\phi4})_{\text{modified}} = (T_{\phi4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})$.

Subset 3b: When $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of three phases reached the critical zone $(Z_{\phi})_{\text{critical}}$ and there was one phase which had a green time equal to $(T)_{\text{min}}$ (or $(T)_{\text{default}}$), then the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the green time of the phases their vehicle queue reached the critical zone. The fuzzy rule for this situation was designed as:

- IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi1})_{\text{critical}} = (T_{\phi1})_{\text{max}}$ AND $(T_{\phi2})_{\text{critical}} = (T_{\phi2})_{\text{max}}$ AND $(T_{\phi3})_{\text{critical}} = (T_{\phi3})_{\text{max}}$ AND $(T_{\phi4}) = (T_{\phi4})_{\text{min}}$; THEN $(T_{\phi1})_{\text{modified}} = (T_{\phi1})_{\text{max}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3$ AND $(T_{\phi2})_{\text{modified}} =$

$$(T_{\phi 2})_{\max} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3 \text{ AND } (T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\max} + ((T)_{\text{cycle}} - (T)_{\text{total}})/3 \text{ AND } (T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\min}$$

Case 4: When the vehicle queue of FOUR phases had reached the critical zone interval $(Z)_{\text{critical}}$, then the fuzzy rules were designed as follow:

Fuzzy rule set 1: when $(T)_{\text{total}} < (T)_{\text{cycle}}$ and vehicle queue of four phases reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all other phases are specified as the green time in the green time distribution model, and the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was added to the green time of the four phases with $(Z_{\phi})_{\text{critical}}$ equally. The fuzzy rule was designed as follow:

- IF $(T)_{\text{total}} < (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\max}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\max}$ AND $(T_{\phi 3})_{\text{critical}} = (T_{\phi 3})_{\max}$ AND $(T_{\phi 4})_{\text{critical}} = (T_{\phi 4})_{\max}$, THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\max} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\max} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\max} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\max} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$

Fuzzy rule set 2: when $(T)_{\text{total}} = (T)_{\text{cycle}}$ and vehicle queue of four phases had reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the (T_{ϕ}) for all phases were specified as the green time in the green time distribution model. The fuzzy rule was designed as:

- IF $(T)_{\text{total}} = (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\max}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\max}$ AND $(T_{\phi 3})_{\text{critical}} = (T_{\phi 3})_{\max}$ AND $(T_{\phi 4})_{\text{critical}} = (T_{\phi 4})_{\max}$, THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\max}$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\max}$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\max}$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\max}$.

Fuzzy rule set 3: when $(T)_{\text{total}} > (T)_{\text{cycle}}$ and vehicle queue of four phases had reached the critical zone $(Z_{\phi})_{\text{critical}}$, then the time difference between $(T)_{\text{cycle}}$ and $(T)_{\text{total}}$ was deducted from the four phases equally. Fuzzy rule was designed as:

IF $(T)_{\text{total}} > (T)_{\text{cycle}}$ AND $(T_{\phi 1})_{\text{critical}} = (T_{\phi 1})_{\text{max}}$ AND $(T_{\phi 2})_{\text{critical}} = (T_{\phi 2})_{\text{max}}$ AND $(T_{\phi 3})_{\text{critical}} = (T_{\phi 3})_{\text{max}}$ AND $(T_{\phi 4})_{\text{critical}} = (T_{\phi 4})_{\text{max}}$; THEN $(T_{\phi 1})_{\text{modified}} = (T_{\phi 1})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 2})_{\text{modified}} = (T_{\phi 2})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 3})_{\text{modified}} = (T_{\phi 3})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$ AND $(T_{\phi 4})_{\text{modified}} = (T_{\phi 4})_{\text{table}} + ((T)_{\text{cycle}} - (T)_{\text{total}})/4$

4.5. Stage 3: Initialization of the Control System

Stage 3 was designed using steps 6 to 9, as shown in Figure 43, for initialization of the control system. Where, the stage inputs were the control system models, green time distribution models, and the fuzzy rules; while the output of this phase was the actual green time distribution models.

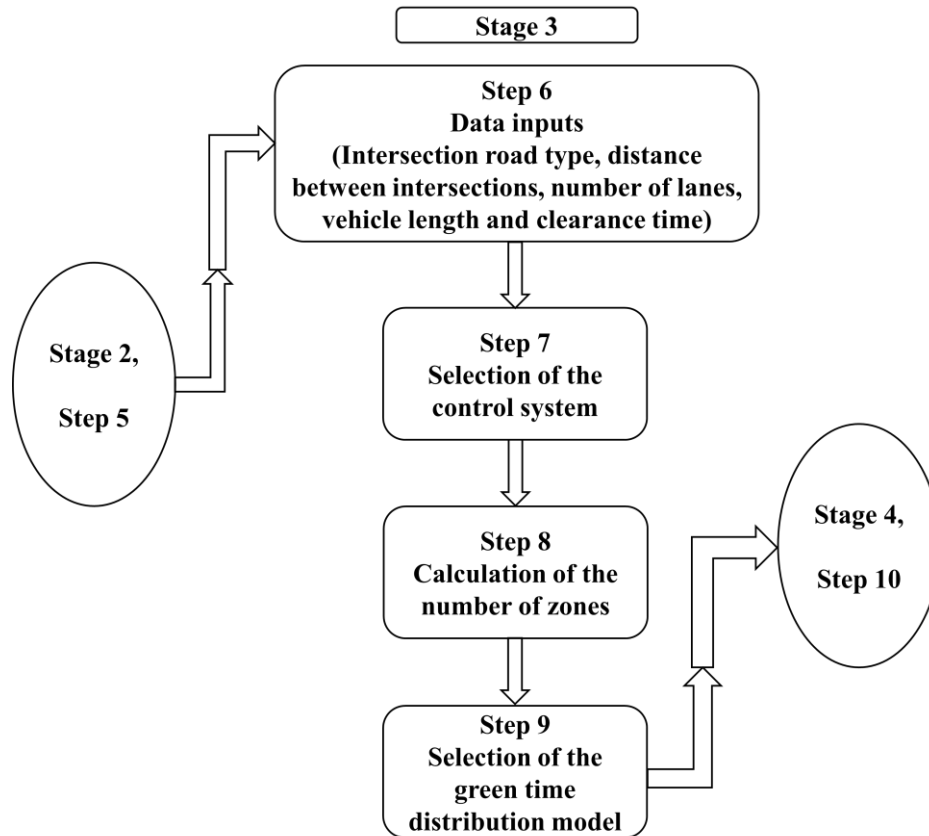


Figure (43)

Steps Followed to Initialize of the Control System (Stage 3)

4.5.1. Step 6: Data inputs

There are several inputs specified in step 6, which were used in different steps based on their calls and functions in the selection and actual run processes. These inputs are the intersection in terms of road types (used for selection the control system model), distance between intersections (L_d) (used for selection the green time distribution model), number of lanes (n_ϕ), average vehicle length (V_l) (used for running process), and clearance time (T_c) (used for modification process).

4.5.2. Step 7: Selection of the control model

At this step, the system processes the intersection roads' types (input) by the first set of the fuzzy rules (5A.1) to select the actual control system from the seven developed control systems.

4.5.3. Step 8: Calculation of the number of zones

The system is calling the distance (L_d) and calculates the number of zones at each intersection phase.

4.5.4. Step 9: Selection of the green time distribution model

The system processes the calculated number of zones by the second set of fuzzy rules (5A.2) to select the actual green time distribution model from the eighty-one available models.

4.6. Stage 4: Execution of the Developed Control System

Stage 4 was designed using steps 10 to 15, as shown in Figure 44, for execution of the developed control system. Where the phase input was the actual green time distribution model for the controlled intersection and the output was signal timing.

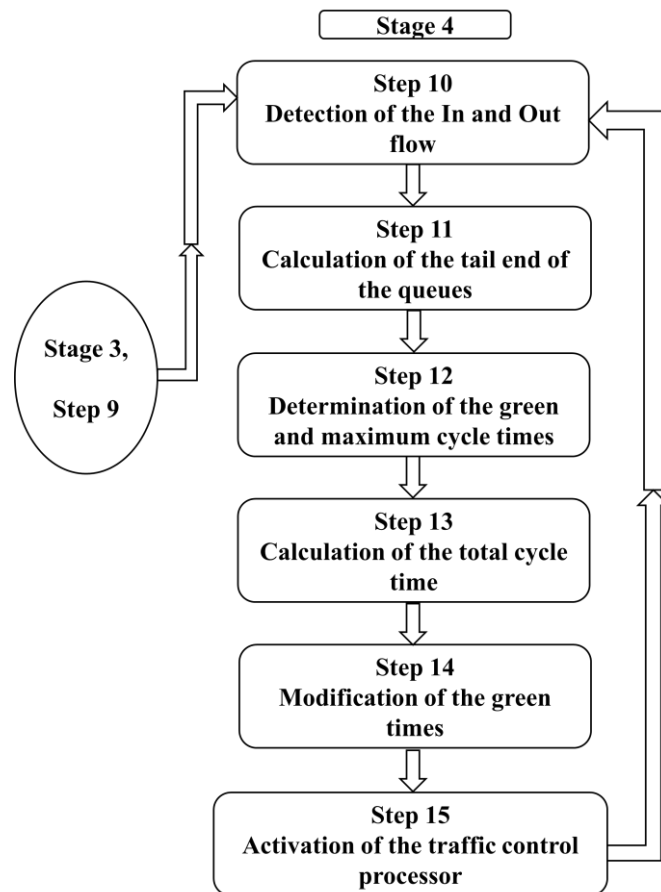


Figure (44)

Steps of Execution of the Developed Control System in Stage 4

Running the developed control system depends on the system inputs, fuzzy rules, and the flow in/out as measured by the system detectors (Figure 45). In figure 45, intersection (X, Y) is the center of the network. The developed control system read that the traffic flow entered the intersection (X, Y) from four directions using data generated by gridlock detectors that were placed at the entrance of the phases. At the same time, the control system reads the traffic flow exiting from the intersection (X, Y) in the four possible directions by using data generated by step-line detectors which were placed at the stop-line. The control system uses the traffic flow readings to calculate the vehicle queue at each phase. The calculated vehicle queues were processed using fuzzy rules to determine

and modify the signal timing. The system gave the traffic signals their action orders.

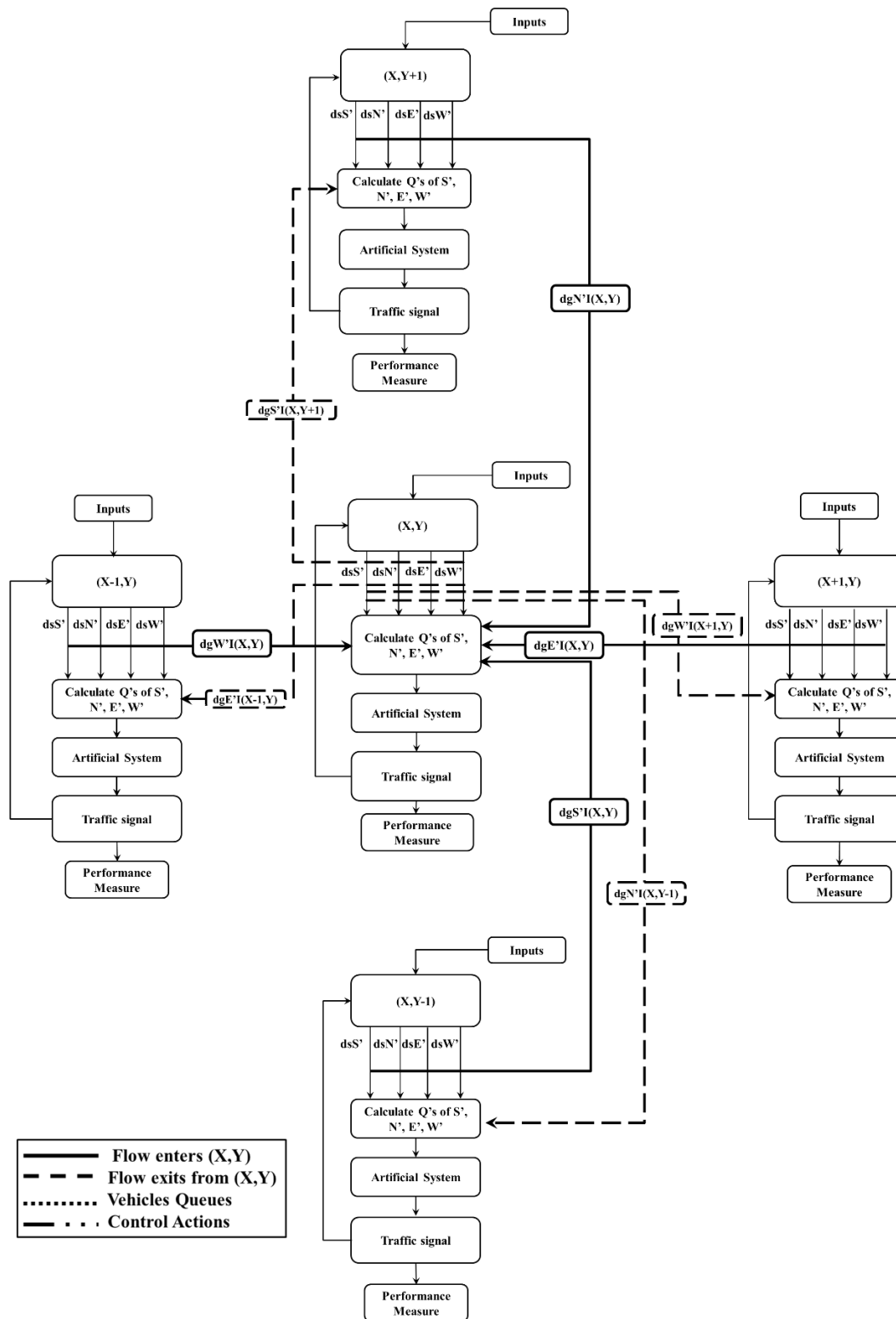


Figure (45)

Running the Developed Control System

4.6.1. Step 10: Detection of the In and Out flow

During step 10, the system monitors the flow reading as it enters the intersection phase from the gridlock detector through the intersection cycle time and monitors the flow reading exits from the intersection phase from stop line detectors for each phase during the green phase time.

The flow that enters the intersection phases comes from the surrounded intersections are shown in the intersection example (X, Y) (Figure 46). The exit flow from the intersection phases which enter the surrounded intersections are shown in the intersection example (X, Y) (Figure 47).

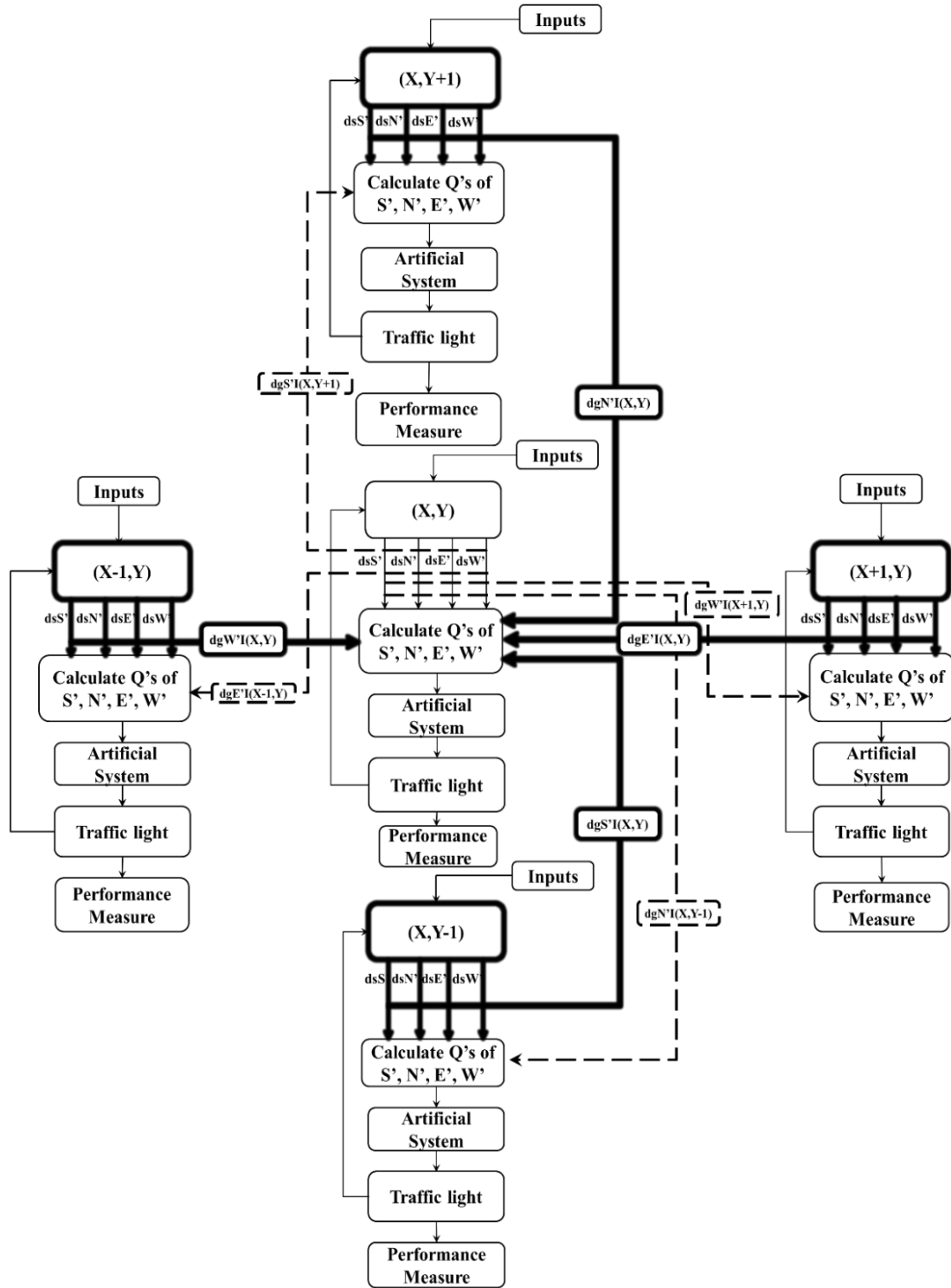


Figure (46)

Flow Entering the Controlled Intersection from Surrounded Intersections

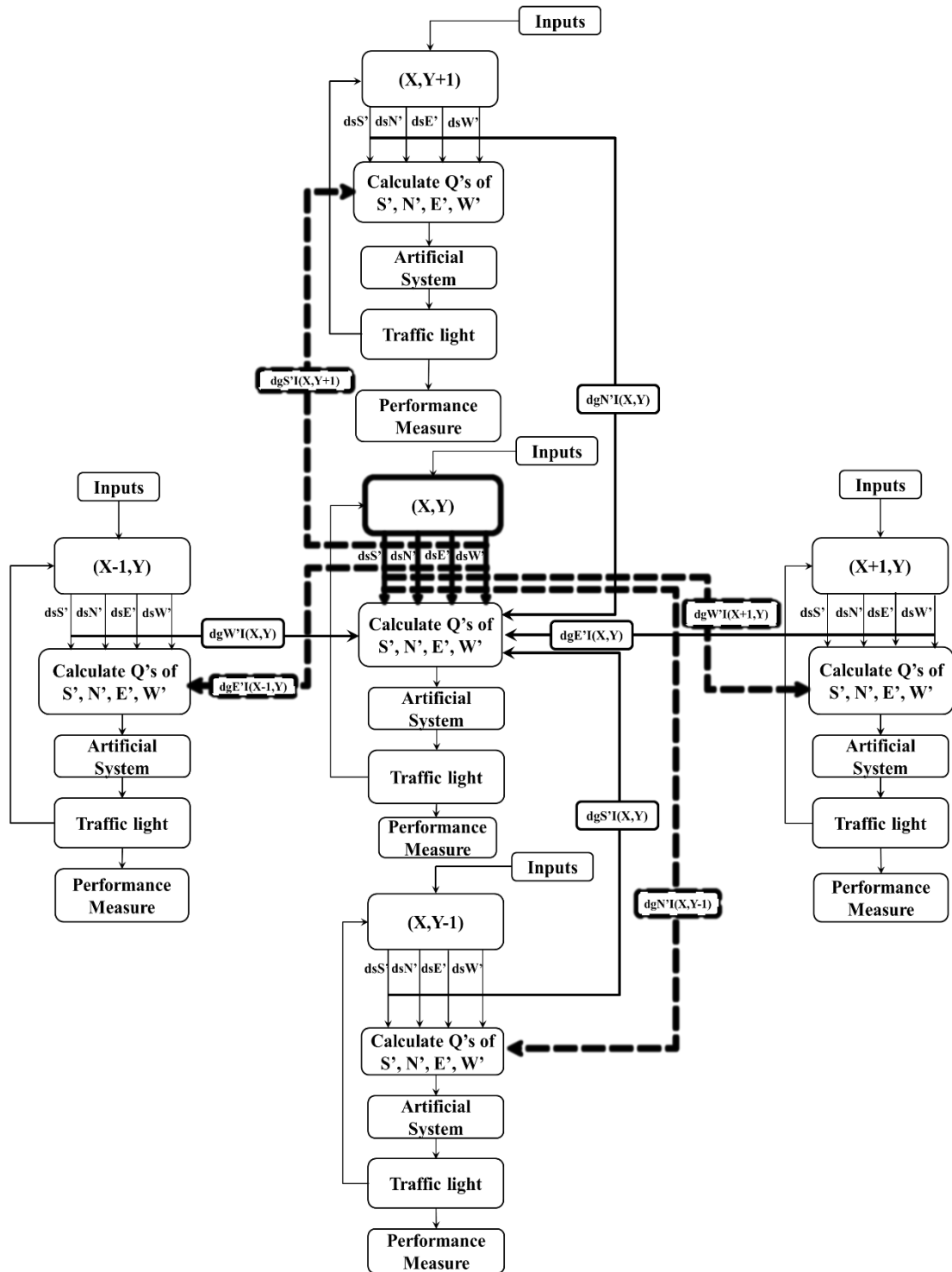


Figure (47)

Flow Exiting from the Controlled Intersection and Entering the Surrounding Intersections

4.6.2. Step 11: Calculation of the location of the tail end of the queues (vehicle queues)

The vehicle queue at an intersection phase was formed because of the vehicle residual through the cycles. The system at this step calculates the vehicle residual using the following equation;

$$(R_{i+1})_{\phi} = (\text{Flow}_{\phi})_{\text{In}} - (\text{Flow}_{\phi})_{\text{Out}} + (R_i)_{\phi} \quad \text{Eq.17}$$

Where:

- $(R_{i+1})_{\phi}$: Number of residual vehicles formed in the cycle $i+1$.
- $(\text{Flow}_{\phi})_{\text{In}}$: Number of vehicles entering the intersection phase during the cycle time.
- $(\text{Flow}_{\phi})_{\text{Out}}$: Number of vehicles exiting from the intersection phase during the green phase time.
- $(R_i)_{\phi}$: Number of the residual vehicles from the cycle i .

After calculating the vehicle residual, the system calculates the queue length in each phase of the intersection using the following equation:

$$Z_{\phi q} = \frac{(R_{i+1})_{\phi}}{n_{\phi}} * V_l \quad \text{Eq.18}$$

Where:

- $Z_{\phi q}$: Queue length at the intersection phase (m).
- n_{ϕ} : Number of lanes for the considered intersection phase.
- $(R_{i+1})_{\phi}$: Number of the residual vehicles that are formed during the cycle $i+1$.
- V_l : Average vehicle length (m).

4.6.3. Step 12: Determination of the green and maximum cycle times

The control system processes the calculated vehicle queue from the previous step ($Z_{q\phi}$) to determine the green times (T_ϕ), clearance time (T_c), and the maximum cycle time (T_{cycle}) from a specified green time distribution model. The control system applied fuzzy rules designed at step 5B.1 on the selected green time distribution model to determine the signal timings.

4.6.4. Step 13: Calculation of the total cycle time

Using green times (T_ϕ) and clearance time (T_c) as determined in the previous step, the control system at this step calculated the total cycle time (T_{total}) using Eq. 19.

$$T_{\text{total}} = (T_{S'})_{\text{modified}} + (T_{N'})_{\text{modified}} + (T_{E'})_{\text{modified}} + (T_{W'})_{\text{modified}} + T_{cS'} + T_{cN'} + T_{cE'} + T_{cW'} \quad \text{Eq.19}$$

Where;

- T_ϕ : Green time (sec.)
- T_c : Clearance time (sec.)

During the clearance time of the last phase, the system modifies the determined green time in the next step (step 14).

4.6.5. Step 14: Modification of the green phases' timings

The modification process is an important process in the control system which occurs during the clearance time of the last phase. The system at step 14 processes the vehicle queues and their locations in the intersection phases with the relation between (T_{cycle}) and (T_{total}) by applying fuzzy rules (step 5B.2) to modify and change the control system green phases times.

4.6.6. Step 15: Activation of the traffic control processor

At this step, the control system sends to the traffic signal the actions for the next cycle timing.

4.7. Reporting of Outputs

The control system provides a report which includes intersection cycle time, green times, phases flow in $(\text{flow})_{\text{In}}$, phases flow out $(\text{flow})_{\text{out}}$ and vehicle queue length which are used during system analysis.

Chapter Five

Validation of the Traffic Control System

5.1. Introduction

5.2. Data Collection

5.3. Control System Validation

5.4. Process 1: System Set up

5.5. Process 2: First Iteration

5.6. Process 3: Determination of the Green Times

Chapter Five

Validation of the Traffic Control System

5.1. Introduction

To examine the validity of the control system, it should be applied in a real-life situation; however, application of a real-life test faces difficulties due to the high cost extensive time required for the setup of the detectors and the need for the approvals from several ministries. Therefore, actual historical data will be used for traffic simulation of an existing grid network which was controlled by a developed system. Hence, system performance can be measured and compared with the existing traffic control system.

The developed control system will be applied to a network of intersections having the system conditions and criteria. By analyzing the intersections in “Al Asimah” and “Hawally” governorates, thirteen intersections fulfilled the system criteria, and are specified as a research sample. These intersections were simple, four phases each with three vehicle directional movements and formed by a collector, minor and major arterial roads. The intersections formed a grid network with a minimum distance between one intersection and another of 800 m, and a maximum distance of 2400 m, (Figure 48).

The data for the five central intersections in the network (Figure 48) were specified to run the developed control system to measure system performance. Each intersection was connected to four other intersections that affected the flow in and out of the intersection. The specified five intersections were; Intersection No. 2400 (2nd ring road/ Maghreb street), which is the central intersection connected to four intersections, namely; No. 3400 (3rd ring road/ Maghreb street) from South, No. 1400 (1st ring road/ Maghreb street) from North, No. 2350 (2nd ring road/ Cairo street)

from East and intersection No. 2500 (2nd ring road/ Reyad street) from West.

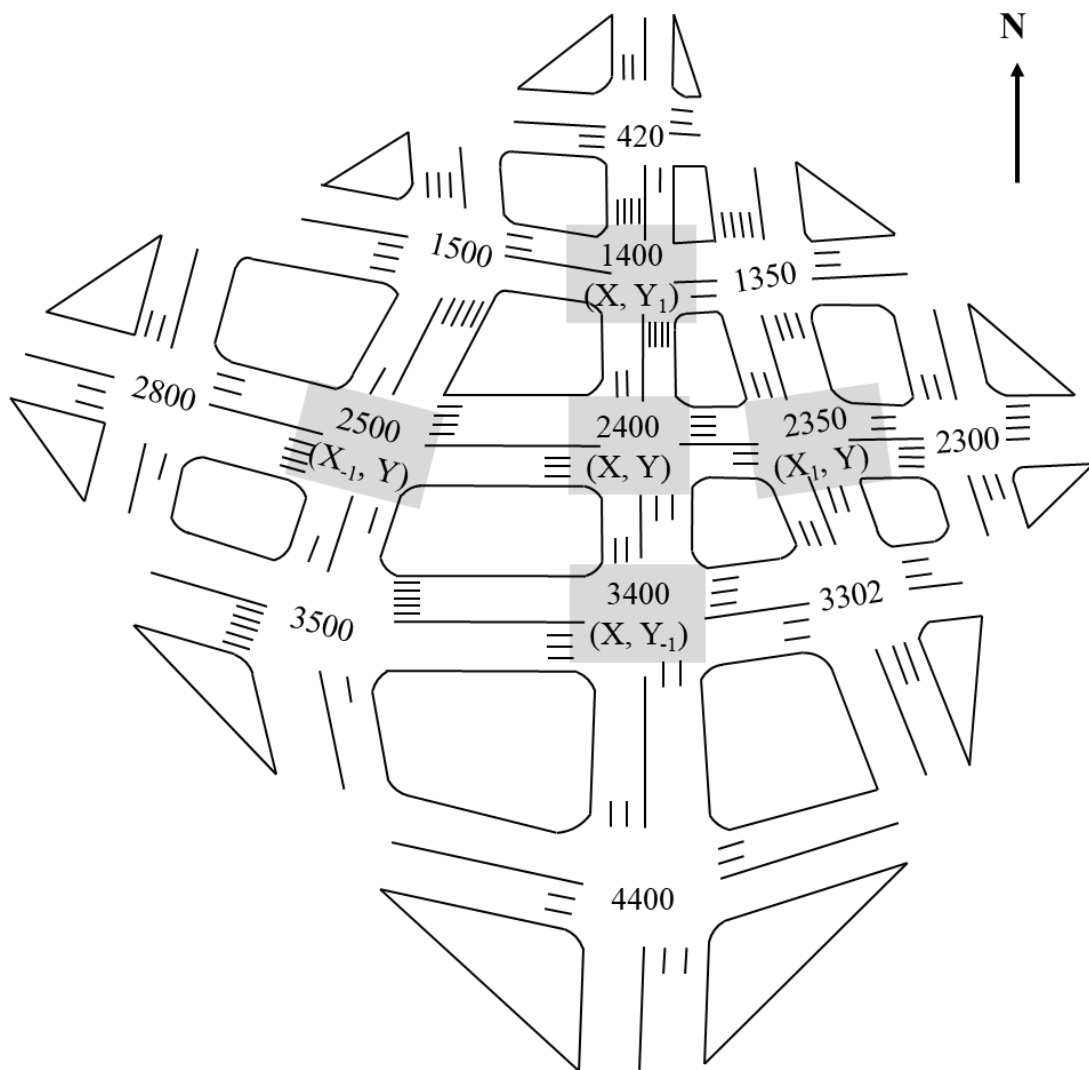


Figure (48)

Sample of Intersections in the Grid Network used for Control System Validation

Intersection No. 3400 is connected to intersections No. 4400 (4th ring road/ Maghreb street) from South, No. 2400 from North, No. 3302 (3rd ring road/ Cairo street) from East, and No. 3500 from West.

Intersection No. 1400 is connected to intersections No. 2400 from South, No. 420 (Shuhada street/ Abdullah Mubarak street) from North, No.

1350 (1st ring road/ Cairo street) from East, and No. 1500 (1st ring road/ Ryad street) from West.

Also, intersection No. 2350 (3rd ring road/ Ryad street) is connected to intersections No. 3302 from South, No. 1350 from North, No. 2300 (2nd ring road/ Istiqlal street) from East, and No. 2400 from West.

Finally, intersection No. 2500 is connected to intersections No. 3500 from South, No. 1500 from North, No. 2400 from East, and No. 2800 (2nd ring road/ Jahra road) from West.

5.2. Data Collection

As mentioned earlier, thirteen intersections were specified as the research sample and the traffic data of these intersections was analyzed. The data was considered for four 15 minutes periods during peak periods. The geometries (intersection type, road types, and the number of lanes at each phase), and timing plans for these intersections were collected and shown in Appendix (9).

The vehicle flow data of the five central intersections were collected and analyzed by calculating traffic flow. The traffic flow was characterized by a heavy traffic flow for the intersections' four phases. The results for the flow analysis of the specified intersections showed that the highest vehicle counts per intersection were for intersections No. 2400 and No. 3400 on Monday (11th Jan.), No. 1400 on Friday (15th Jan.), No. 2350 on Thursday (14th Jan.), and No. 2500 on Saturday (16th Jan.). Based on this analysis, Monday 11th Jan. 2016 was the most congested day and its data was selected to be used in the simulated run of the developed control system and to be compared with the results. Based on the traffic flow

analysis, rush periods were specified as 6:45 - 7:00, 14:15 - 14:30, 17:15 - 17:30, and 21:30 - 21:45 for the control system simulated run.

5.3. Control System Validation

To achieve the study objective, the system should be validated in an actual situation; however, as was mentioned earlier; it was difficult to run the system in an actual situation. The system was therefore applied to a simulated data using three steps' processes (Figure 49).

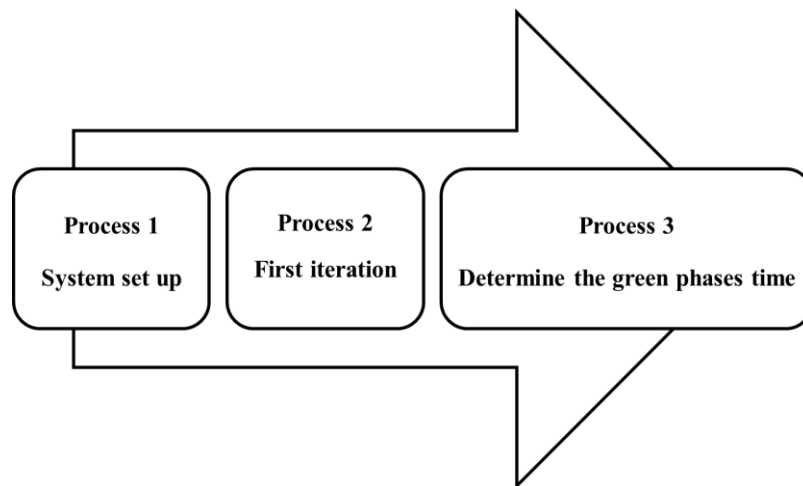


Figure (49)

Control System Simulated Run Processes

Running of the system is initiated by setting up the system to select the actual green time distribution model in the first process. The control system was developed to run continuously, but since the running period times are specified based on the data analysis, the first iteration was required to start up the system (second process). In the third process, the system determined the green phases time continuously up to the end of the period and reported the determined data to be used for measuring the system performance. Each process is fulfilled through several steps as shown in Figure 50.

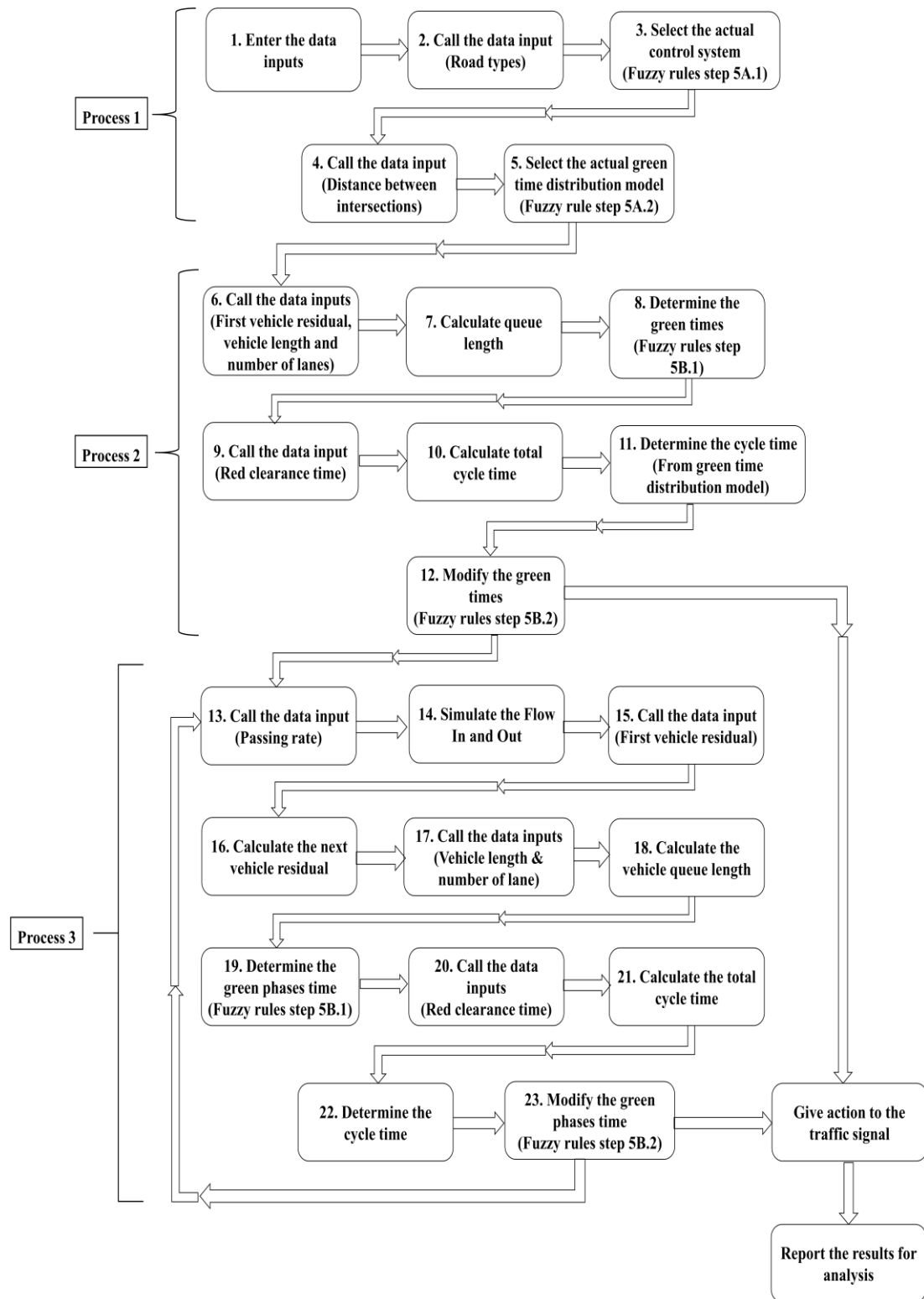


Figure (50)
Steps for the Control System Simulated Run

5.4. Process 1: System Set up

The simulated run was initiated by a system set up through several steps as can be seen from Figure 51. These are further discussed in the following sub-sections.

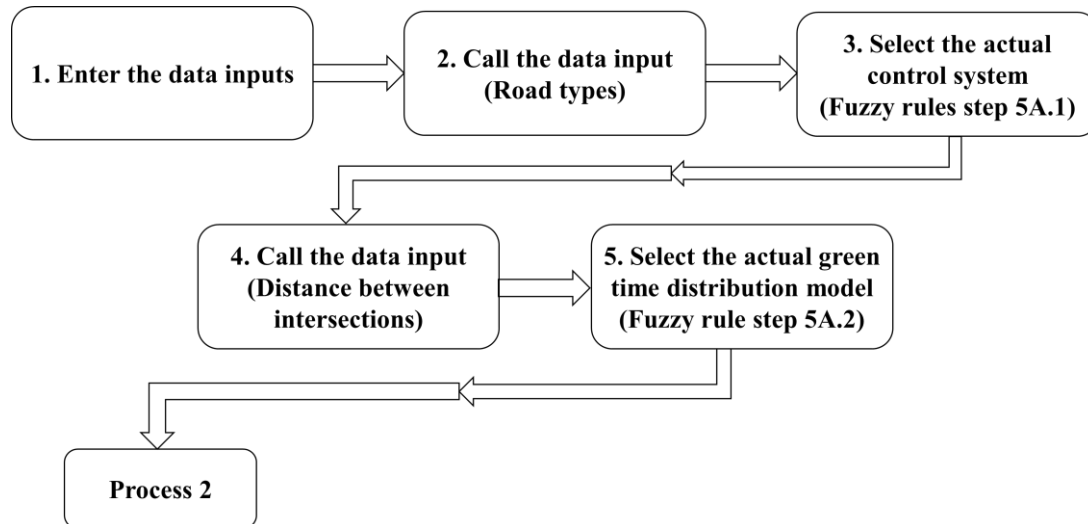


Figure (51)

**Steps of the Process 1 for the System set up in the Control System
Simulated Run**

5.4.1. Enter the data inputs

At step 1 (Figure 51) of process 1, several data inputs were specified, and others were simulated to be used in running the control system based on their calls and functions. The following inputs were: average vehicle length ($V_l = 7$ m) (section 1.5), clearance time ($T_c = 2$ sec) (section 1.5), intersection roads' types, number of the lanes at each phase and the running period were specified based on the system constraints and controlled intersection's geometries.

The flows in and out from various phases were simulated by using the passing rate for the vehicles through each phase at pre specified running periods. The vehicle passing rate time was calculated by dividing the total green phase time during the specified running period over number of

vehicles passing the intersection phase for each lane as shown in equation 20.

$$\text{Passing Rate Time} = \frac{\text{Total Green Phase Time X Number of Lane}}{\text{Total Number of Vehicle Passed through period}} \quad \text{Eq. 20}$$

Example 5.1 shows the vehicle passing rate time calculations for phase S' of intersection 2400 at 7:00 AM.

Table (21)

Passing Rate Time Calculation of Intersection 2400

Passing Rate of Intersection (X,Y) No. 2400					
Time of Day	Description	$\phi 2(S', n=3)$	$\phi 4(N', n=3)$	$\phi 1(E', n=4)$	$\phi 3(W', n=4)$
6:45 - 7:00	No. Of Vehicle Passed through 15 min.	159	73	453	363
	Phase time (sec.)	40	25	80	45
	No. of lane	3	3	4	4
	Cycle time (sec.)	190			
	Period Time (sec.)	900			
	No. of Cycle per Period (sec.)	4.7			
	Total Phase time (sec.)	189.5	118.4	378.9	213.2
	Passing Rate (sec./veh/lane)	3.6	4.9	3.3	2.3

As shown in Table 21, number of vehicles passing phase S' summed to 159 vehicles for 15 minutes, where the green phase time was 40 seconds, and number of lanes on this phase was 3. The cycle time was 190 seconds during this period, during the 15 minutes (900 seconds) the corresponding number of cycles during this period totaled to 4.7 (900/190). The sum of the green times for phase S' was 189.5 seconds (total phase time = phase time X No. of cycle per period = 40 X 4.7). By using Eq. 20, the passing rate time of the S' phase was equal to 3.6 (passing rate time = (189.5 X 3) / 159). The observed intersections' road types, distance between intersections, number of lanes, period time to be controlled and the vehicle passing rate are presented in Appendix (11) and were used as inputs to the control system software. The front-page of the control system software at the first run was blank (Figure 52). Data inputs were used, so the control system started to use the system calculation functions and fuzzy rules.

					Start Time End Time Car Length (M) 7 Red clearance time (RC) 2 Total time in Seconds		X, Y2 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)																	
					X-1, Y1 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					X, Y1 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					XI, Y1 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)									
X-2, Y Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					X-1, Y Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					X, Y Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					XI, Y Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					X2, Y Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)				
					X-1, Y-1 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					X, Y-1 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)					XI, Y-1 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)									
										X, Y-2 Phase S' N' E' W' Phase Road Type Distance Length (m) Number of Lane (n) Passing Rate (PR)														

Figure (52)
Data Inputs in the Control System Software (Front page of the software)

5.4.2. Call the data entry (Road types)

The system returns the intersection roads' types from the data inputs at this step.

5.4.3. Select the actual control system (Fuzzy rules step 5A.1)

The system processes the intersection roads types to select the actual control system by using fuzzy rules (step 5A.1) for each intersection.

5.4.4. Call the data entry (Length distance)

The system returns the distances between intersections from the data inputs.

5.4.5. Select the actual green time distribution model (Fuzzy rules step 5A.2)

The system processes the distances to select the actual green time distribution models for each intersection using fuzzy rules (step 5A.2). The output of process 1 was the green time distribution model for each intersection that was used as an input into process 2.

5.5. Process 2: First Iteration

The first iteration was needed to compensate for the missing flow data where the flows in and out from the intersection phases were simulated. The first iteration in process 2 employs several steps (Figure 53).

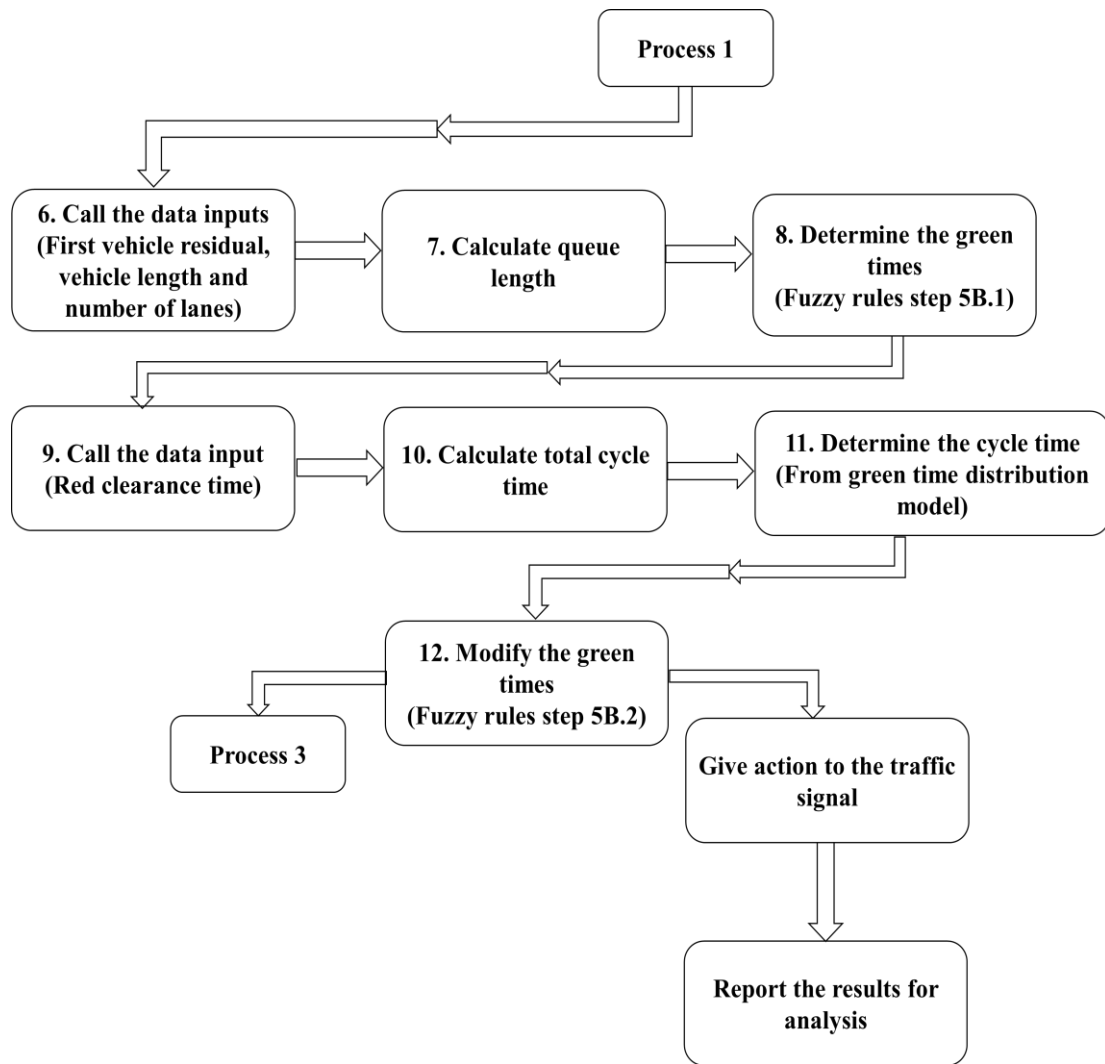


Figure (53)

Steps Employed for the Process 2 to Execute the First Iteration of the Control System During the Simulated Run

5.5.1. Call the data inputs (First vehicle residual, average vehicle length and number of lanes)

The system calls for the data inputs that are needed to estimate the queue length at each intersection phase. The inputs being called at this step are the first vehicle residual, average vehicle length and number of lanes.

5.5.2. Calculate the vehicle queue length

At step 7, the system calculates the queue length for the first iteration at each phase by using the data inputs which are called in step 6 employing Eq. 21:

$$Zq = \frac{R1}{n} * V_l \quad \text{Eq. 21}$$

Where,

- Zq : Vehicle queue length at intersection phase (m)
- R_1 : First vehicle residual (vehicle)
- n : Number of lanes
- V_l : Average vehicle length (m)

5.5.3. Determine the green times (Fuzzy rules step 5B.1)

Based on the calculated vehicle queue length (Zq) at each intersection phase, the system at step 8 determines the green time ($T\phi$) for the second cycle ($i+1$). The green phases times were determined by processing the calculated vehicle queue using fuzzy rules (step 5B.1) of the specified green time distribution model (TS' , TN' , TE' , and TW').

5.5.4. Call the data input (Red clearance time)

The system at step 9 calls the clearance time for the sequential phases ($T_{cS'}$), ($T_{cN'}$), ($T_{cE'}$), and ($T_{cW'}$), which are all assumed to be equal to 2 seconds for all intersection roads types. Clearance times were used to calculate total green time (T)_{total}.

5.5.5. Calculate the total cycle time

At step 10, the control system calculates the total cycle time (T)_{total} for cycle ($i+1$) by using Eq. 22;

$$T_{\text{total}} = T_{S'} + T_{c1} + T_{N'} + T_{c2} + T_{E'} + T_{c3} + T_{W'} + T_{c4} \quad \text{Eq. 22}$$

Where;

- T: Green phase time (sec.)
- Tc: Clearance time (sec.)

Total cycle time was calculated in order to modify the determined green time, by studying the relationship between the $(T)_{\text{total}}$ and $(T)_{\text{cycle}}$. As mentioned earlier, the system modified the determined green times at the clearance time of the last phase.

5.5.6. Determine the cycle time

The timing parameters were filled in the green time distribution model, where the cycle time was specified for each control system type. In step 11, the system determines the specified cycle time (T_{cycle}) from the selected green time distribution model (section 5.4.5).

5.5.7. Modify the green phases time (Fuzzy rules step 5B.2)

At step 12, the system processed the calculated total time and the specified cycle time using fuzzy rules (step 5B.2) and was based on the relationship between these times; the green times that are determined in step 8 were therefore modified.

The system gave the traffic signal the action to operate by determined green times and the cycle time for the next cycle. Signal timings were also reported and were used in measuring the control system performance.

5.6. Process 3: Determination of the Green Times

Since the green and cycle times of the first iteration are calculated during process 2, then the system calculated the green and cycle times for the specified periods through several iterations of process 3, which consisted of several steps (Figure 54).

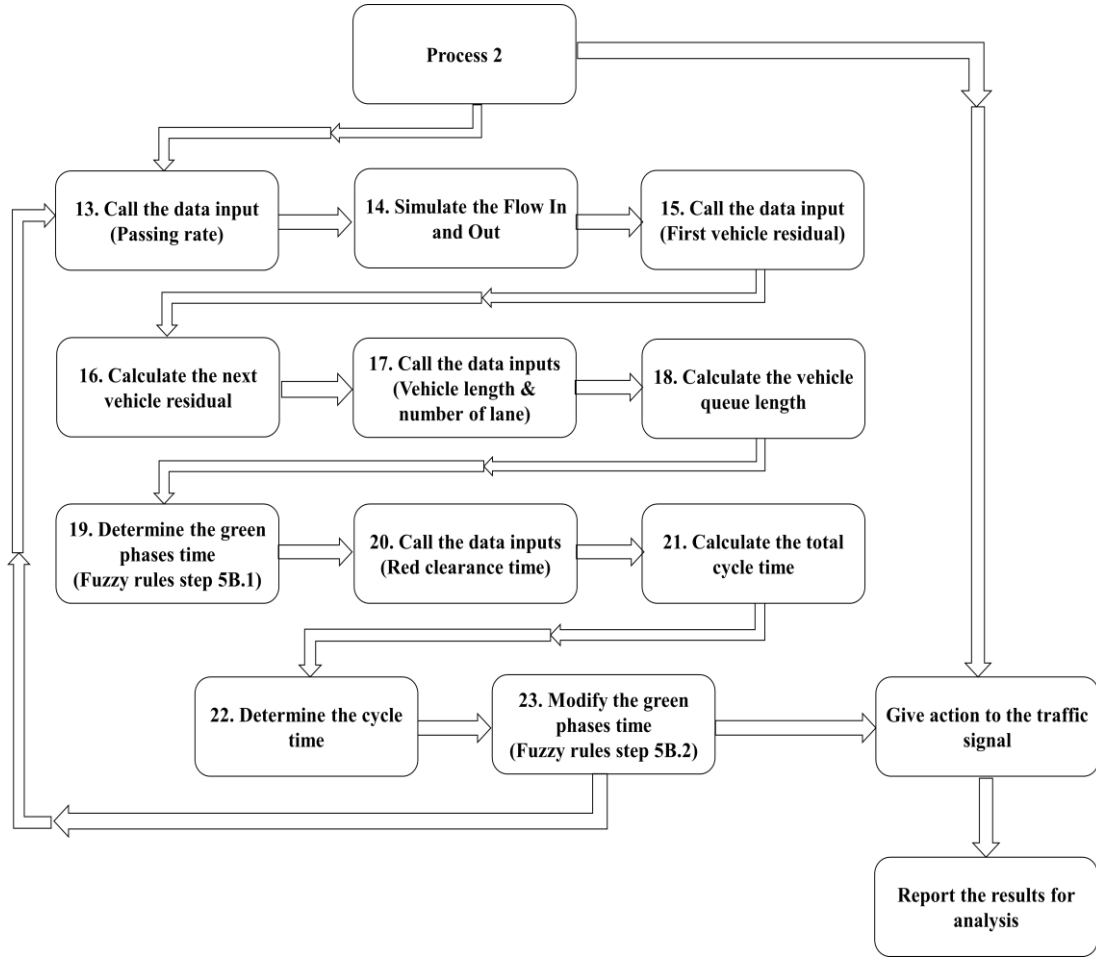


Figure (54)

Steps of Process 3 for Determining the Green Times by the Control System Simulated Run

5.6.1. Call the data input (Passing rate)

During step 13, the system calls the calculated passing rate times which were then used for simulating vehicle flow.

5.6.2. Simulate the Flow In/Out

During step 14, the system calculates the out-flow from the intersection phases of cycle (i+1) using Eq. 23;

$$(\text{Flow}_\phi)_{\text{Out}} = \frac{T\phi}{PR} * n \quad \text{Eq. 23}$$

Where,

- $(Flow_{\phi})_{Out}$: Number of vehicles exiting from the intersection phase. (veh.)
- T_{ϕ} : Green phase time (sec.)
- PR: Passing rate time (sec./veh.)
- n: Number of lanes.

The out-flow $(Flow_{\phi})_{Out}$ from the intersection phase was distributed to the other intersection phases with varying percentages. To simulate the in-flow to the intersection phases $(Flow_{\phi})_{In}$, the out-flow from a specific intersection phase was counted manually for a specified period for several days. By counting number of vehicles passing through the intersection phases and their directions, the traffic analysis showed that 76% of the out-flow went straight through the intersection phase, 17.5% took a left turn and 6.5% took a right turn. Based on the traffic signal operation manual, the out-flow from an intersection phase was 80% straight through, 15% left turn and 5% right turn (Buckholz, 2012). These percentages are almost like the site counted percentages. The percentages of the traffic signal operation manual are used in designing the control system. The out-flow from intersection phases entering the next intersection through the cycle time are shown in Figure 55.

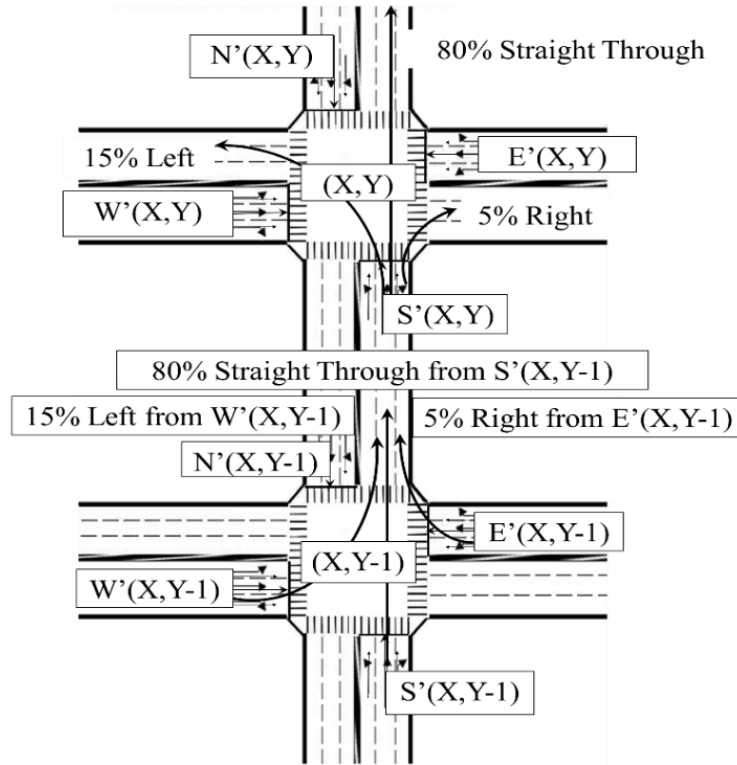


Figure (55)

In Flow to the Intersection (X, Y) from South Phase

For example, the flow entering $S'(X, Y)$ was coming from 80% of $(\text{flow})_{\text{out}}$ from $S'(X, Y-1)$ plus 15% of $(\text{flow})_{\text{out}}$ from $W'(X, Y-1)$ plus 5% of $(\text{flow})_{\text{out}}$ from $E'(X, Y-1)$. The same flow distribution was assumed for the other phases as, the flow entering $N'(X, Y)$ was coming from 80% of $(\text{flow})_{\text{out}}$ from $N'(X, Y+1)$ plus 15% of $(\text{flow})_{\text{out}}$ from $E'(X, Y+1)$ plus 5% $(\text{flow})_{\text{out}}$ from $W'(X, Y+1)$. The flow entering $E'(X, Y)$ was coming from 80% of $(\text{flow})_{\text{out}}$ from $E'(X+1, Y)$ plus 15% $(\text{flow})_{\text{out}}$ from $S'(X+1, Y)$ plus 5% of $(\text{flow})_{\text{out}}$ from $N'(X+1, Y)$. Finally, the flow entering $W'(X, Y)$ was coming from 80% of $(\text{flow})_{\text{out}}$ from $W'(X-1, Y)$ plus 15% of $(\text{flow})_{\text{out}}$ from $N'(X-1, Y)$ plus 5% of $(\text{flow})_{\text{out}}$ from $S'(X-1, Y)$.

At step 14, the system calculates and simulates the $(\text{Flow})_{\text{in}}$ for the intersection phases by applying the previous percentages on the calculated $(\text{Flow})_{\text{out}}$.

5.6.3. Call the data input (First vehicle residual)

The first vehicle residual (R_1) is called by the control system at step 15. This is used for the calculation of the cycle residual (R_{i+1}) during the next step.

5.6.4. Calculate the following vehicle residual

The $(\text{Flow } \phi)_{\text{In}}$ and $(\text{Flow } \phi)_{\text{Out}}$ of the cycle $(i+1)$ were simulated in step 14, and the vehicle residual of the previous cycle (R_1) were used in step 16 to calculate the vehicle residual of the next cycle (R_{1+i}) using Eq. 24;

$$R_{i+1} = (\text{Flow } \phi)_{\text{In}} - (\text{Flow } \phi)_{\text{Out}} + R_1 \quad \text{Eq. 24}$$

5.6.5. Call the data inputs (Average vehicle length and number of lane)

The system will be calling the average vehicle length and the number of lanes from the data inputs to be used with the vehicle residual (R_{i+1}) in the next step.

5.6.6. Calculate the queue length

Step 18, the system will calculate the queue length (Z_q) for the cycle $(i+1)$ using Eq. 21.

5.6.7. Determine the green phases time (Fuzzy rules step 5B.1)

The process at step 8 is repeated in step 19 but by using the updated queue length to determine the green times for the next cycle $(i+2)$. This process was repeated for every cycle while the system was controlling the traffic signal.

5.6.8 Call the data input (Red clearance time)

The system at step 20 was calling the red clearance time from the data inputs for all intersections phases, which was equal to 2 sec.

5.6.9. Calculate the total cycle time

At step 21, the total cycle time $(T)_{\text{total}}$ for the cycle $(i+2)$ was calculated using Eq. 22.

5.6.10. Determine the cycle time

In step 22, the system determined the specified cycle time $(T)_{\text{cycle}}$ from the selected green time distribution model.

5.6.11. Modify the green phases time (Fuzzy rules step 5B.2)

At step 23, the system processes the calculated total time and the specified cycle time by using fuzzy rules (step 5B.2) and was based on the relation between these times; the green times that are determined in step 22 were then modified.

The control system gives the traffic signal the action to operate, and it reports the new signal timings to be used for measuring the control system performance. Steps 13 to 23 are repeated to determine the green times and the cycle times throughout the control time periods.

Running the developed control system for validation as mentioned before was for specific periods that were selected based on the traffic analysis. The signal timings were reported by the system to be used for measuring the developed system performance and to be compared with the existing control system.

Chapter Six

Results and Discussion

6.1. Introduction

6.2. Results of the Intersections

6.3. Performance Analysis of the Intersections

6.4. Results and Performance of the Network

6.5. Summary of the Results

Chapter Six

Results and Discussion

6.1. Introduction

The simulated traffic data for a real situation of a network consisting of thirteen intersections were used to run and test the developed control system. The results for five central intersections of the grid network were analyzed and compared with actual historical traffic data. The performance of the existing and developed control systems was compared in this chapter.

6.2. Results of the Intersections

Control system ran simulated data for four periods (6:45 – 7:00, 14:15 – 14:30, 17:15 – 17:30 and 21:30 – 21:45) for all five intersections, i.e. No. 1400 (X, Y1), No. 2350 (X1, Y), No. 2400 (X, Y), No. 2500 (X-1, Y), and No. 3400 (X, Y-1). The results from running the developed control systems consist of the following parameters: number of vehicles along with the green times necessary to allow these vehicles to pass through the intersections' phases; the total number of vehicles passing through all the four phases of each intersection; and the corresponding number of cycles necessary to be executed during specified running periods.

6.2.1. Results of period 6:45 – 7:00

(1) Traffic volume and corresponding green times necessary for the vehicles dissipation through phases: The results for the intersection No. 1400 (X, Y1) of both developed and existing control systems are presented in Figure 56. The x-axis represents the intersections' phases and the y-axis represents the number of vehicles passing through the

intersections' phases. Numbers of vehicles passing the various intersection' phases increased in all phases. The calculated green times needed for the vehicles to pass the various phases during the same period are presented in Figure 57. The x-axis represents the intersections' phases and the y-axis represents the green time needed for vehicles to pass through the intersections' phases. As can be seen, the green times required for the earlier traffic volume to pass the four phases decreased from E' and W' phases and increased from S' and N' phases. That indicates, the green time increased as needed in S' and N' phases by the developed control system, which resulted in greater number of vehicles passing through the intersection's phases. That led to less waiting time and probably less delays.

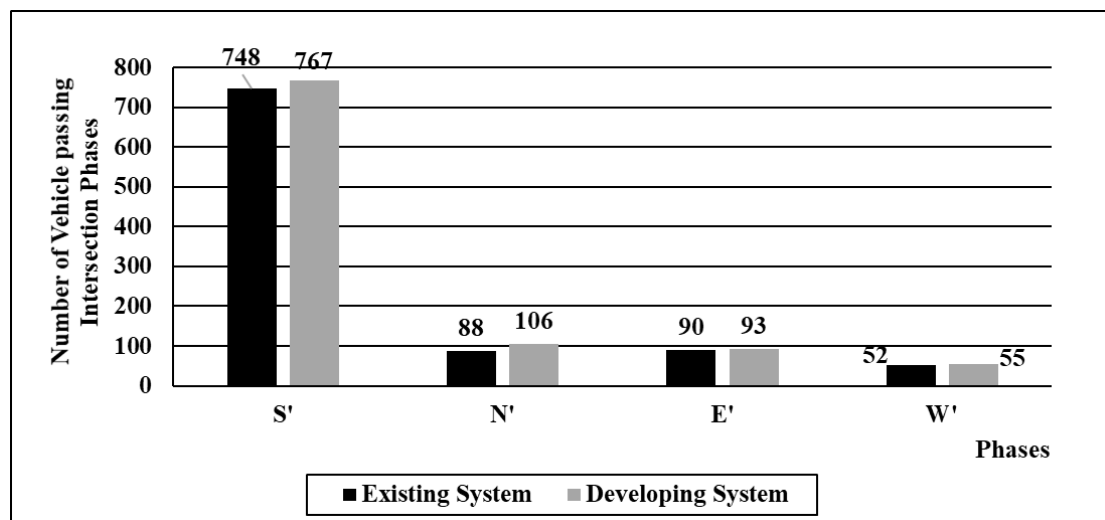


Figure (56)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 1400 (X, Y1) Between 6:45 and 7:00

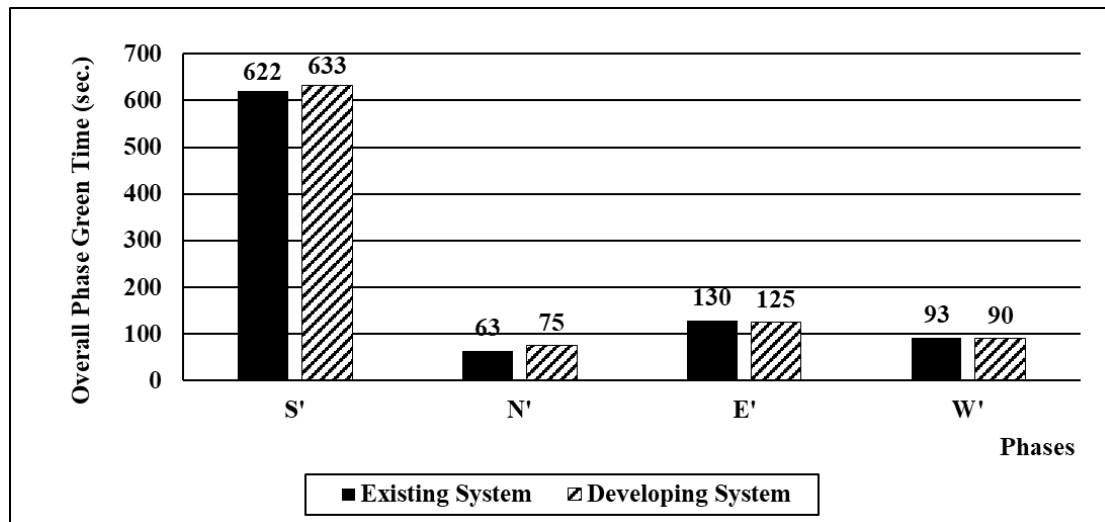


Figure (57)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 1400 (X, Y1) Phases Between 6:45 and 7:00

The results for the intersection No. 2350 (X1, Y) of both developed and existing control systems are presented in Figure 58. Numbers of vehicles passing the various intersection' phases increased from S', N', and W' phases and decreased from E' phase. The green times needed for the vehicles to pass the various phases during the same period are presented in Figure 59. As can be seen, the green times needed to pass the four phases decreased from S', E' and W' phases and increased from N' phase. That shows, there is a large amount of green time loss in S', E', and W' phases resulted from distributing the green time by the existing system. The developed control system partially used the green time loss to increase number of vehicles passing through these phases and canceled the remaining time. The results indicate that the N' phase has higher vehicles flow that not been recognized by the existing system when it distributed the green time. However, the developed control system increased number of vehicles passing through the N' phase by increasing the green time based

on the actual traffic situation. Increasing vehicle flow means less waiting time and delay.

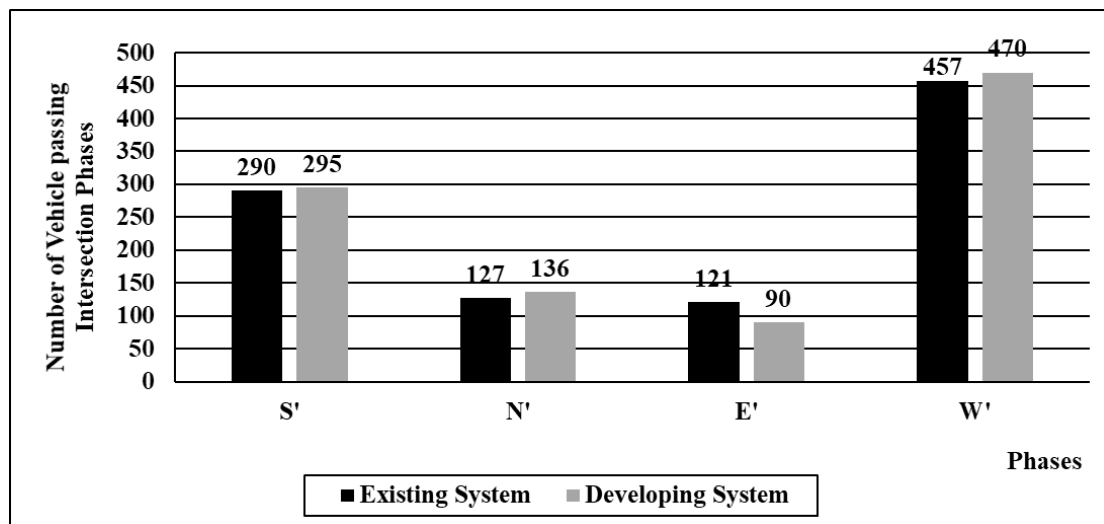


Figure (58)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2350 (X1, Y) Between 6:45 and 7:00

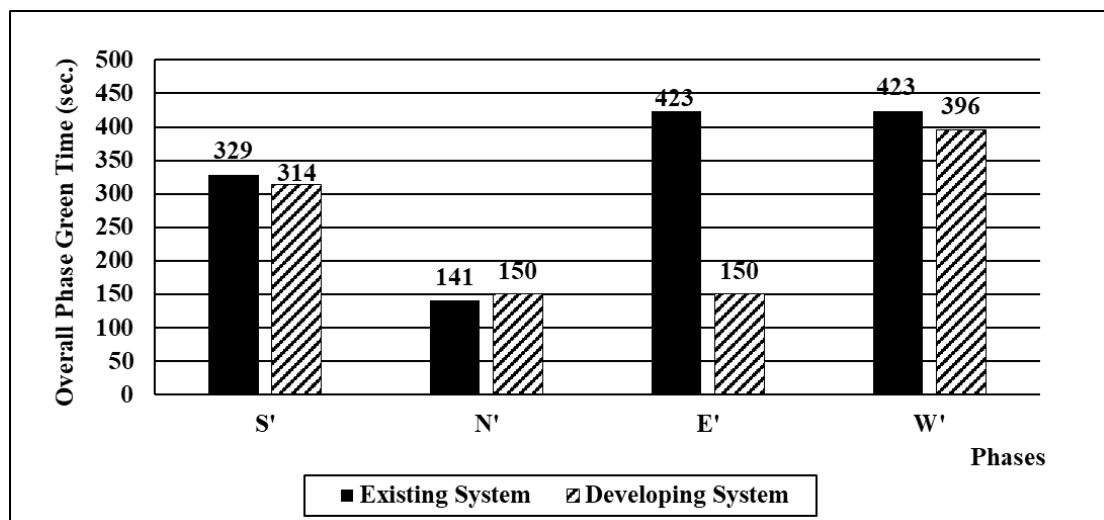


Figure (59)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2350 (X1, Y) Phases Between 6:45 and 7:00

The results for the intersection No. 2400 (X, Y) of both developed and existing control systems are presented in Figure 60. Numbers of vehicles passing the various intersection' phases increased from S', N', E', and W' phases. The green times needed for the vehicles to pass the various phases during the same period are presented in Figure 61. As can be seen, the green times needed to pass the four phases decreased from S' and E' phases and increased from N' and W' phases. That designates, the developed control system used part of the green time loss in S' and E' phases to increase the number of vehicles passing through these phases and decrease the remaining time in order to reduce the waiting times. At the same time, the developed control system distributed the green time to N' and W' phases based on the traffic situation by increasing the green time in order to shorten the vehicle queues.

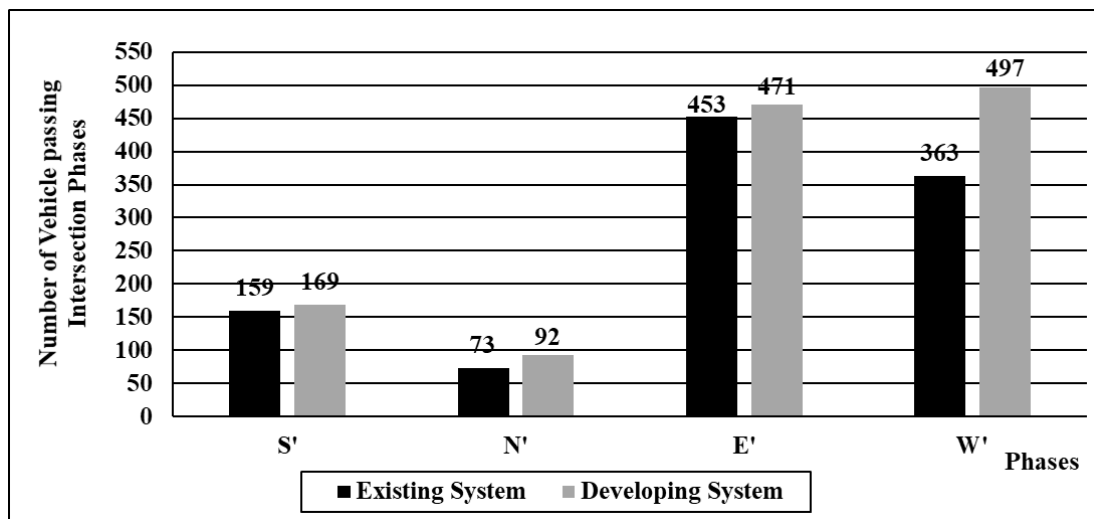


Figure (60)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2400 (X, Y) Between 6:45 and 7:00

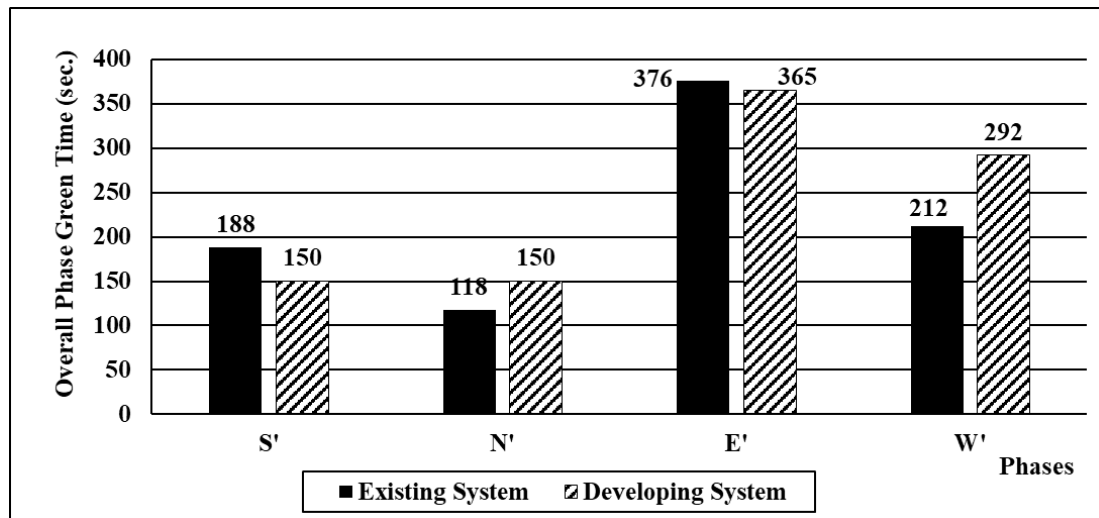


Figure (61)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2400 (X, Y) Phases Between 6:45 and 7:00

The results for the intersection No. 2500 (X-1, Y) of both developed and existing control systems are presented in Figure 62. Numbers of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 63. As can be seen, the green times needed to pass the four phases increased from S', N', E' and W' phases. That indicates, by increasing the green time for the four phases on the new system helped increasing the vehicle flow in all phases.

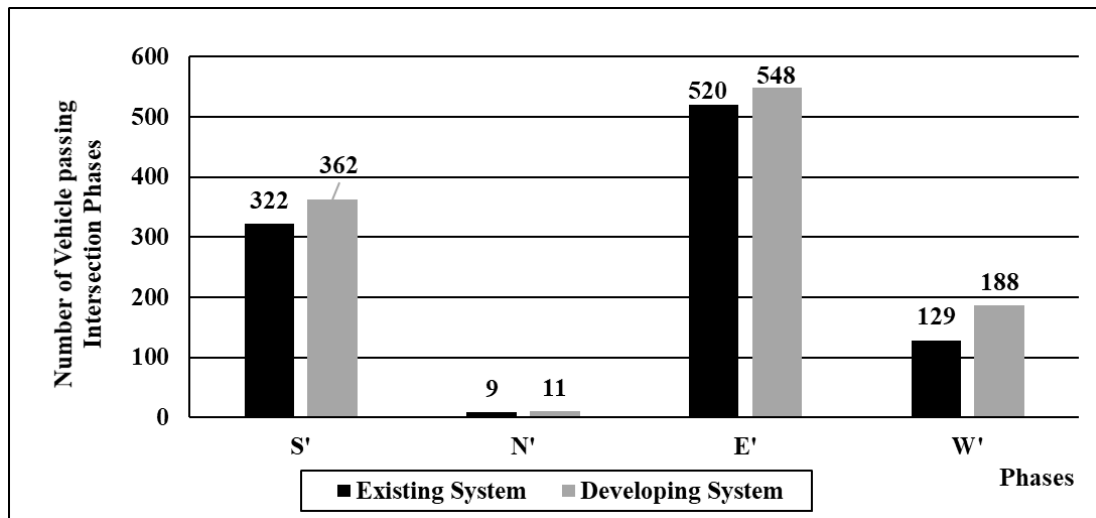


Figure (62)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2500 (X-1, Y) Between 6:45 and 7:00

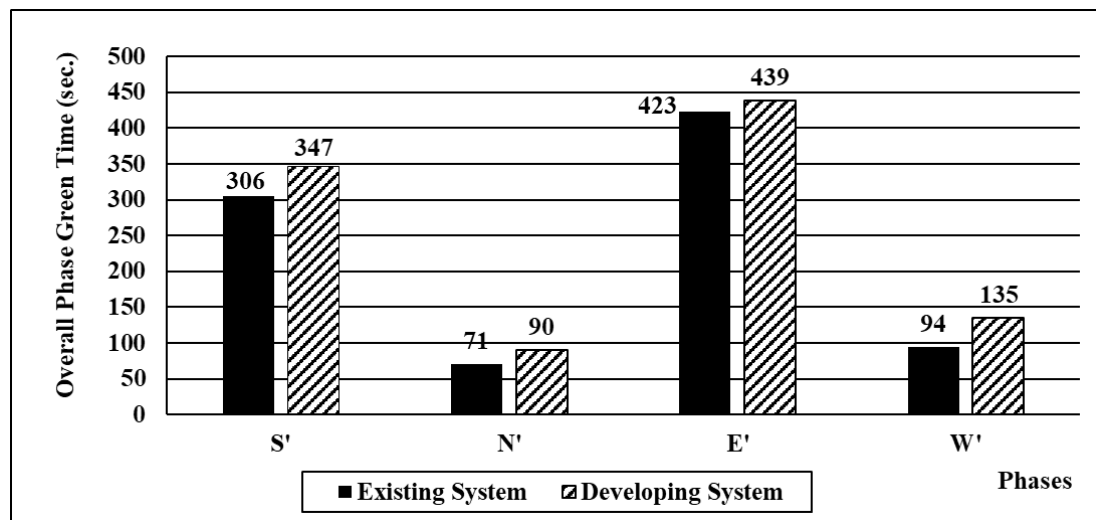


Figure (63)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2500 (X-1, Y) Phases Between 6:45 and 7:00

The results for the intersection No. 3400 (X, Y-1) of both developed and existing control systems are presented in Figure 64. Numbers of vehicles passing the various intersection' phases increased from N', and

W' phases and decreased from S' and E' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 65. As can be seen, the green times needed to pass the four phases decreased from S' phase and increased from N', E' and W' phases. By comparing the existing and developed system, it's been noticed that there is a green time loss that could be used somewhere else to improve the flow through the whole intersection.

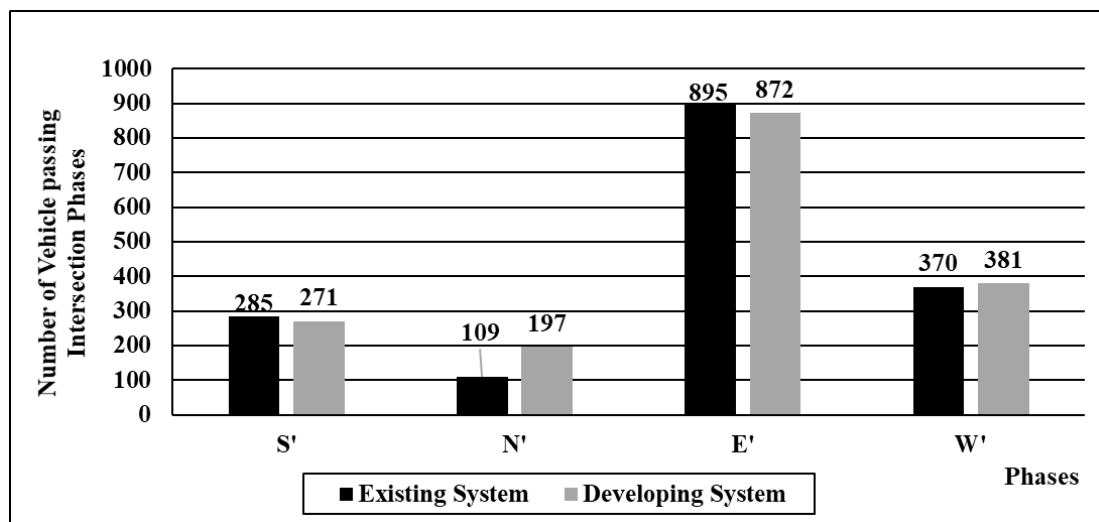


Figure (64)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 3400 (X, Y-1) Between 6:45 and 7:00

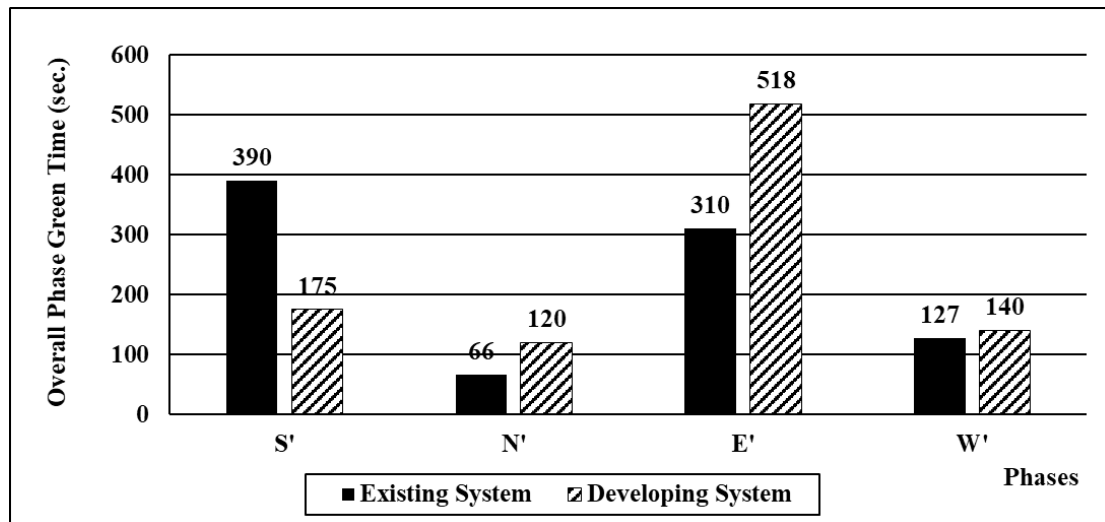


Figure (65)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 3400 (X, Y-1) Phases Between 6:45 and 7:00

(2) Total number of vehicles passing each intersection: As shown in Figure 66, the volume of traffic passing the intersection considering the developed model increased at intersections (No. 1400 (X, Y1), No. 2400 (X, Y), No. 2500 (X-1, Y), and No. 3400 (X, Y-1)) and decreased at intersection No. 2350 (X1, Y). The overall suggestions proved that applying the developed control system on the five intersections improved the rate of flow with the intersections' cycle time.

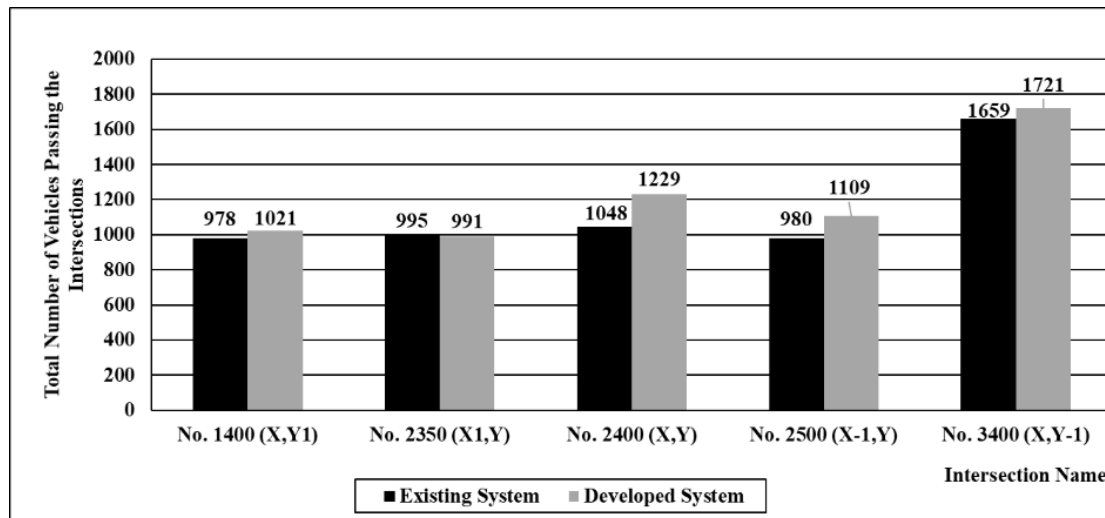


Figure (66)

The Developed Versus Existing Control Systems in Term of Total Number of Vehicles Passing Through the Five Intersections Between 6:45 and 7:00

(3) Number of cycles: As shown in Figure 67, the number of cycles generated by the developed model increased at all intersections (No. 1400 (X, Y1), No. 2350 (X1, Y), No. 2400 (X, Y), No. 2500 (X-1, Y), and No. 3400 (X, Y-1)). That demonstrates, within the time frame of the intersection, the number of cycles increased which led to less waiting times and delays.

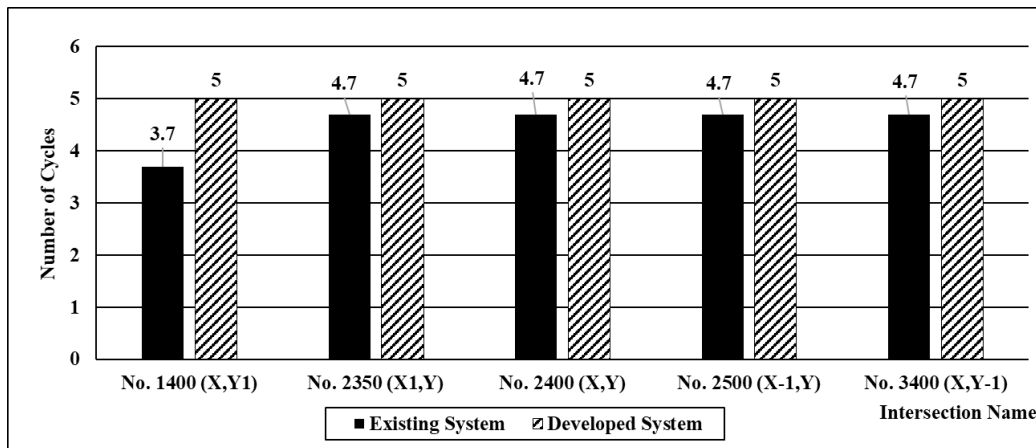


Figure (67)

The Developed Versus Existing Control Systems in Term of Number of Cycles for the Five Intersections Between 6:45 and 7:00

6.2.2. Results of period 14:15 – 14:30

(1) Traffic volume and corresponding green times necessary for the vehicles dissipation through phases: The results for the intersection No. 1400 (X, Y1) of both developed and existing control systems are presented in Figure 68. Numbers of vehicles passing the various intersection' phases increased from S', N', E', and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 69. As can see the green times needed to pass the four phases decreased from N' phase and increased from S', E' and W' phases. That shows, the developed control system utilized the green time loss at N' phase that is resulted from the distribution of the green time in the existing system to increase the green time at other phases. Increasing the green time led to increase the number of vehicles passing through phases.

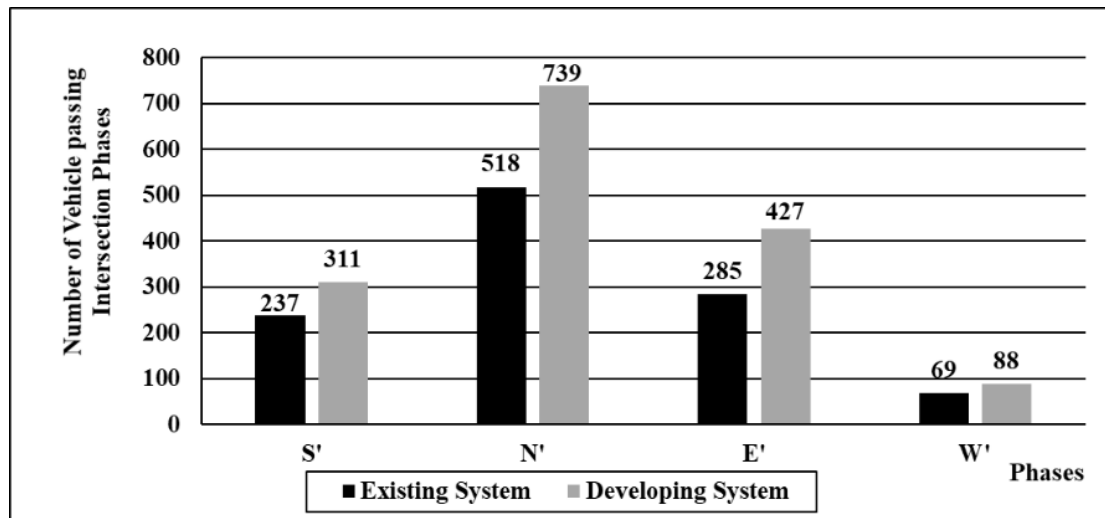


Figure (68)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 1400 (X, Y1) Between 14:15 and 14:30

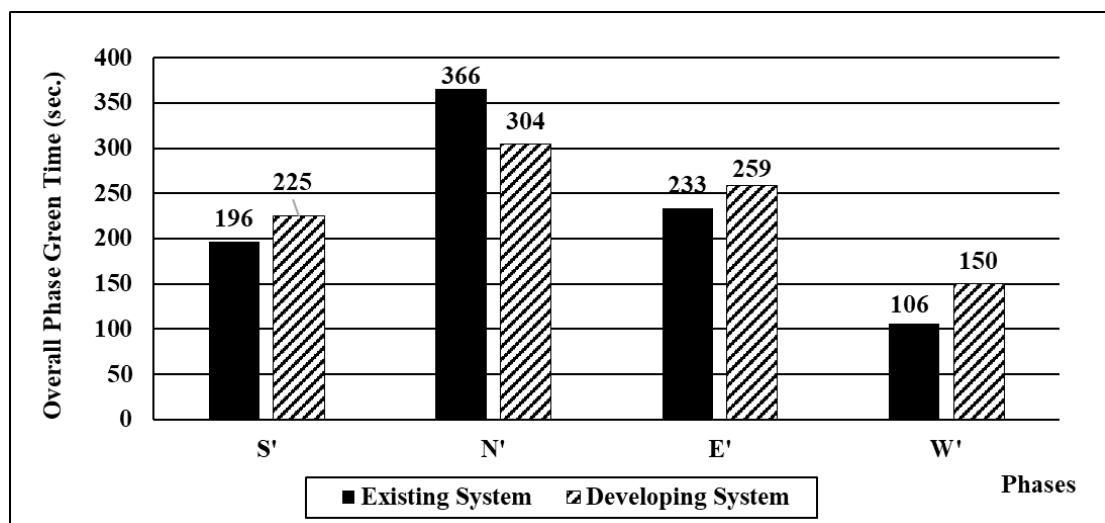


Figure (69)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 1400 (X, Y1) Phases Between 14:15 and 14:30

The results for the intersection No. 2350 (X1, Y) of both developed and existing control systems are presented in Figure 70. Numbers of vehicles passing the various intersection' phases increased from S', N', and E' phases and decreased from W' phase. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 71. As can be seen, the green time needed to pass the four phases decreased from N', E' and W' phases and increased from S' phase. Decreasing the green time and number of vehicles passing through the W' phase indicates that, the phase is given more time than needed by the existing system. In addition, decreasing the green time at N' and E' phases led to increase the number of vehicles passing through, means that, the developed control system reduced the green time loss at these phases in order to increase the green time at the S' phase as needed.

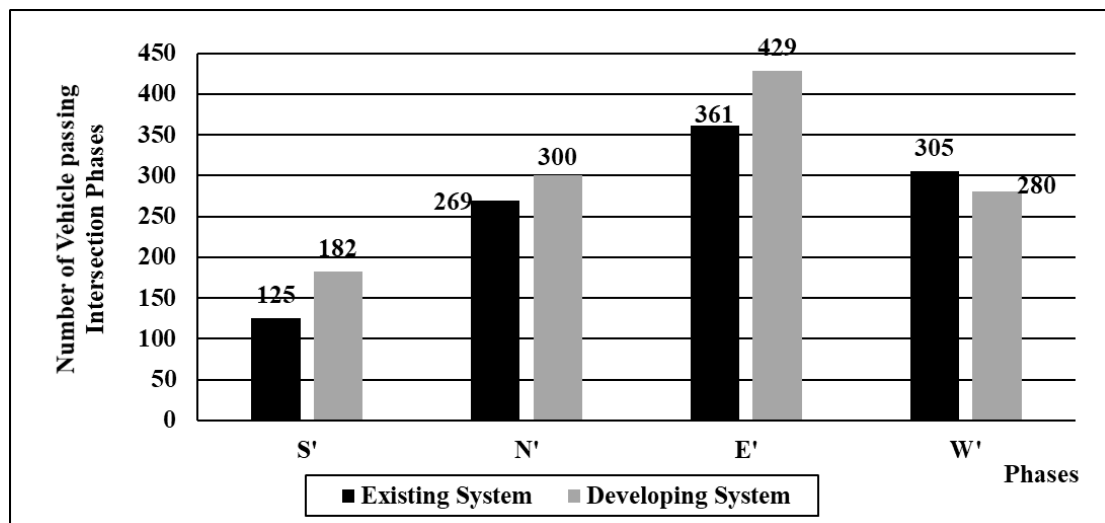


Figure (70)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2350 (X1, Y) Between 14:15 and 14:30

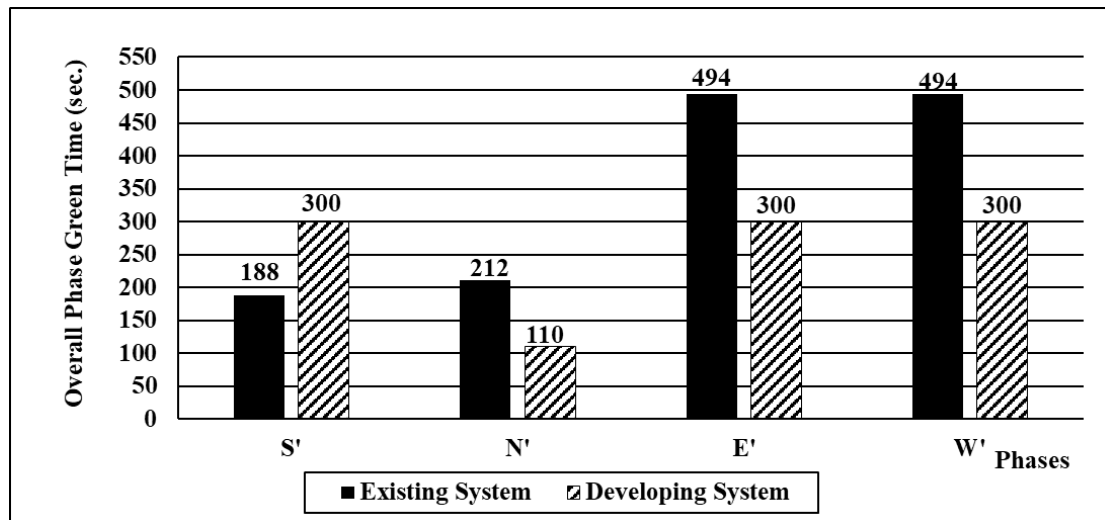


Figure (71)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2350 (X1, Y) Phases Between 14:15 and 14:30

The results for the intersection No. 2400 (X, Y) of both developed and existing control systems are presented in Figure 72. Numbers of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 73. As can be seen, the green time needed to pass the four phases decreased from S' and E' phases and increased from N' and W' phases. That indicates, the green time loss decreased at S' and E' phases to increase the green time as needed in N' and W' phases which means that the presented system modified 50% of the intersection.

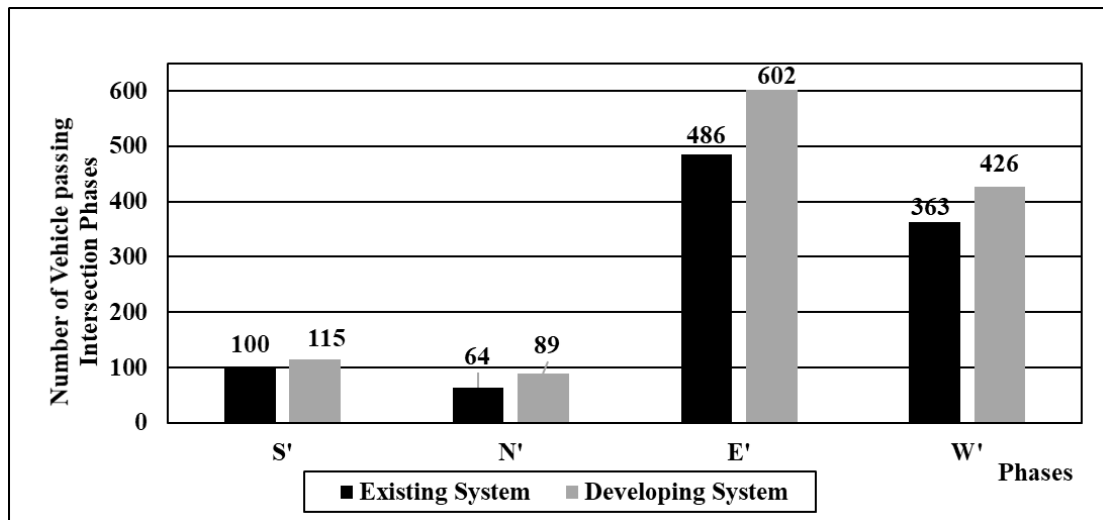


Figure (72)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2400 (X, Y) Between 14:15 and 14:30

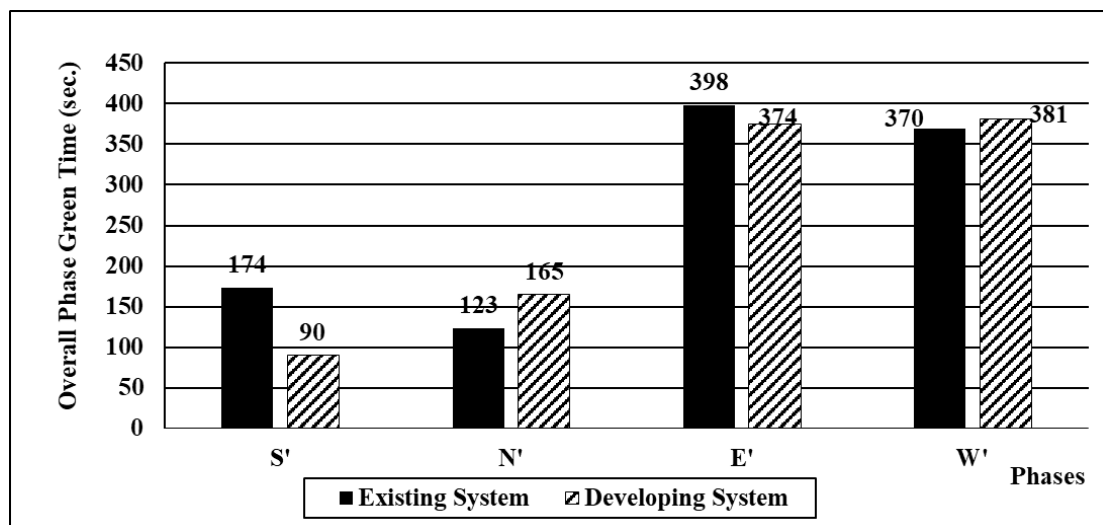


Figure (73)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2400 (X, Y) Phases Between 14:15 and 14:30

The results for the intersection No. 2500 (X-1, Y) of both developed and existing control systems are presented in Figure 74. Numbers of vehicles passing the various intersection' phases increased from S', N' and E' phases and decreased from W' phase. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 75. As can be seen, the green time needed to pass the four phases decreased from W' phase and increased from S', N' and E' phases. Reducing the green time of W' phase allow the developed control system to increase the green time of other phases, which led to increase the number of vehicles passing through.

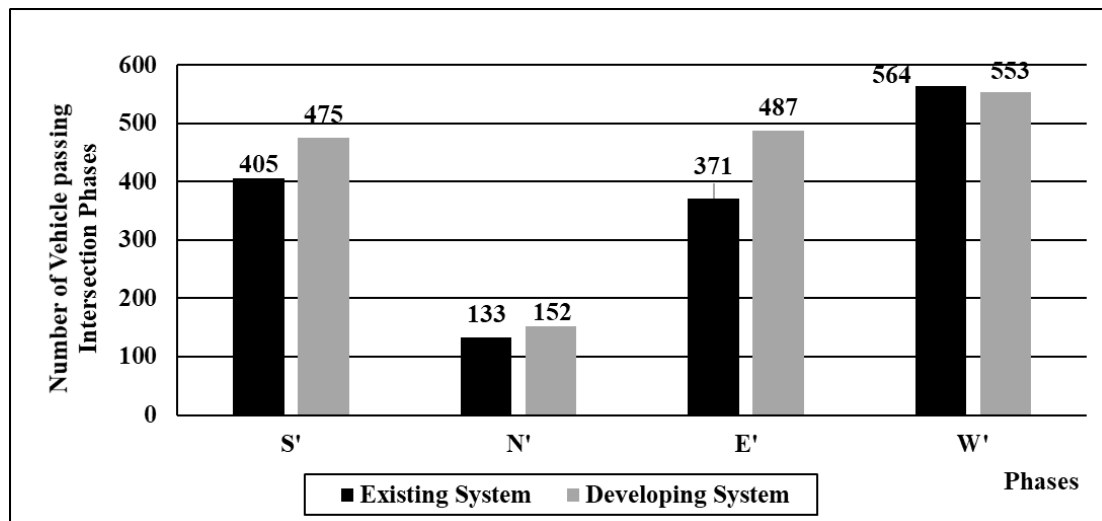


Figure (74)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2500 (X-1, Y) Between 14:15 and 14:30

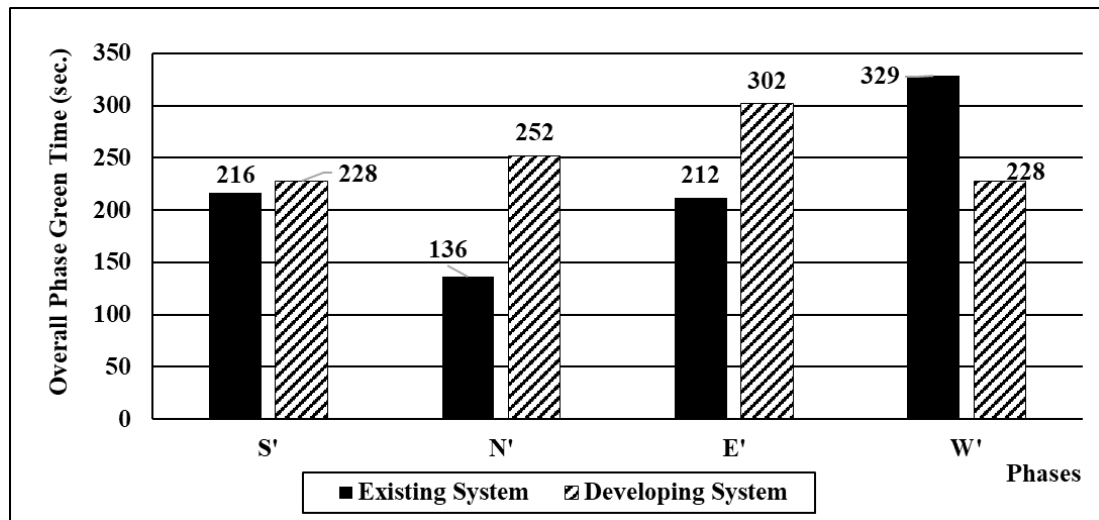


Figure (75)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2500 (X-1, Y) Phases Between 14:15 and 14:30

The results for the intersection No. 3400 (X, Y-1) of both developed and existing control systems are presented in Figure 76. Numbers of vehicles passing the various intersection' phases increased from S', E' and W' phases and decreased from N' phase. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 77. As can be seen, the green time needed to pass the four phases decreased from S' phase, increased from E' and W' phases and remained constant at phase N' phase. It can be noted that the developed control system decreased the green time loss at S' phase and increased the green time at E' and W' phases as needed in order to reduce the vehicle queues and increase the number of vehicles passing through.

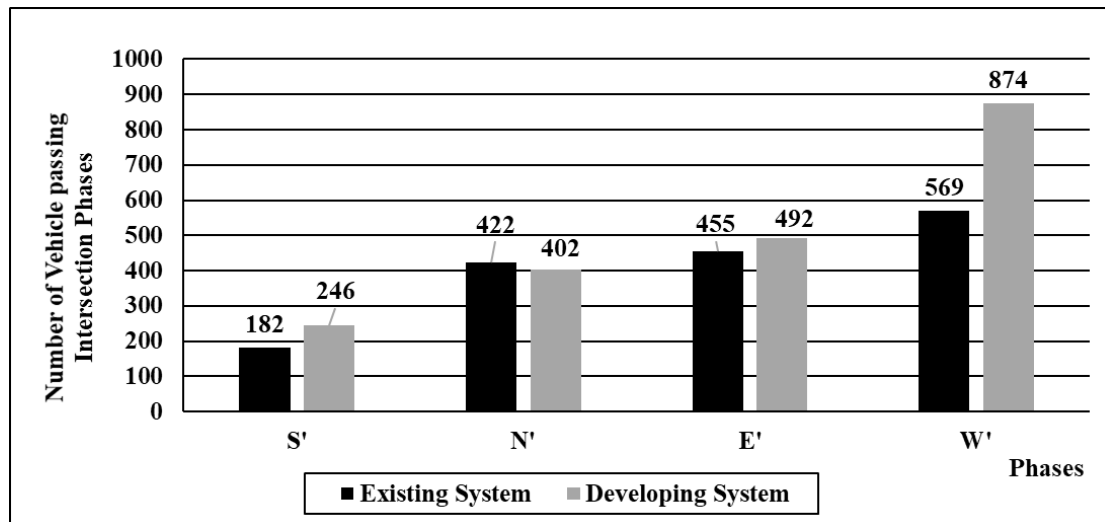


Figure (76)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 3400 (X, Y-1) Between 14:15 and 14:30

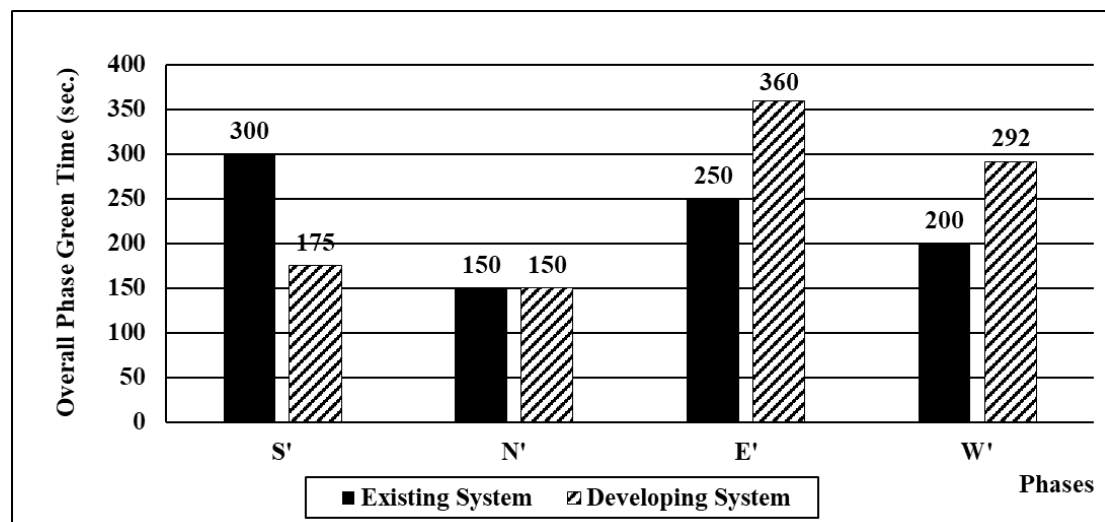


Figure (77)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 3400 (X, Y-1) Phases Between 14:15 and 14:30

(2) Total number of vehicles passing each intersection: As shown in Figure 78, the volume of traffic passing the intersection considering the developed model increased for all five intersections (No. 1400 (X, Y1), No. 2350 (X1, Y), No. 2400 (X, Y), No. 2500 (X-1, Y), and No. 3400 (X, Y-1)). That means, the developed control system improved the intersections traffic flow, which means, shorter queues and probably less delays.

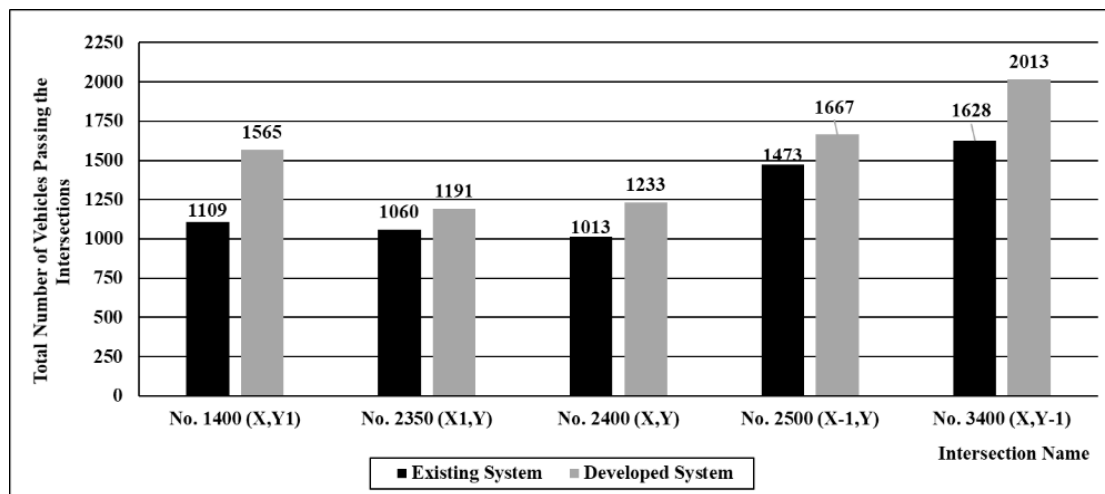


Figure (78)

The Developed Versus Existing Control Systems in Term of Total Number of Vehicles Passing Through the Five Intersections Between 14:15 and 14:30

(3) Number of cycles: As shown in Figure 79, the number of cycles generated by the developed model increased at intersections No. 2350 (X1, Y) and No. 2500 (X-1, Y), decreased at intersections No. 1400 (X, Y1) and No. 2400 (X, Y), and remained constant at intersection No. 3400 (X, Y-1). The developed control system improved the number of cycles of some intersections relatively than others.

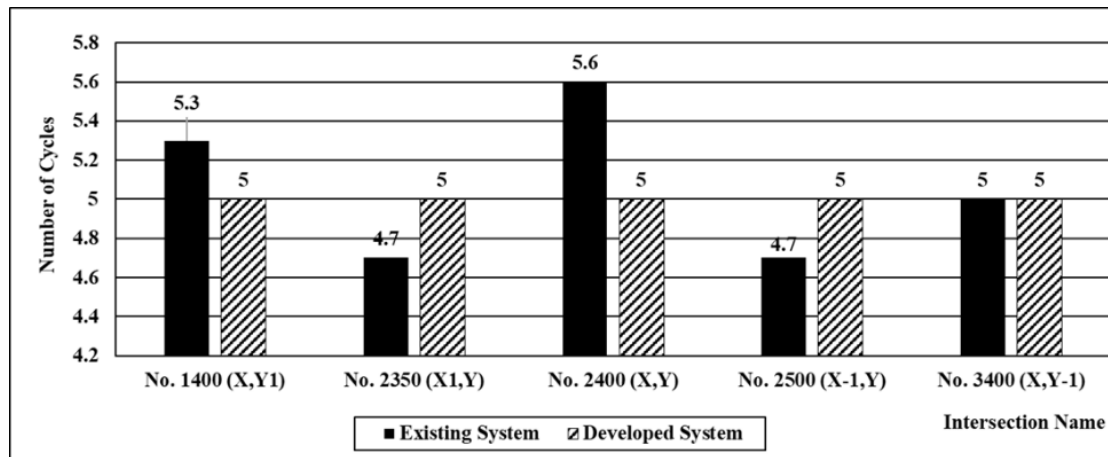


Figure (79)

The Developed Versus Existing Control Systems in Term of Number of Cycles for the Five Intersections Between 14:15 and 14:30

6.2.3. Results of period 17:15 – 17:30

(1) Traffic volume and corresponding green times necessary for the vehicles dissipation through phases: The results for the intersection No. 1400 (X, Y1) of both developed and existing control systems are presented in Figure 80. Numbers of vehicles passing the various intersection' phases were increased from N', E', and W' phases and decreased from S' phase. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 81. As can be seen, the green times needed for vehicles to pass the four phases decreased from S' phase and increased from N', E' and W' phases. That indicates, there is a green time loss at S' phase resulted from the distribution of the green time by the existing system. The developed control system decreased the green time loss in order to increase the number of vehicles passing through other phases.

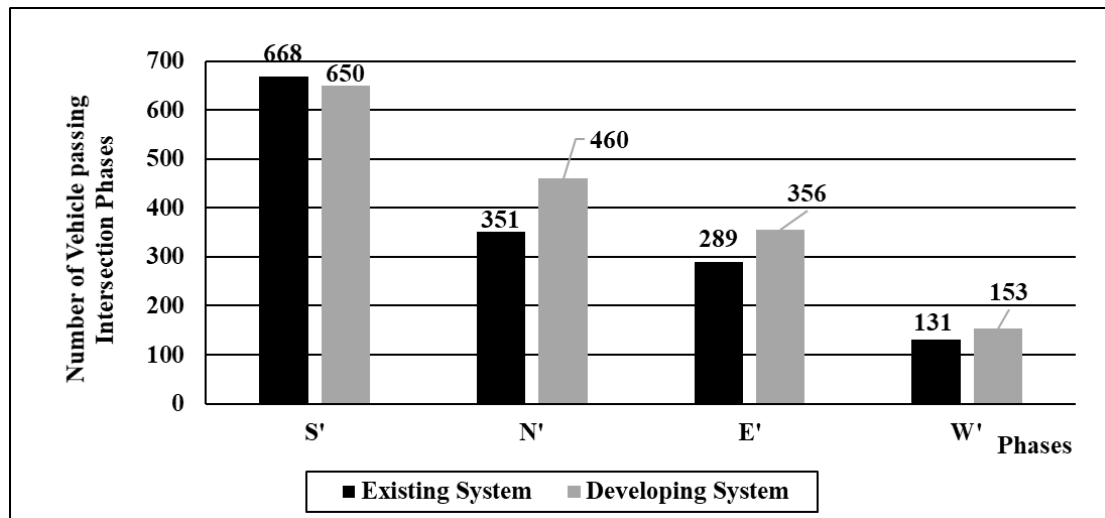


Figure (80)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 1400 (X, Y1) Between 17:15 and 17:30

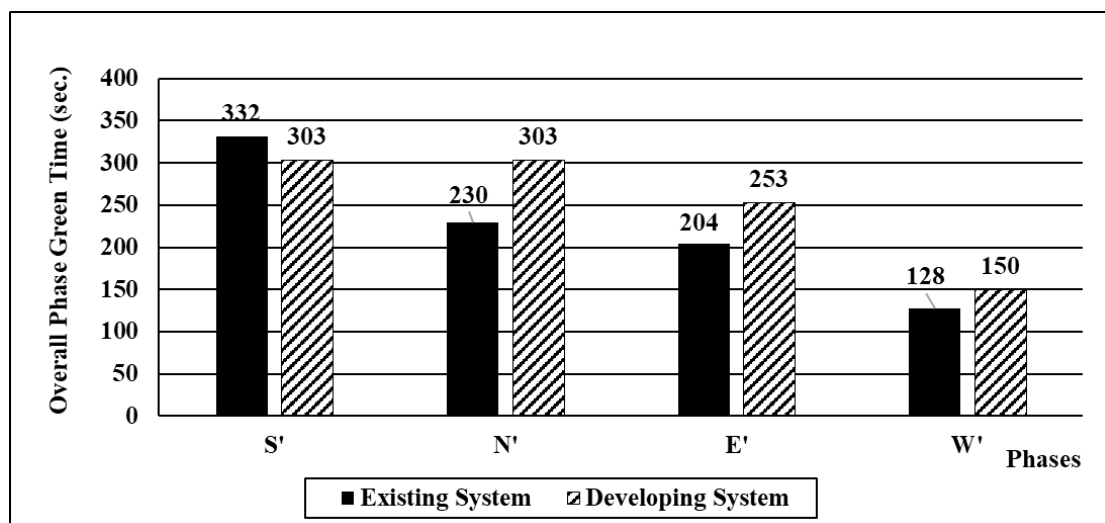


Figure (81)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 1400 (X, Y1) Phases Between 17:15 and 17:30

The results for the intersection No. 2350 (X1, Y) of both developed and existing control systems are presented in Figure 82. Numbers of vehicles passing the various intersection' phases increased from S' and N' phases and decreased from E' and W' phases. The green times needed for vehicles to pass the various phases at the same period are presented in Figure 83. As can be seen the green times needed to pass the four phases decreased from E' and W' phases and increased from S' and N' phases. That shows, the existing control system distributed the green time of the E' and W' phases more than needed. While the developed control system increased the green time of the S' and N' phases to increase the vehicles flow and to shorten the waiting times.

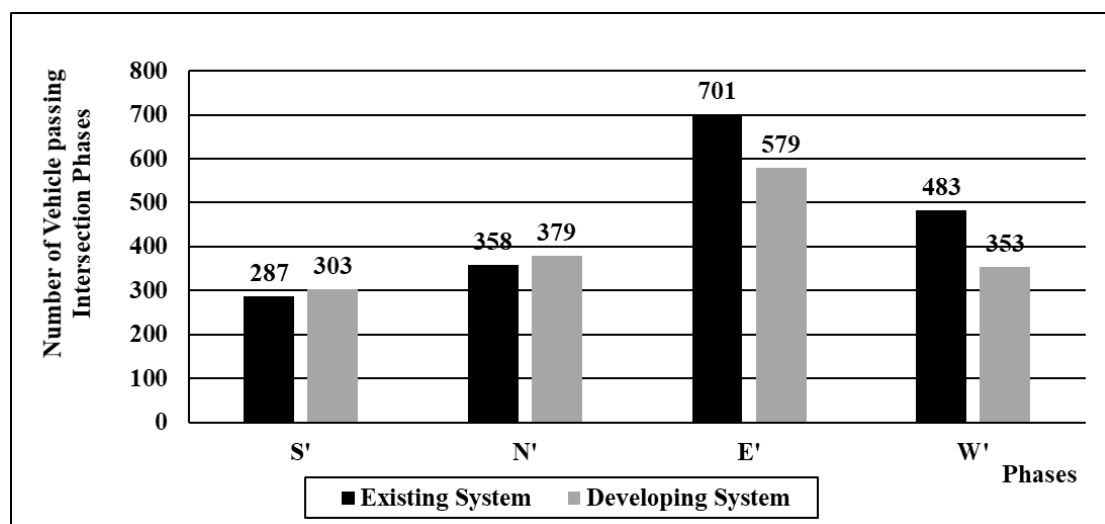


Figure (82)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2350 (X1, Y) Between 17:15 and 17:30

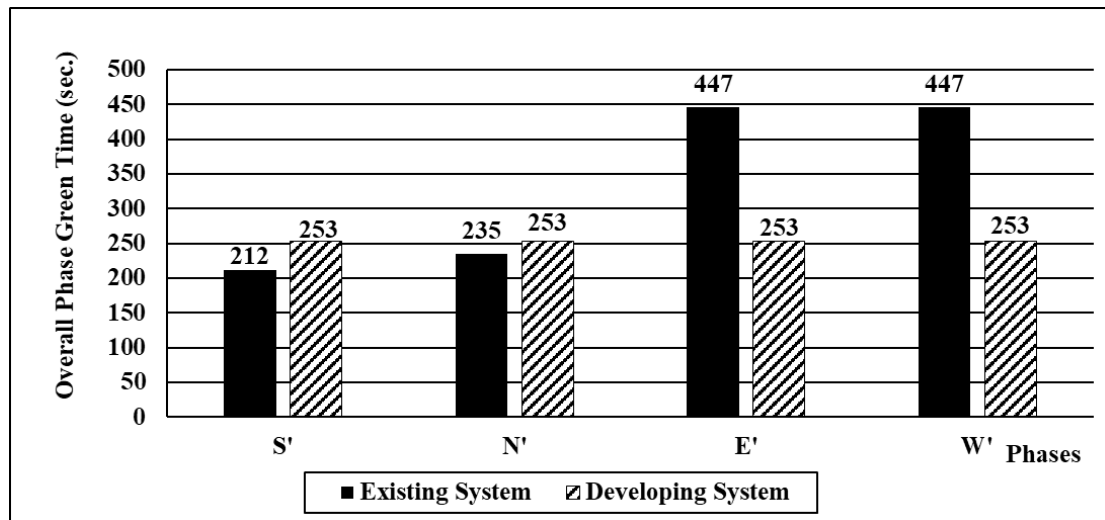


Figure (83)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2350 (X1, Y) Phases Between 17:15 and 17:30

The results for the intersection No. 2400 (X, Y) of both developed and existing control systems are presented in Figure 84. Numbers of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 85. As can be seen, the green times needed to pass the four phases increased from S', N', E' and W' phases. That shows, the green times are distributed by the developed control system based on the traffic situation, which assists in increasing vehicle flow passing through the intersection' phases.

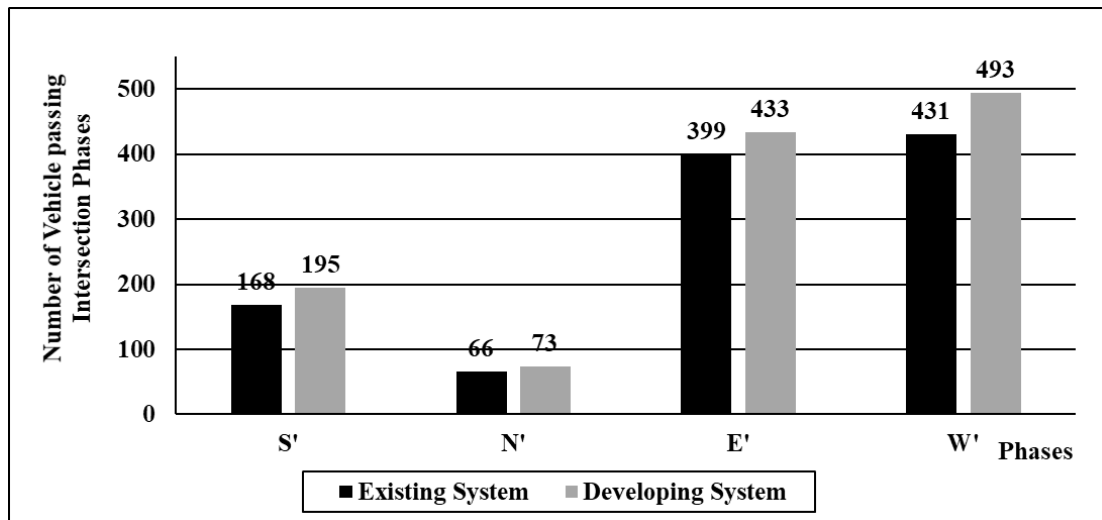


Figure (84)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2400 (X, Y) Between 17:15 and 17:30

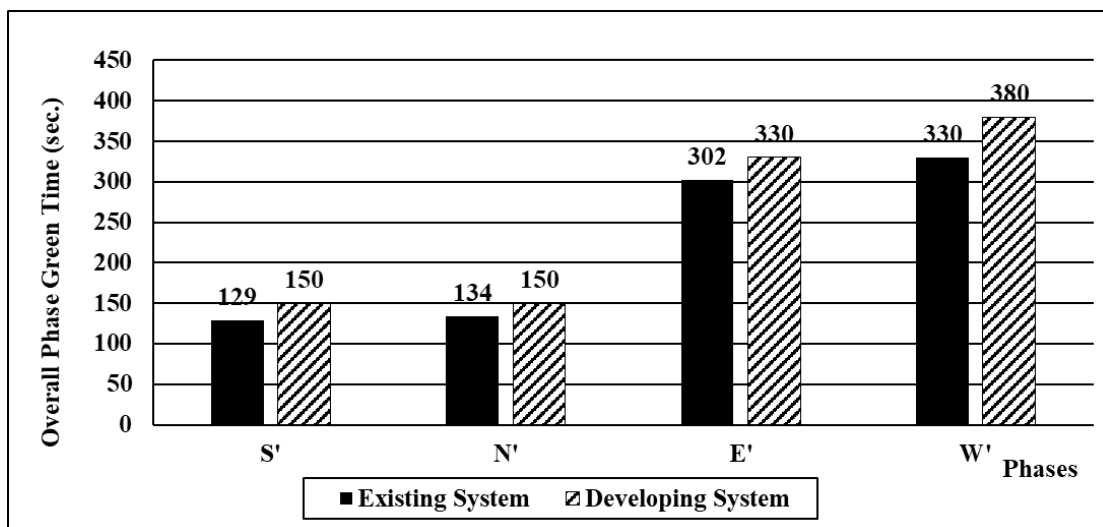


Figure (85)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2400 (X, Y) Phases Between 17:15 and 17:30

The results for the intersection No. 2500 (X-1, Y) of both developed and existing control systems are presented in Figure 86. Numbers of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 87. As can be seen, the green times needed to pass the four phases increased from S', N', E' and W' phases. That indicates, the developed control system increased the green times as needed to reduce the vehicle queues and shorten the waiting times.

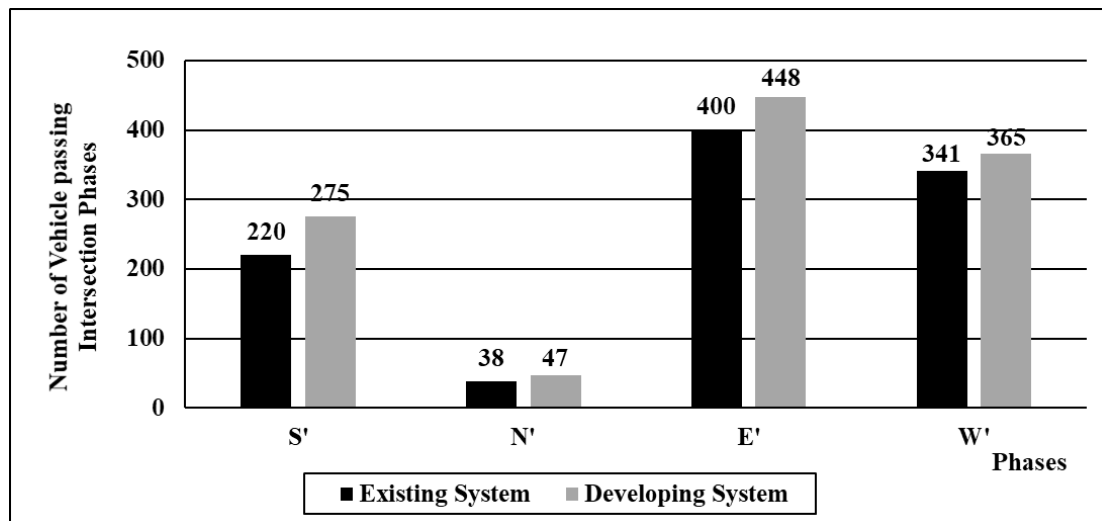


Figure (86)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2500 (X-1, Y) Between 17:15 and 17:30

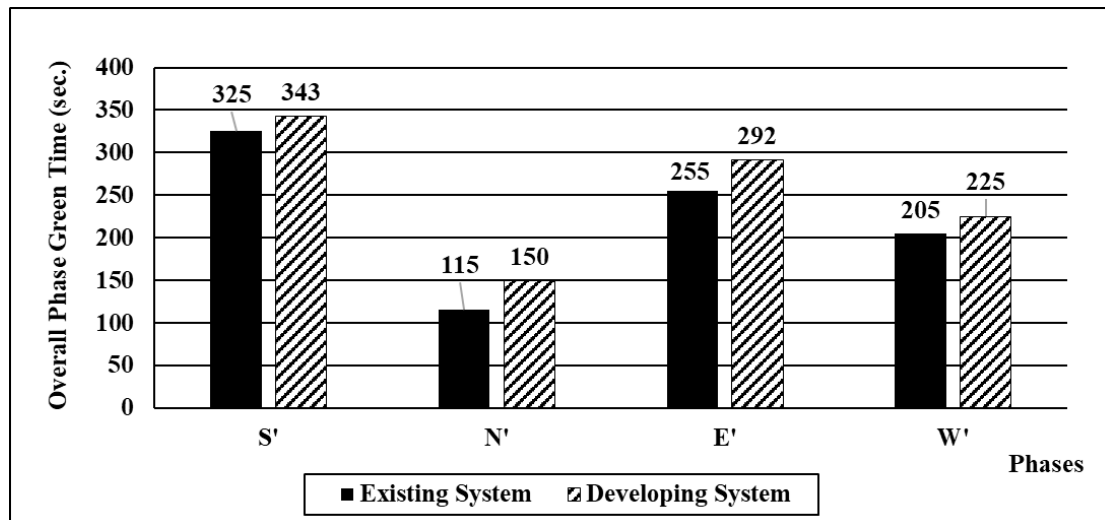


Figure (87)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2500 (X-1, Y) Phases Between 17:15 and 17:30

The results for the intersection No. 3400 (X, Y-1) of both developed and existing control systems are presented in Figure 88. Numbers of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 89. As can be seen, the green times needed to pass the four phases are increased from S', N', E' and W' phases. As a result, number of vehicles passing through the intersection' phases are increased by increasing the green time through the developed control system. That probably shorten the vehicle queues and waiting time.

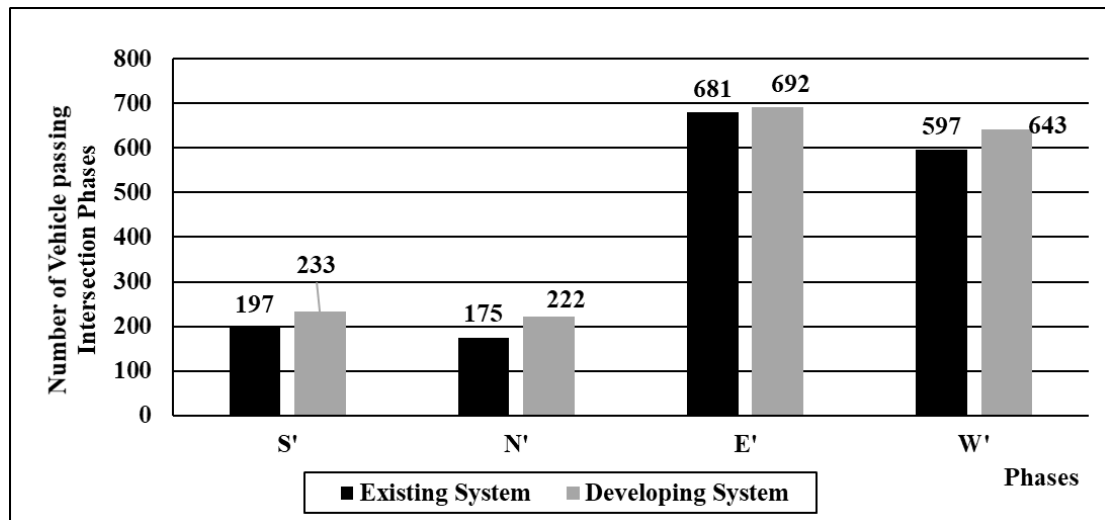


Figure (88)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 3400 (X, Y-1) Between 17:15 and 17:30

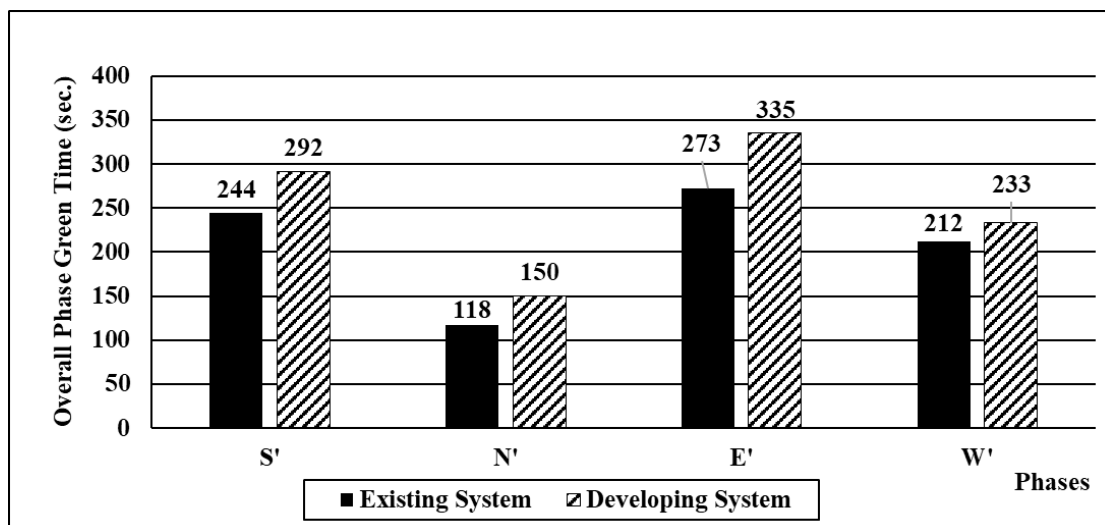


Figure (89)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 3400 (X, Y-1) Phases Between 17:15 and 17:30

(2) Total number of vehicles passing each intersection: As shown in Figure 90, the volume of traffic passing the intersection considering the developed model increased at intersections (No. 1400 (X, Y1), No. 2400 (X, Y), No. 2500 (X-1, Y), and No. 3400 (X, Y-1)) and decreased at intersection No. 2350 (X1, Y). That indicates, the developed control system improved the vehicle flow for four intersections out of five which means less waiting times and shorter delays at these intersections.

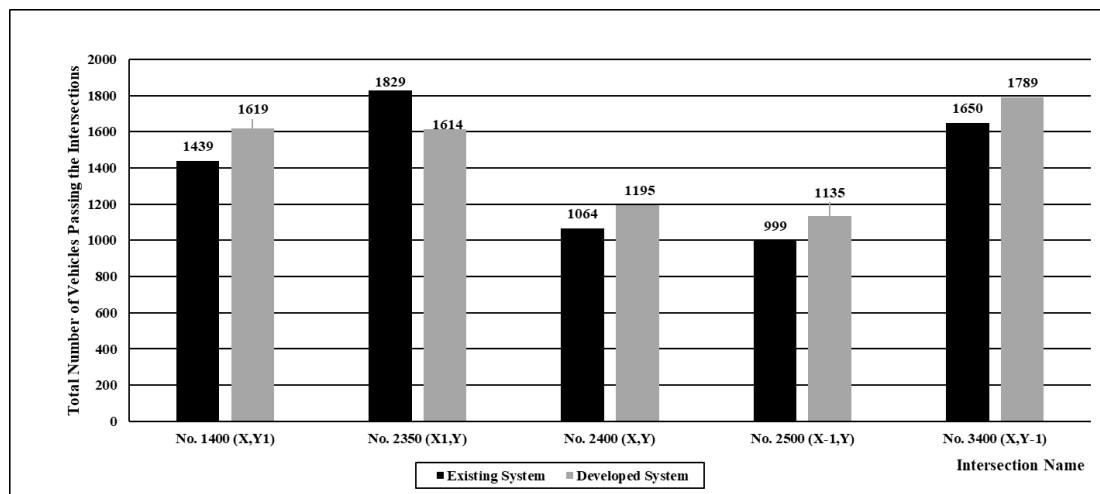


Figure (90)

The Developed Versus Existing Control Systems in Term of Total Number of Vehicles Passing Through the Five Intersections Between 17:15 and 17:30

(3) Number of cycles: As shown in Figure 91, the number of cycles generated using the developed model increased at intersections No. 2350 (X1, Y) and No. 3400 (X, Y-1), and decreased at intersections No. 1400 (X, Y1) and No. 2400 (X, Y), respectively. However, it remained constant at intersection No. 2500 (X-1, Y). That indicates, the developed control system improved some of the intersections in term of the increasing number of cycles at each intersection.

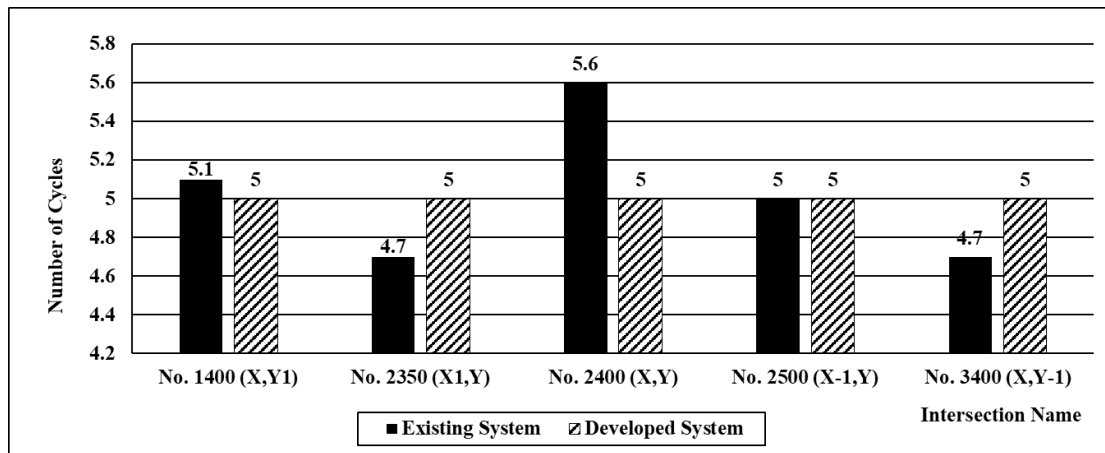


Figure (91)

The Developed Versus Existing Control Systems in Term of Number of Cycles for the Five Intersections Between 17:15 and 17:30

6.2.4. Results of period 21:30 – 21:45

(1) Traffic volume and corresponding green times necessary for the vehicles dissipation through phases: The results for the intersection No. 1400 (X, Y1) of both developed and existing control systems are presented in Figure 92. Numbers of vehicles passing the various intersection' phases increased at S', N', E', and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 93. As can be seen, the green times needed to pass the four phases decreased from S' phase and increased from N', E' and W' phases. That indicates, the green time loss at S' phase is decreased by the developed control system which allow the system to increase the green time at other phases. That means, shorter waiting and delay times.

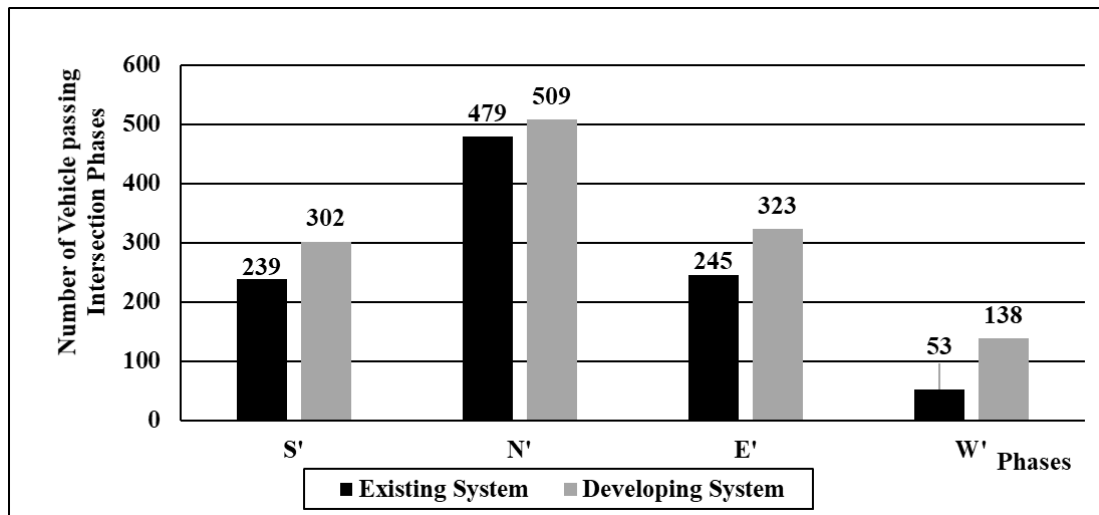


Figure (92)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 1400 (X, Y1) Between 21:30 and 21:45

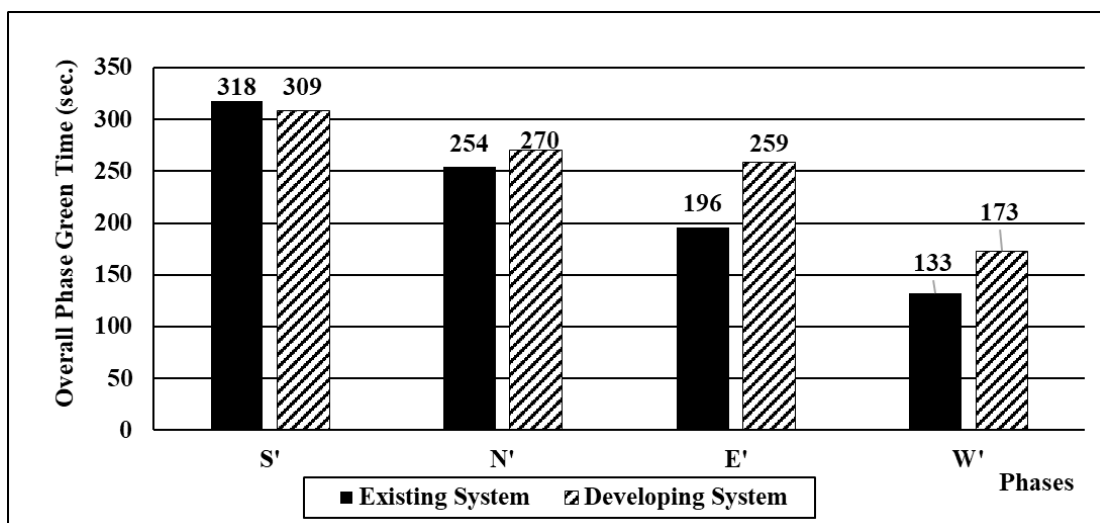


Figure (93)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 1400 (X, Y1) Phases Between 21:30 and 21:45

The results for the intersection No. 2350 (X1, Y) of both developed and existing control systems are presented in Figure 94. Number of vehicles passing the various intersection' phases increased from S', N' and W' phases and decreased from E' phase. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 95. As can be seen, the green times needed to pass the four phases decreased from S', E' and W' phases and increased from N' phase. The green time at E' phase and the number of vehicles passing decreased, which means that there is a green time loss at this phase resulted by the existing system. As well as in S' and W' phases, however the number of vehicles passing through the phases increased which means that, the green time loss at these phases is large. The decrease in the green time at the last phases allow the developed control system to increase the green time at N' phase and to increase the vehicle flow.

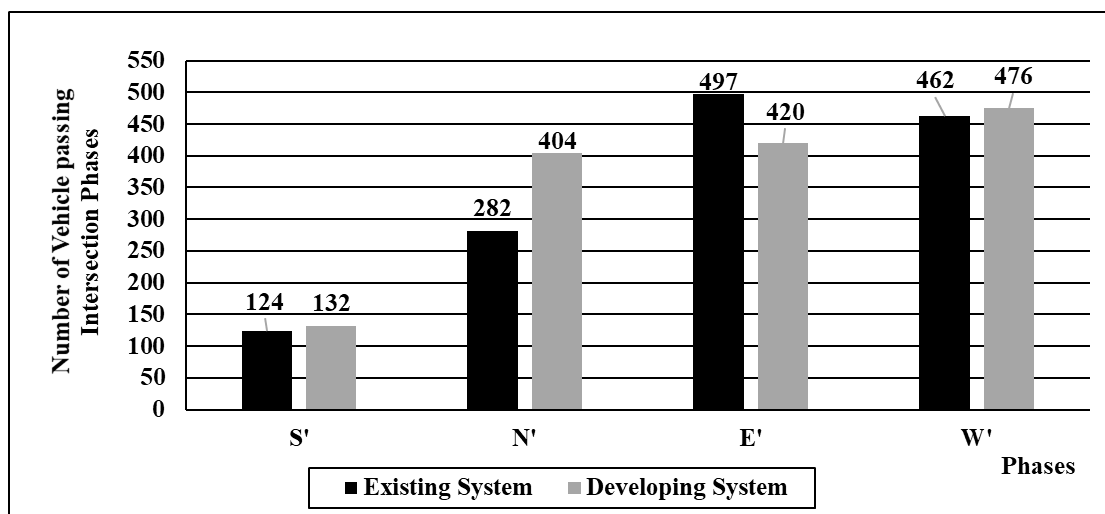


Figure (94)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2350 (X1, Y) Between 21:30 and 21:45

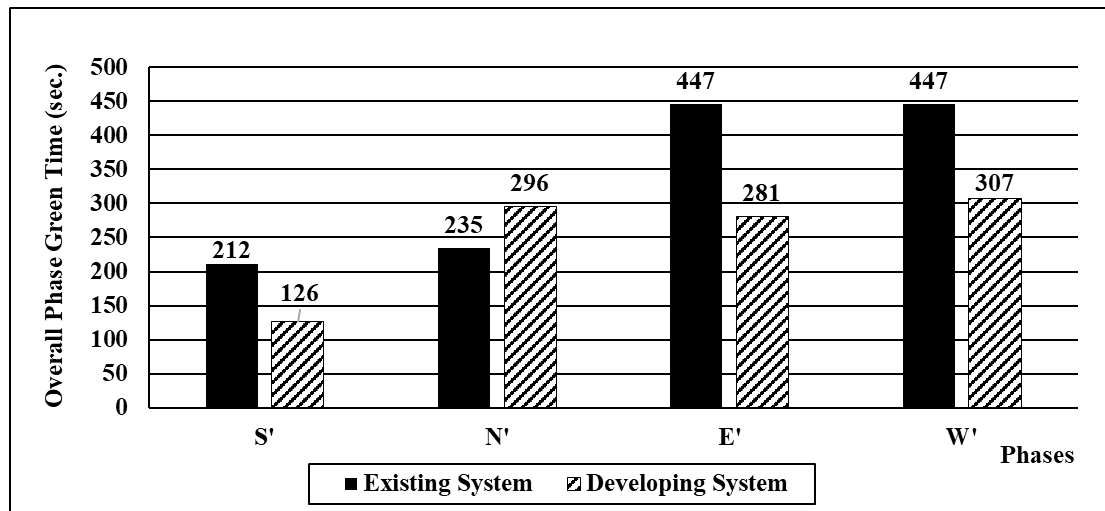


Figure (95)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2350 (X1, Y) Phases Between 21:30 and 21:45

The results for the intersection No. 2400 (X, Y) of both developed and existing control systems are presented in Figure 96. Number of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 97. As can be seen, the green times needed to pass the four phases decreased from E' phase and increased from S', N', and W' phases. That indicates, the green time loss at E' phase is large, whereas the developed control system partially used the extra time to increase the number of vehicles passing through. The green time at other phases increased and led to increase in the vehicle flow, which means that, the existing control system did not distribute the green time based on the traffic situation.

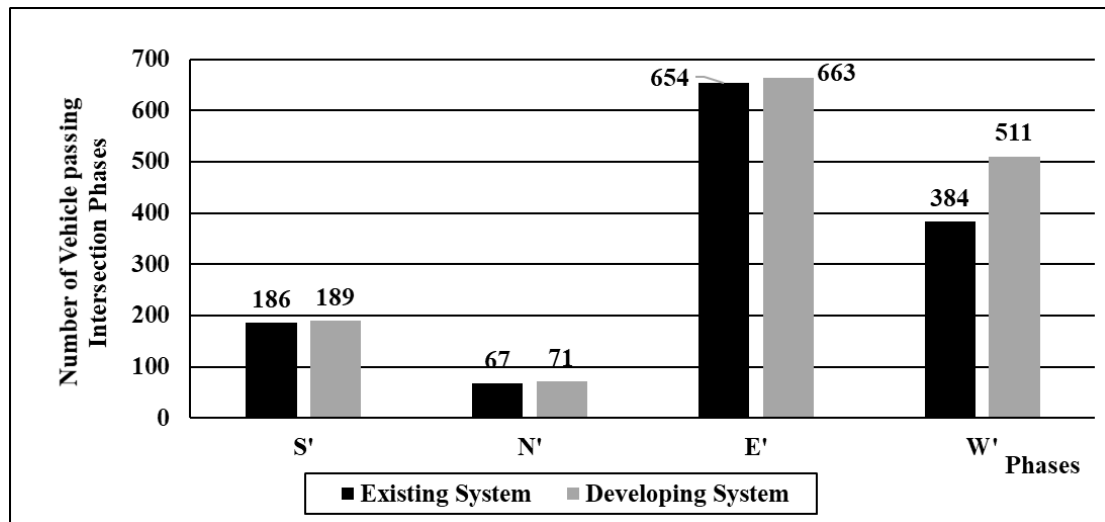


Figure (96)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2400 (X, Y) Between 21:30 and 21:45

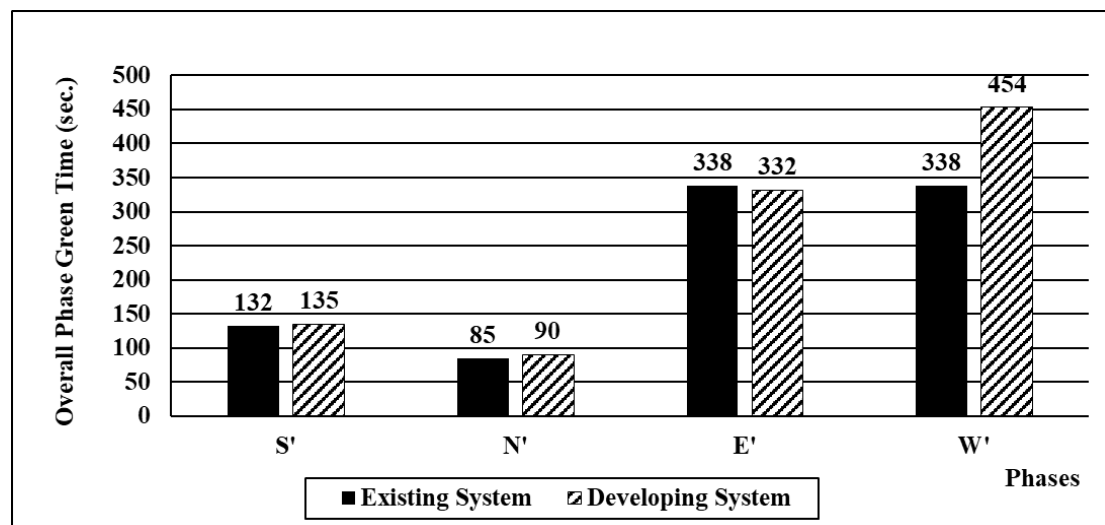


Figure (97)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2400 (X, Y) Phases Between 21:30 and 21:45

The results for the intersection No. 2500 (X-1, Y) of both developed and existing control systems are presented in Figure 98. Numbers of vehicles passing the various intersection' phases increased from N', E' and W' phases and decreased from S' phase. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 99. As can be seen, the green times needed to pass the four phases decreased from S' phase and increased from N', E' and W' phases. That designates, the green time given to S' phase by the existing control system is more than needed, for that, the developed control system increased the green time at other phases in order to speed up the vehicles passing through.

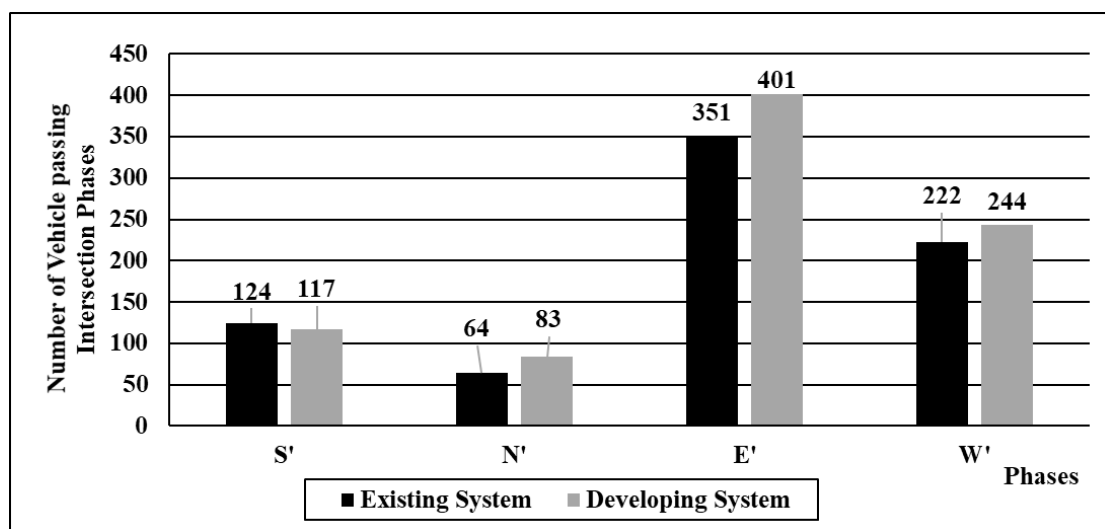


Figure (98)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 2500 (X-1, Y) Between 21:30 and 21:45

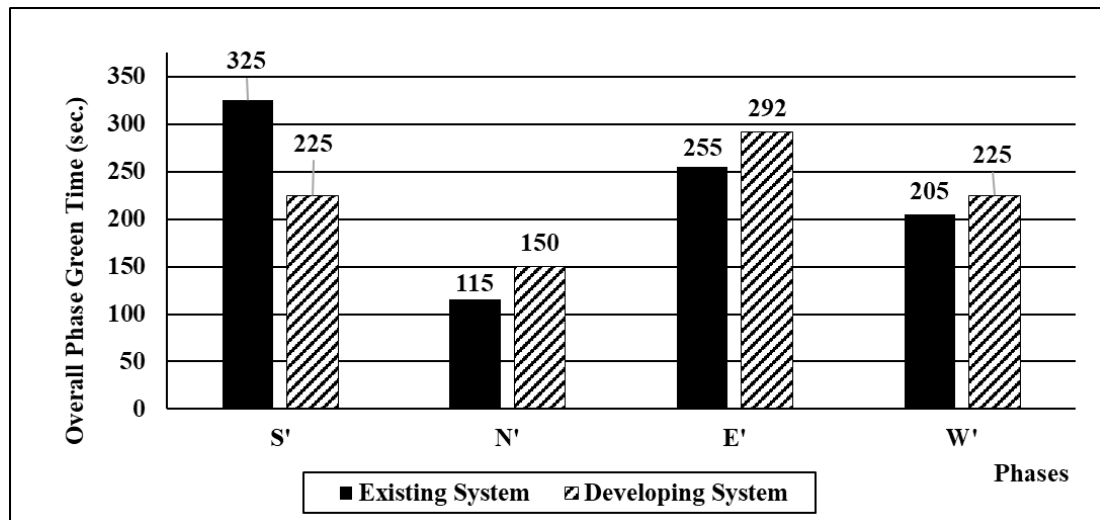


Figure (99)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 2500 (X-1, Y) Phases Between 21:30 and 21:45

The results for the intersection No. 3400 (X, Y-1) of both developed and existing control systems are presented in Figure 100. Numbers of vehicles passing the various intersection' phases increased from S', N', E' and W' phases. The green times needed for the vehicles to pass the various phases at the same period are presented in Figure 101. As can be seen, the green times needed to pass the four phases decreased from E' and increased from S', N' and W' phases. That shows, the green time given to E' phase by the existing system is more than needed where the developed control system partially used the green time loss to increase the number of vehicles passing through this phase and decreased the remaining time. The results indicate that the number of vehicles passing through the other phases is improved by increasing the green time as needed.

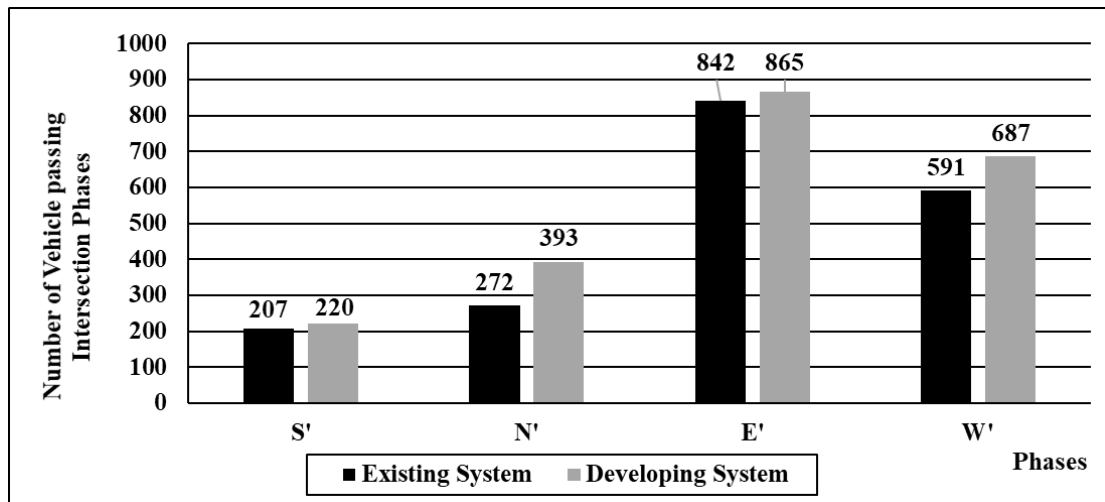


Figure (100)

The Developed Versus Existing Control Systems in Term of Number of Vehicles Passing Through Intersection No. 3400 (X, Y-1) Between 21:30 and 21:45

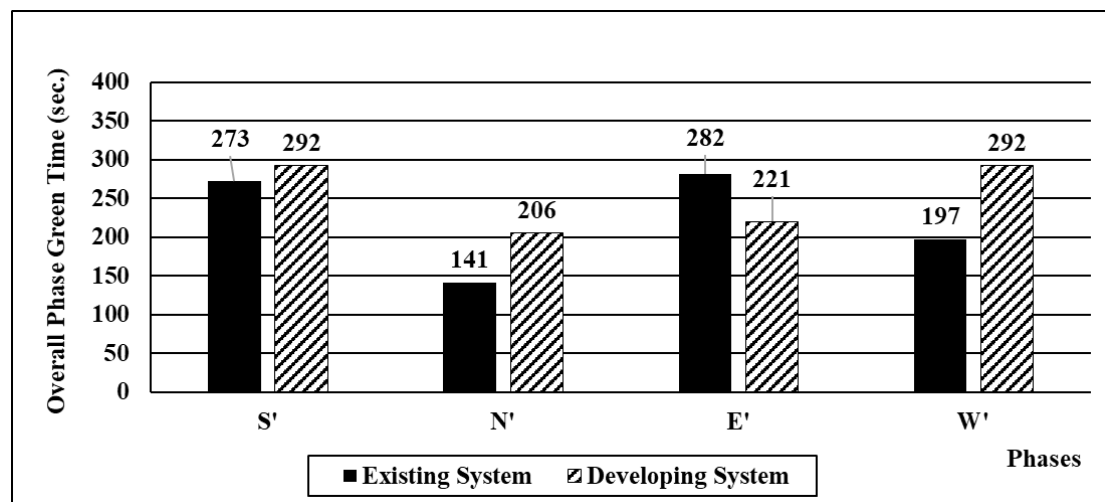


Figure (101)

The Developed Versus Existing Control Systems in Term of Green Time Needed for Vehicles to Pass Through Intersection No. 3400 (X, Y-1) Phases Between 21:30 and 21:45

(2) Total number of vehicles passing each intersection: As shown in Figure 102, the volume of traffic passing the intersection considering the developed model increased at intersections (No. 1400 (X, Y1), No. 2350 (X1, Y), No. 2400 (X, Y), No. 2500 (X-1, Y), and No. 3400 (X, Y-1). That indicates, the developed control system improved the traffic flow at five intersections.

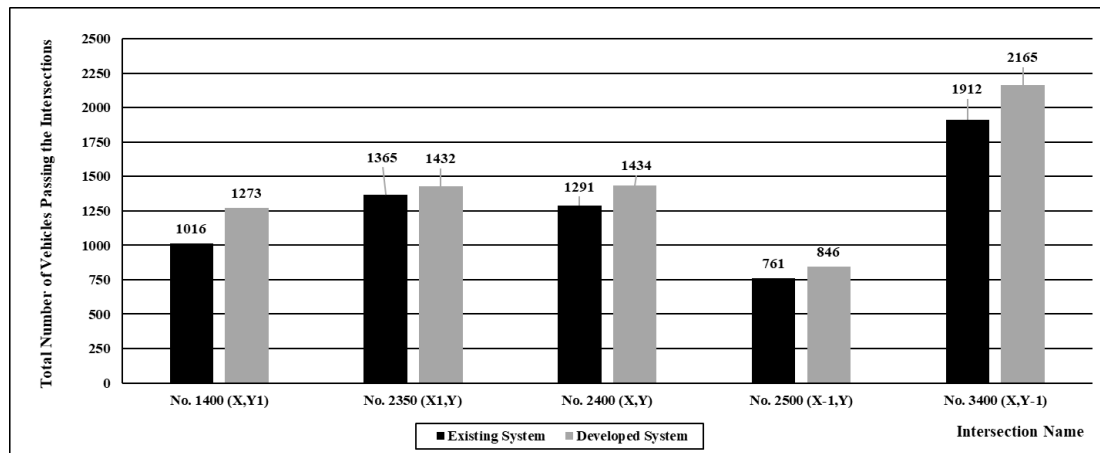


Figure (102)

The Developed Versus Existing Control Systems in Term of Total Number of Vehicles Passing Through the Five Intersections Between 21:30 and 21:45

(3) Number of cycles: As shown in Figure 103, the number of cycles generated by the developed model increased at intersections No. 2350 (X1, Y), No. 2400 (X, Y) and No. 3400 (X, Y-1), and decreased at intersections No. 1400 (X, Y1), respectively. It remained constant at intersection No. 2500 (X-1, Y). That indicates, the developed control system improved the performance of three intersections corresponding to the number of cycles.

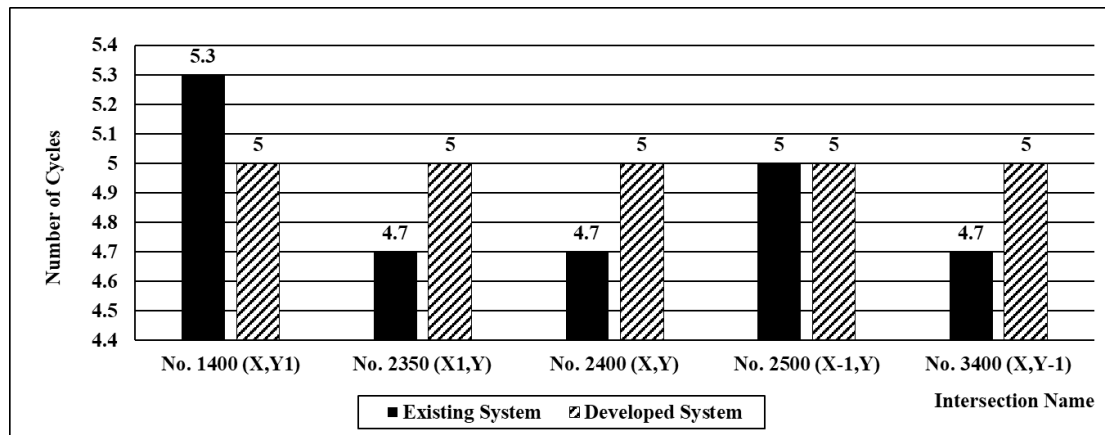


Figure (103)

The Developed Versus Existing Control Systems in Term of Number of Cycles for the Five Intersections Between 21:30 and 21:45

6.3. Performance Analysis of the Intersections

The results for four considered peak periods (6:45 – 7:00, 14:15 – 14:30, 17:15 – 17:30 and 21:30 – 21:45) for all 20 phases at five tested intersections, i.e. No. 1400 (X, Y1), No. 2350 (X1, Y), No. 2400 (X, Y), No. 2500 (X-1, Y) and No. 3400 (X, Y-1)) were analyzed and used to compare the performance of the developed and the existing control systems. This was based on the percentage differences of the following parameters: number of vehicle dissipation during each phase, the usable green times for the various phases, the sum of the vehicles passing through each intersection during all the four phases, and frequency of the cycles during the specified periods.

6.3.1. Performance measures of period 6:45 – 7:00

(1) Percentages of the differences between number of vehicles dissipating the various intersections' phases are presented in Figure 104, while the corresponding percentages of the differences between the necessary green times to allow vehicles to pass intersections for all four

phases are presented in Figure 105. These percentages were calculated based on the results presented in Figures 56 – 65.

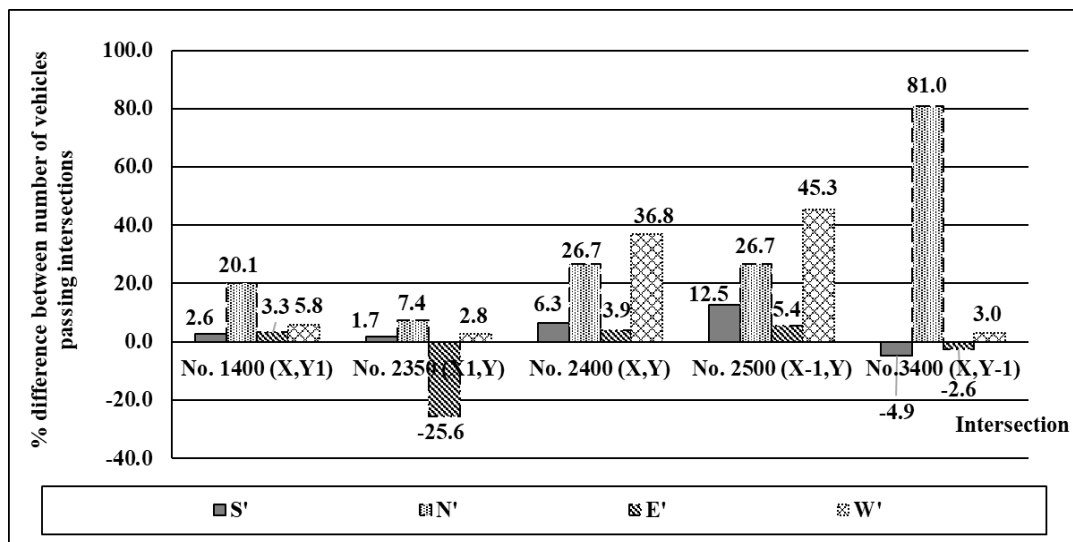


Figure (104)

Percentage Difference Between the Developed system and Existing One in Term of Number of Vehicles Crossing the Various Intersections Between 6:45 and 7:00

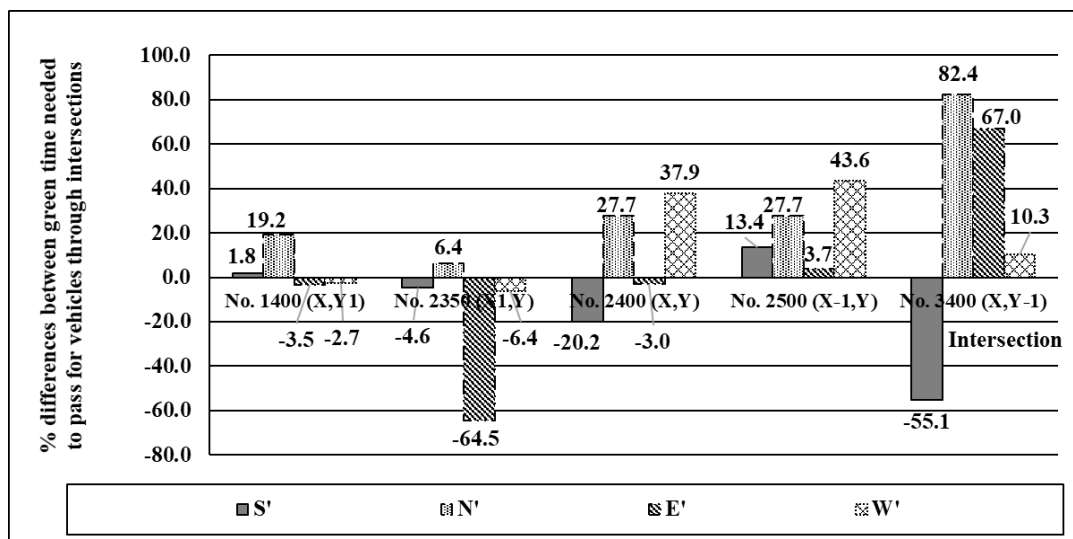


Figure (105)

Percentage Difference Between the Developed system and Existing One in Term of Necessary Green Time to Allow Vehicles to Cross the Intersections Phases Between 6:45 and 7:00

From the earlier two Figures, number of vehicles crossing intersection No. 1400 (X, Y1) showed an increase of 2.6% ($\frac{767-748}{748} \times 100$), 20.1%, 3.3%, and 5.8%, for the S', N', E' and W' phases, respectively, as a result of using the developed model. The utilization of the green times for the vehicles to pass E' and W' phases decreased by 3.5% and 2.7%, respectively, and increased by 1.8% and 19.2% when passing through S' and N' phases, respectively. That means, the green time is distributed by the developed control system based on the traffic situation. The developed control system decreased the green time in 2 phases and increased the green time in the other 2 phases. The results showed an improvement in the vehicle flow at the four phases of the intersection.

Number of vehicles crossing intersection No. 2350 (X1, Y) showed an increase of 1.7%, 7.4%, and 2.8% for the S', N', and W' phases, respectively, and a decrease of 25.6% for the E' phase. The utilization of the green times for the vehicles to pass S', E' and W' phases decreased by 4.6%, 64.5%, and 6.4%, respectively, and increased by 6.4% when passing through N' phase, respectively. The developed control system utilized the green time loss at E' phase resulted from the existing control system to increase the green time at the other three phases. That means, the developed control system improved the number of vehicles passing through 3 phases out of 4 phases. Moreover, the developed control system improved 3 phases by decreasing the green time.

Number of vehicles crossing intersection No. 2400 (X, Y) showed an increase of 6.3%, 26.7%, 3.9% and 36.8% for the S', N', E' and W' phases. The utilization of the green times for the vehicles to pass S' and E' phases decreased by 20.2% and 3%, respectively, and increased by 27.7% and 37.9% when passing through N' and W' phases, respectively. The developed control system partially used the green time loss at S' phase in

order to increase the number of vehicles and cancelled the remaining time. At the same time, the system increased the green time at N', E' and W' phases which led to increase the number of vehicles passing through these phases. To summarize, the developed control system improved the number of vehicles passing through intersection' phases. Also, it improved 2 phases by decreasing the green time.

Number of vehicles crossing intersection No. 2500 (X-1, Y) showed an increase of 12.5%, 26.7%, 5.4% and 45.3% for the S', N', E' and W' phases, respectively. The utilization of the green times for the vehicles to pass S', N', E' and W' phases increased by 13.4%, 27.7%, 3.7% and 43.6% when passing through S', N', E' and W' phases respectively. That mean, the green time is distributed by the developed control system based on the traffic situation, where the traffic flow at 4 phases is improved.

Number of vehicles crossing intersection No. 3400 (X-1, Y) showed an increase of 81% and 3% for the N' and W' phases, and a decrease of 4.9% and 2.6% for the S' and E' phases, respectively. The utilization of the green times for the vehicles to pass S' phases decreased by 55.1% and increased by 82.4%, 67%, and 10.3% when passing through N', E' and W' phases, respectively. The developed control system improved the traffic of one phase only and did not positively affected the other phases. At the same time, the developed control system improved one phase in terms of decreasing the green time.

By summarizing the previous results, the amount of vehicle passing through various phases and intersections has clearly increased. Out of the five considered intersections and the four phases only 3 cases out of 20 showed a drop in the number of vehicles crossing the various intersections.

Moreover, the green time is assigned by decreasing it from 8 phases and increasing it in 12 phases to achieve the objective of increasing the traffic flow.

(2) Percentages of the differences in sum of the vehicles passing through the four phases of various intersections during 6:45 to 7:00 four phases between the developed system and existing one are presented in Figure 106. These percentages were calculated based on the results presented in Figure 66. It is very clear that all, but one, intersections showed increases in traffic volume crossing the various intersections. That means, the developed control system performed better than the existing one in term of the total number of vehicles passing through the intersections within the network.

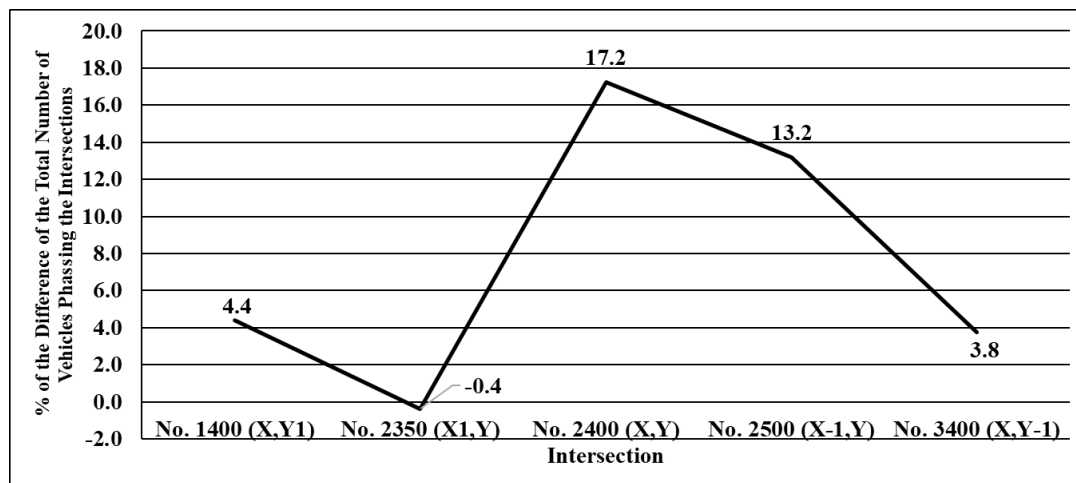


Figure (106)

The Sum of Percentage Differences Between the Developed System and the Existing Condition in Terms of Frequency of Vehicle Dissipation Through All the Phases Between 6:45 and 7:00

Number of vehicles passing the intersection No. 1400 (X, Y1) increased by 4.4%, and decreased by 0.4% at intersection No. 2350 (X1, Y). Furthermore, it increased by 17.2% at intersection No. 2400 (X, Y), by 13.2% at intersection No. 2500 (X-1, Y) and by 3.8% at intersection No.

3400 (X, Y-1). That means, the vehicle flow of 4 out of 5 intersections are improved by the developed control system. While the decrease in the 5th intersection (No. 2350 (X1, Y) is almost neglected percentage.

(3) Percentages of the differences between the developed and the existing systems in terms of the frequencies of utilization cycles during 15 minutes' period between 6:45 and 7:00 are presented in Figure 107. These percentages were calculated based on the results presented in Figures 67. Number of cycles at intersection No. 1400 (X, Y1) increased by 35.1%, and by 6.4% for the other intersections. Although number of cycles in four phases remained constant, the vehicles flow improved by the developed control system. That indicates, the green times at the cycles specified by the existing system are not distributed as needed for each phase within the intersection. While the number of cycles at intersection No. 1400 (X, Y1) increased by the developed control system and that led to shorten the waiting time and probably delays.

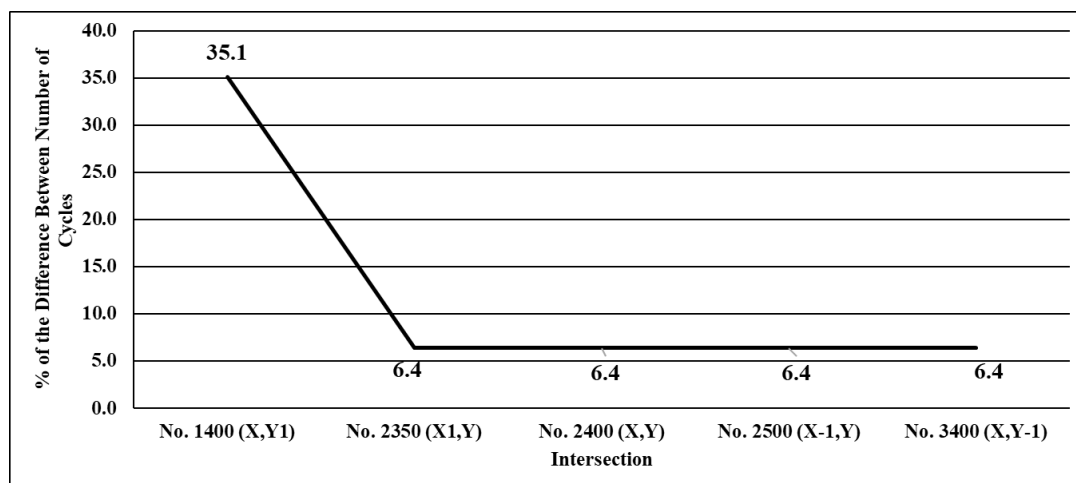


Figure (107)

The Percentage Differences Between the Developed System and the Existing One in Terms of Frequencies of Utilization Cycles During 15 Minutes' Period Between 6:45 and 7:00

6.3.2. Performance measures of period 14:15 – 14:30

(1) Percentages of the differences between number. of vehicles dissipating the various intersections' phases are presented in Figure 108, while the corresponding percentages of the differences between the necessary green times to allow vehicles to pass intersections for all four phases are presented in Figure 109. These percentages were calculated based on the results presented in Figures 68 – 77.

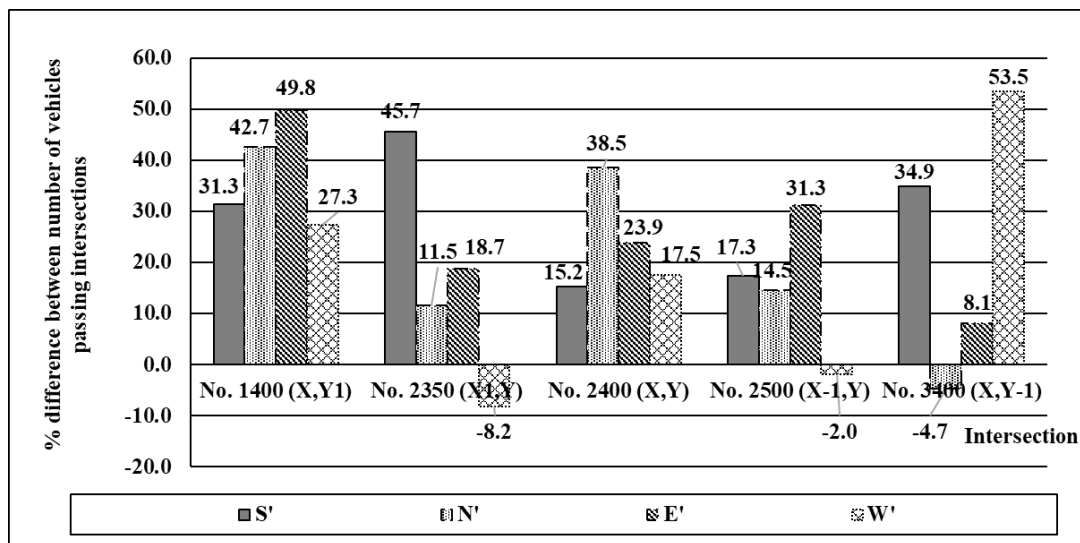


Figure (108)

Percentage Difference Between the Developed system and Existing One in Term of Number of Vehicles Crossing the Various Intersections Between 14:15 and 14:30

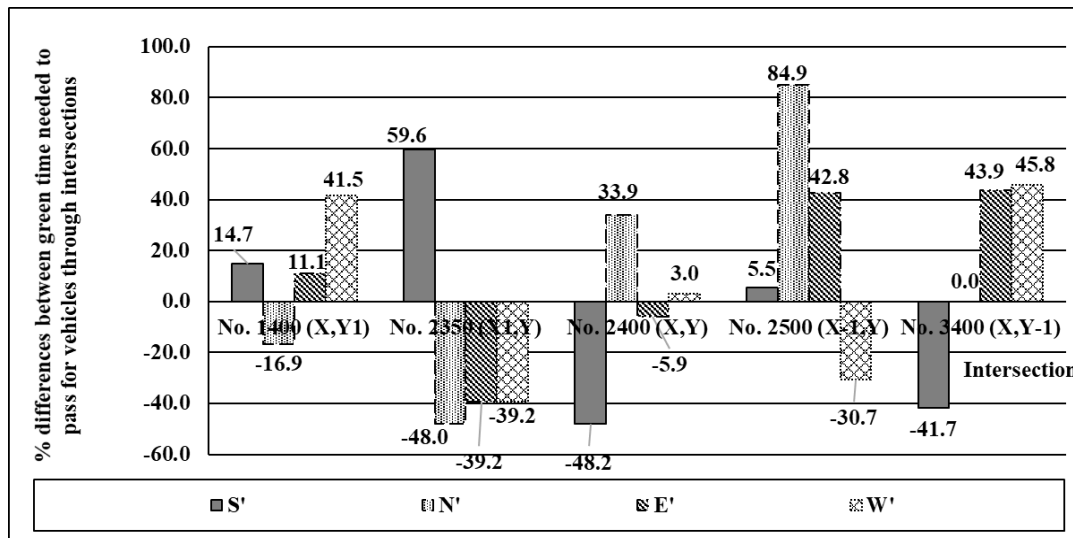


Figure (109)

Percentage Difference Between the Developed system and Existing One in Term of Necessary Green Time to Allow Vehicles to Cross the Intersections Phases Between 14:15 and 14:30

From the earlier two Figures, number of vehicles crossing intersection No. 1400 (X, Y1) showed an increase of 31.3%, 42.7%, 49.8% and 27.3% for the S', N', E', and W' phases, respectively. The utilization of the green times for the vehicles to pass N' phase decreased by 16.9% and increased by 14.7%, 11.1%, and 41.5% when passing through S', E' and W' phases, respectively. The developed control system partially used the green time loss at N' phase to increase the number of vehicles passing through. That led to improve the traffic flow at 4 phases of the intersection. In addition, the developed control system improves 1 phase by decreasing the green time.

Number of vehicles crossing intersection No. 2350 (X1, Y) showed an increase of 45.7%, 11.5%, and 18.7% for the S', N' and E' phases, and decrease by 8.2% for the E' phase. The utilization of the green times for the vehicles to pass S', E' and W' phases decreased by 48%, 39.2%, and 39.2%, respectively, and increased by 59.6% when passing through N' phase. The developed control system partially used the green time loss to

increase the number of vehicles and canceled the remaining green time at N' and E' phases. The green time loss at the W' phase decreased by the developed control system based on the traffic situation. Decreasing the green time at 3 phases allows the developed control system to increase the green time at the S' phase as needed to increase the number of vehicles passing through the S' phase. The results showed that, the developed control system improved 3 phases, while it has a negative impact on the 4th phase. Moreover, the developed control system improved 3 phases by decreasing the green time.

Number of vehicles crossing intersection No. 2400 (X, Y) showed an increase of 15.2%, 38.5%, 23.9%, and 17.5% for the S', N', E' and W' phases, respectively. The utilization of the green times for the vehicles to pass S' and E' phases decreased by 48.2% and 5.9%, respectively, and increased by 33.9% and 3% when passing through N' and W' phases, respectively. That means, there is a large amount of green time loss at S' and E' phases resulted by the existing control system, while the developed control system used part of the time to improve the traffic flow and cancelled the remaining. The number of vehicles passing through N' and W' phases improved by the developed control system through increasing the green time. The results showed that the developed control system improved the traffic situation in terms of the traffic flow in 4 phases, and specifically decreasing the green time in 2 phases.

Number of vehicles crossing intersection No. 2500 (X-1, Y) showed an increase of 17.3%, 14.5%, 31.3% for the S', N' and E' phases, and decrease by 2% for the W' phase. The utilization of the green times for the vehicles to pass W' phase decreased by 30.7% and increased by 5.5%, 84.9% and 42.8% when passing through S', N' and E' phases. That indicates, the developed control system decreased the green time at W' which led to decrease the number of vehicles passing through the phase.

At the same time, the green time of 3 other phases increased by the developed control system in order to increase the number of vehicles passing through the phases. That means, the green time is distributed by the developed control system based on the traffic situation that led to improve the traffic flow of 3 phases where it has a negative impact on the fourth phase. In addition, the developed control system improved 1 phase by decreasing the green time.

Number of vehicles crossing intersection No. 3400 (X-1, Y) showed an increase of 34.9%, 8.1%, and 53.5% for the S', E' and W' phases, and decrease by 4.7% for the N' phase. The utilization of the green times for the vehicles to pass S' phase decreased by 41.7% and increased by 43.9% and 45.8% when passing through E' and W' phases. It remained constant at N'. That indicates, the developed control system partially used the green time loss at S' phase to increase the vehicle flow and cancelled the rest of the time loss. Decreasing the green time at S' phase allowed the developed control system to increase the green time at E' and W' phases. That led to increase the number of vehicles passing through. Furthermore, the N' phase time remained constant as there is no significant change in vehicle flows with changing time. The results showed that the developed control system improved 3 phases, while it had a negative impact on the fourth phase. Additionally, the developed control system improved one phase by decreasing the green time while has no effect on one phase where the time remained constant.

By summarizing the previous results, the amount of vehicle passing through various phases and intersections has clearly increased. Only 3 out of 20 cases of the five considered intersections showed a drop in the number of vehicles crossing the various intersections, whereas each intersection has 4 phases. Additionally, the utilization of the green times

for the vehicles to pass through the phases of the five intersections decreased in some phases and increased in others. Out of the 5 considered intersections and the 4 phases only 8 cases out of 20 showed drop in the green time, one case showed no changes in the green time while the other 11 cases showed increased in the green time needed to dissipate the vehicles.

(2) Percentages of the differences in sum of the vehicles passing through the four phases of various intersections during 14:15 to 14:30 between the developed system and existing one are presented in Figure 110. These percentages were calculated based on the results presented in Figure 78. It is very clear that all intersections showed increases in traffic volume crossing the various intersections.

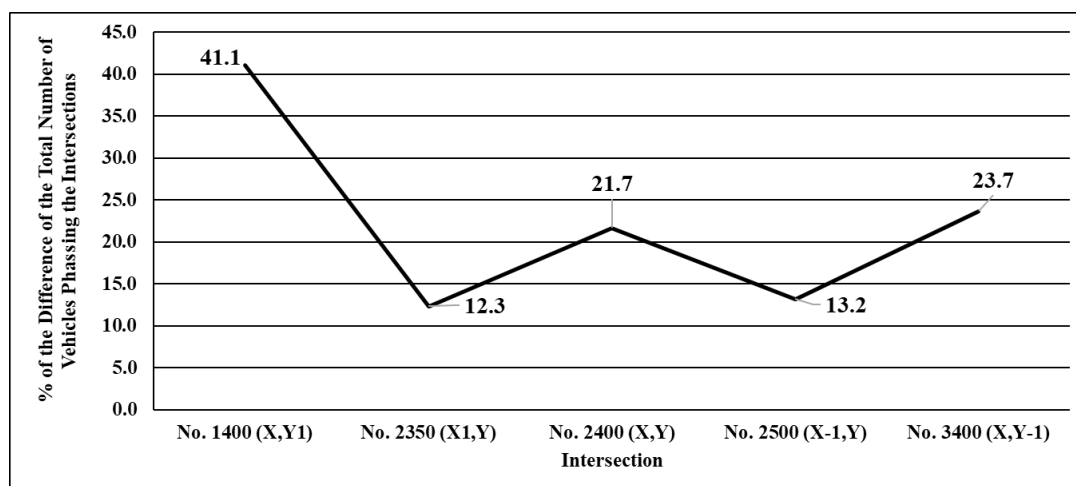


Figure (110)

The Sum of Percentage Differences Between the Developed System and the Existing Condition in Terms of Frequency of Vehicle Dissipation Through All the Phases Between 14:15 and 14:30

Number of vehicles passing the intersection No. 1400 (X, Y1) increased by 41.1%, by 12.3% at intersection No. 2350 (X1, Y), by 21.7% at intersection No. 2400 (X, Y), by 13.2% at intersection No. 2500 (X-1, Y) and by 23.7% at intersection No. 3400 (X, Y-1), respectively. That

means, the developed control system improved the total number of vehicles passing through all 5 intersections.

(3) Percentages of the differences between the developed and the existing systems in terms of the frequencies of utilization cycles during 15 minutes' period between 14:15 and 14:30 are presented in Figure 111. These percentages were calculated based on the results presented in Figures 79. Number of cycles at intersections No. 2350 (X1, Y) and No. 2500 (X-1, Y) increased by 6.4%, decreased by 5.7% and 10.7% at intersections No. 1400 (X, Y1) and No. 2400 (X, Y), and remained constant and intersection No. 3400 (X, Y-1).

The number of cycles at the considered five intersections increased by the developed control system in 2 out of 5 cases, which means shorter cycles and shorter waiting times. Regardless the cycle number decrement in 2 cases and a constant cycle number in one case out of 5 cases, the developed control system overall improved the vehicle flow. That means, there is a green time loss among these intersections resulted by the existing control system where it decreased by the developed one.

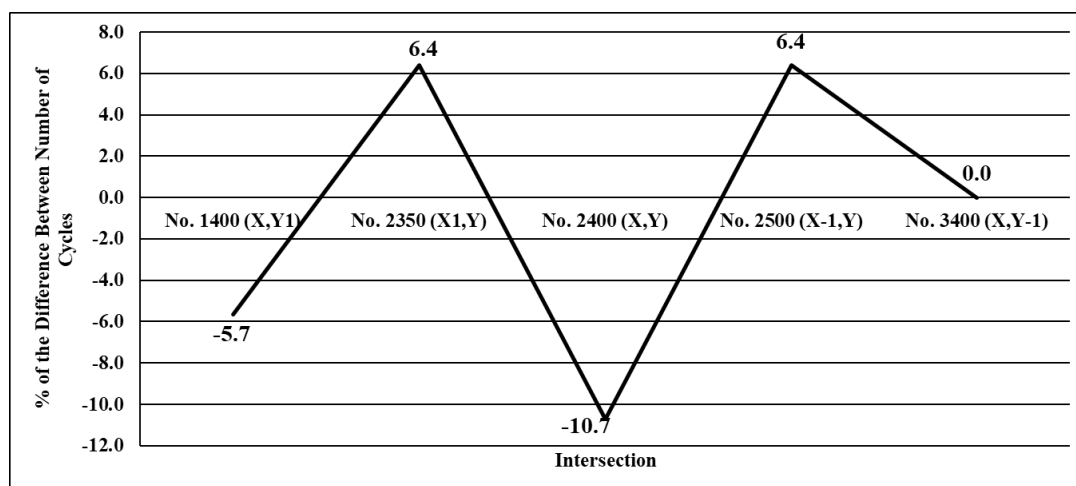


Figure (111)

The Percentage Differences Between the Developed System and the Existing One in Terms of Frequencies of Utilization Cycles During 15 Minutes' Period Between 14:15 and 14:30

6.3.3. Performance measures of period 17:15 – 17:30

(1) Percentages of the differences between number of vehicles dissipating the various intersections' phases are presented in Figure 112, while the corresponding percentages of the differences between the necessary green times to allow vehicles to pass intersections for all four phases are presented in Figure 113. These percentages were calculated based on the results presented in Figures 80 – 89.

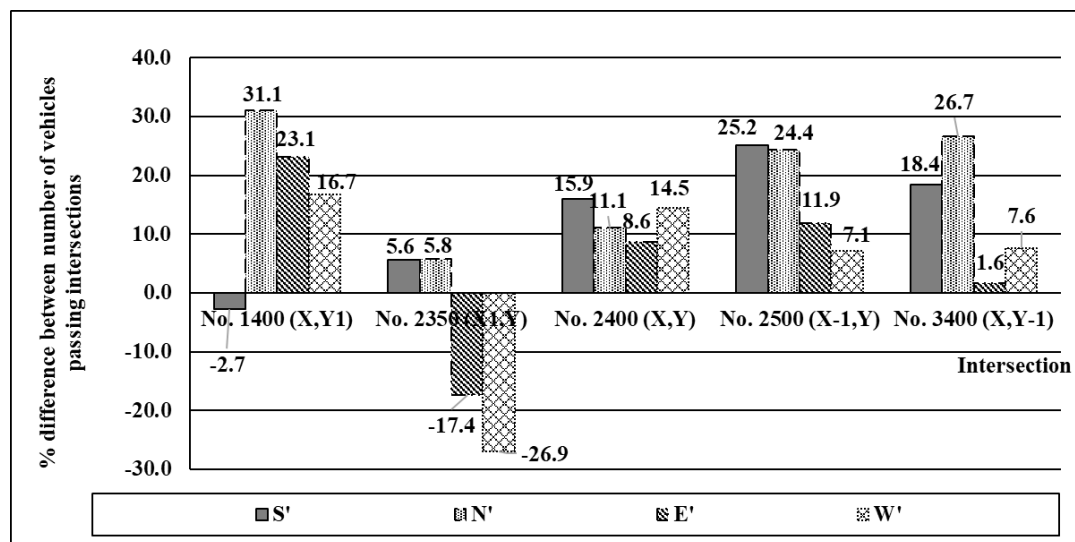


Figure (112)

Percentage Difference Between the Developed system and Existing One in Term of Number of Vehicles Crossing the Various Intersections Between 17:15 and 17:30

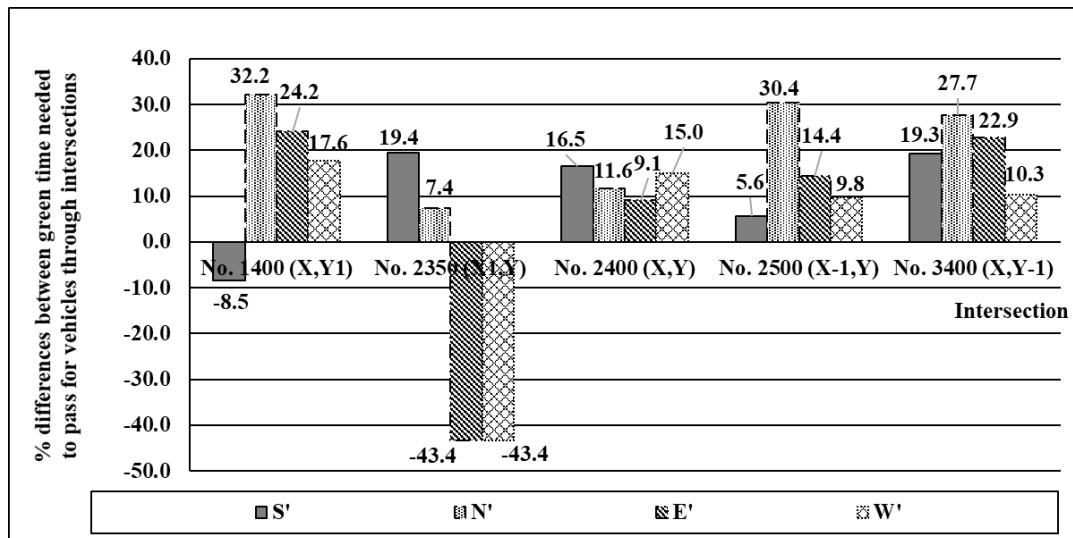


Figure (113)

Percentage Difference Between the Developed system and Existing One in Term of Necessary Green Time to Allow Vehicles to Cross the Intersections Phases Between 17:15 and 17:30

From the earlier two Figures, number of vehicles crossing intersection No. 1400 (X, Y1) showed an increase of 31.1%, 23.1%, and 16.7% for the N', E', and W' phases, respectively, and a decrease of 2.7% for the S' phase. The utilization of the green times for the vehicles to pass S' phase decreased by 8.5% and increased by 32.2%, 24.2%, and 17.6% when passing through N', E' and W' phases, respectively. The developed control system decreased the green time loss at S' phase. At the same time, it increased the green time at other phases based on the traffic situation. To increase the number of vehicles passing through N', E', and W' phases, the system increased the green time of these phases.

The results showed an improvement in vehicle flow at 3 out of 4 phases and an improvement in green time at one out of 4 phases in the intersection.

Number of vehicles crossing intersection No. 2350 (X1, Y) showed an increase of 5.6% and 5.8% for the S' and N' phases, respectively, and a decrease of 17.4% and 26.9% for the E' and W' phases. The utilization of

the green times for the vehicles to pass E' and W' phases decreased by 43.4% and increased by 19.4% and 7.4% when passing through S' and N' phases, respectively. The developed control system decreased the green time loss at E' and W' phases which led to decrease the number of vehicles passing through these phases. At the same time, number of vehicles passing through S' and N' phases increased by increasing the green time through the developed control system. That indicates, the green times is not distributed by the existing control system based on the traffic situation. The results showed vehicle flow improvement in 2 out of 4 phases in the intersection. Furthermore, the developed control system improved 2 phases by decreasing the green time.

Number of vehicles crossing intersection No. 2400 (X, Y) showed an increase of 15.9%, 11.1%, 8.6%, and 14.5% for the S', N', E' and W' phases, respectively. The utilization of the green times for the vehicles to pass S', N', E' and W' phases increased by 16.5%, 11.6%, 9.1% and 15%, respectively. Number of vehicles crossing intersection No. 2500 (X-1, Y) showed an increase of 25.2%, 24.4%, 11.9% and 7.1% for the S', N', E' and W' phases, respectively. The utilization of the green times for the vehicles to pass S', N', E' and W' phases increased by 5.6%, 30.4%, 14.4% and 9.8%, respectively. Number of vehicles crossing intersection No. 3400 (X-1, Y) showed an increase of 18.4%, 26.7%, 1.6%, and 7.6% for the S', E', N' and W' phases, respectively. The utilization of the green times for the vehicles to pass S', N', E' and W' phases increased by 19.3%, 27.7%, 22.9%, and 10.3%, respectively. The last three intersections results showed increment in green time and number of vehicles passing through intersections' phases. That means, the developed control system improved the vehicle flow at these intersections' phases.

The overall results showed that, the amount of vehicle passing through various phases and intersections has clearly increased. For example, 3 out of 20 cases of the five considered intersections showed a drop in the number of vehicles crossing the various intersections.

In addition, the utilization of the green times for the vehicles to pass through the phases of the five intersections decreased in some phases and increased in others. For example, 3 out of 20 cases of the five considered intersections showed drop in the green time while the other 17 cases showed increased in the green time needed to dissipate the vehicles.

(2) Percentages of the differences in sum of the vehicles passing through the four phases of various intersections during 17:15 to 17:30 between the developed system and existing one are presented in Figure 114. These percentages were calculated based on the results presented in Figure 90. It is very clear that all, but one, intersections showed increases in traffic volume crossing the various intersections. That means, the developed control system performed better than the existing one in terms of total number of vehicles passing through the network intersections.

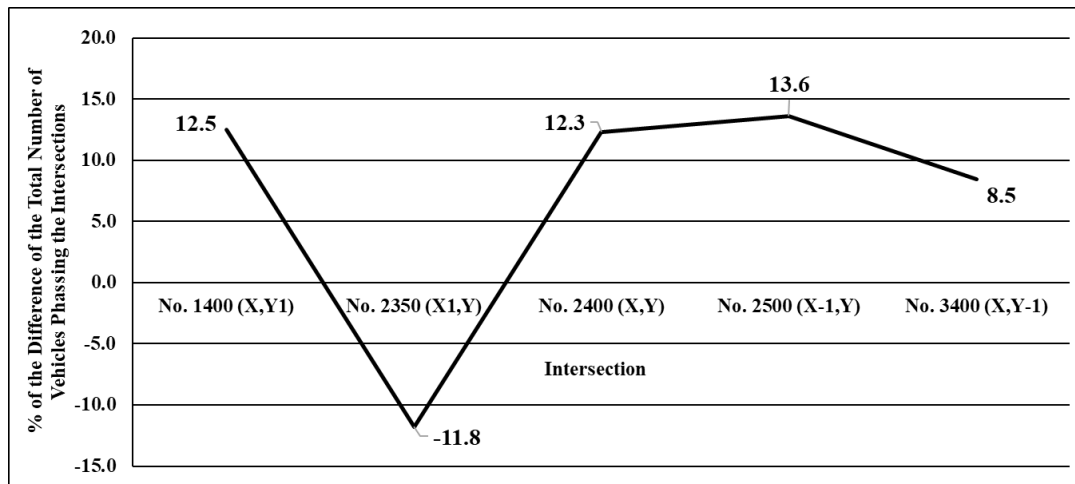


Figure (114)

The Sum of Percentage Differences Between the Developed System and the Existing Condition in Terms of Frequency of Vehicle Dissipation Through All the Phases Between 17:15 and 17:30

Number of vehicles passing the intersection No. 1400 (X, Y1) increased by 12.5%, by 12.3% at intersection No. 2400 (X, Y), by 13.6% at intersection No. 2500 (X-1, Y), and by 8.5% at intersection No. 3400 (X, Y-1). It decreased by 11.8% at intersection No. 2350 (X1, Y). The results showed that the developed control system improved the total number of vehicles passing through 4 out of 5 intersections. The number of vehicles passing through the intersection No. 2350 (X1, Y) decreased, which means the existing control system performed better than the developed one.

(3) Percentages of the differences between the developed and the existing systems in terms of the frequencies of utilization cycles during 15 minutes' period between 17:15 and 17:30 are presented in Figure 115. These percentages were calculated based on the results presented in Figures 91. Number of cycles at intersections No. 2350 (X1, Y) and No. 3400 (X, Y-1) increased by 6.4%, decreased by 2% and 10.7% at intersections No. 1400 (X, Y1) and No. 2400 (X, Y), respectively.

Remained constant at intersection No. 2500 (X-1, Y). The results showed that, the developed control system improved the number of cycles of 2 intersections which probably led to shorten cycles and shorten waiting times. The number of cycles dropped in other 2 intersections and remained constant in the last one, but at the same time the number of vehicles passing through the intersections improved, which means that the cycle time specified by the existing control system is not based on the traffic situation while the developed control system used the maximum allowable time based on the intersections properties to improve the vehicle flow.

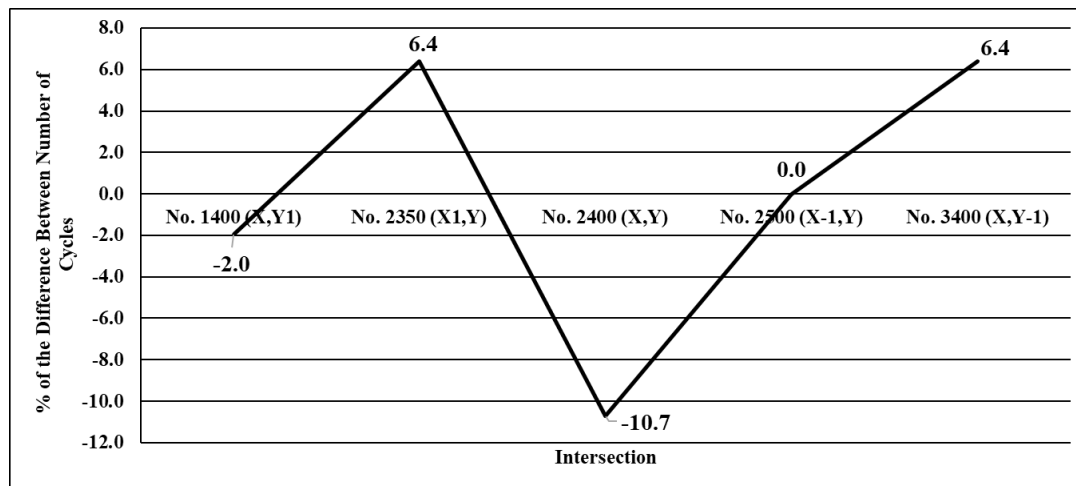


Figure (115)

The Percentage Differences Between the Developed System and the Existing One in Terms of Frequencies of Utilization Cycles During 15 Minutes' Period Between 17:15 and 17:30

6.3.4. Performance measures of period 21:30 – 21:45

(1) Percentages of the differences between number of vehicles dissipating the various intersections' phases are presented in Figure 116, while the corresponding percentages of the differences between the necessary green times to allow vehicles to pass intersections for all four

phases are presented in Figure 117. These percentages were calculated based on the results presented in Figures 92 – 101.

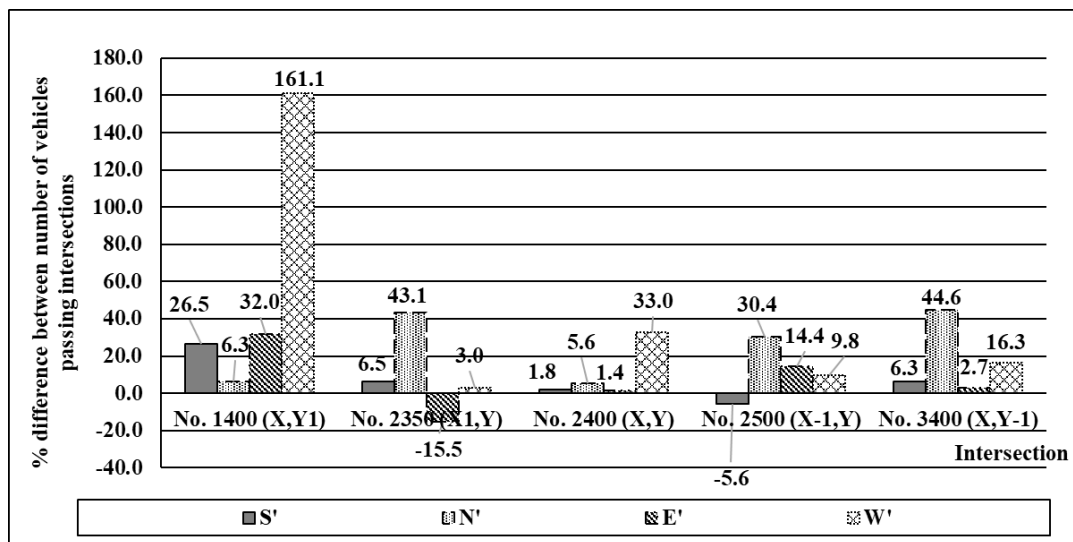


Figure (116)

Percentage Difference Between the Developed system and Existing One in Term of Number of Vehicles Crossing the Various Intersections Between 21:30 and 21:45

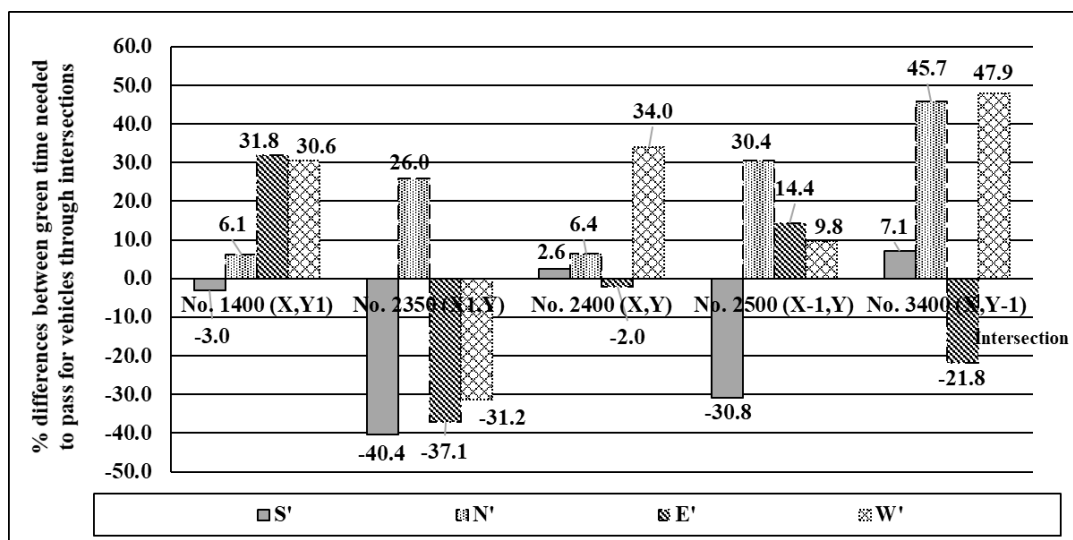


Figure (117)

Percentage Difference Between the Developed system and Existing One in Term of Necessary Green Time to Allow Vehicles to Cross the Intersections Phases Between 21:30 and 21:45

From the earlier two Figures, number of vehicles crossing intersection No. 1400 (X, Y1) showed an increase of 26.5%, 6.3%, 32.0% and 161.1% for the S', N', E', and W' phases, respectively. The utilization of the green times for the vehicles to pass S' phase decreased by 3% and increased by 6.1%, 31.8% and 30.6% when passing through N', E' and W' phases, respectively. The developed control system partially used the green time loss to increase the number of vehicles passing through S' phase. At the same time, the developed control system increased the number of vehicles passing through N', E' and W' phases by increasing the green time. That means, the developed control system improved the vehicle flow at all intersection' phases. In addition, it improved one phase by decreasing the green time.

Number of vehicles crossing intersection No. 2350 (X1, Y) showed an increase of 6.5%, 43.1%, and 3.0% for the S', N' and W' phases, respectively, and a decrease of 15.5% for the E' phase. The utilization of the green times for the vehicles to pass S', E' and W' phases decreased by 40.4%, 37.1%, and 31.2%, respectively, and increased by 26.0% when passing through N' phase. It seems that, there is a green time loss at S', E', and W' phases where the developed control system partially used the green time loss to increase the number of vehicles at S' and W' phases. The results showed that, the developed control system improved the vehicle flow at 3 out of 4 phases. Moreover, the developed control system improved 3 phases by decreasing the green time.

Number of vehicles crossing intersection No. 2400 (X, Y) showed an increase of 1.8%, 5.6%, 1.4% and 33.0% for the S', N', E', and W' phases, respectively. The utilization of the green times for the vehicles to pass E' phase decreased by 2% and increased by 2.6%, 6.4%, and 34.0% when passing through S', N', and W' phases, respectively. The developed control

system improved the vehicle flow at all intersection' phases. Additionally, it improved one phase by decreasing the green time.

Number of vehicles crossing intersection No. 2500 (X-1, Y), showed an increase of 30.4%, 14.4%, and 9.8% for the N', E' and W' phases, respectively, and a decrease by 5.6% for the S' phase. The utilization of the green times for the vehicles to pass S' phase decreased by 30.8% and increased by 30.4%, 14.4%, and 9.8% when passing through N', E' and W' phases, respectively. The results showed that, the developed control system improved the intersection' phases by increasing the green time at 3 phases. In addition, it improved one phase only by decreasing the green time.

Number of vehicles crossing intersection No. 3400 (X-1, Y), showed an increase of 6.3%, 44.6%, 2.7%, and 16.3% for the S', E', N' and W' phases, respectively. The utilization of the green times for the vehicles to pass E' phase decreased by 21.8% and increased by 7.1%, 45.7%, and 47.9% when passing through S', N' and W' phases, respectively. The developed control system decreased the green time at E' phase and at the same time increased it at S', N, and W' phases to increase the number of vehicles passing through. The results showed that, the developed control system improved the vehicles flow at 4 phases. In addition, it improved one phase by decreasing the green time.

(2) Percentages of the differences in sum of the vehicles passing through the four phases of various intersections during 21:30 to 21:45 between the developed system and existing one are presented in Figure 118. These percentages were calculated based on the results presented in Figure 102. It is very clear that all intersections showed increases in traffic volume crossing the various intersections. That means, the performance of the developed control system is better than the existing one in terms of the total number of vehicles passing through the intersections.

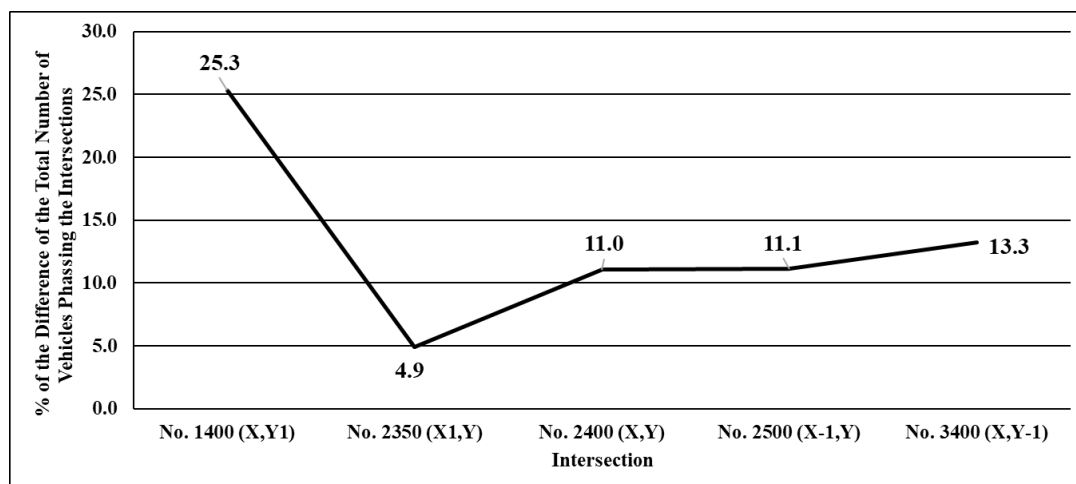


Figure (118)

The Sum of Percentage Differences Between the Developed System and the Existing Condition in Terms of Frequency of Vehicle Dissipation Through All the Phases Between 21:30 and 21:45

Number of vehicles passing the intersection No. 1400 (X, Y1) increased by 25.3%, by 4.9% at intersection No. 2350 (X1, Y), by 11%, 11.1%, and 13.3% at intersections No. 2400 (X, Y), 2500 (X-1, Y) and No. 3400 (X, Y-1), respectively. The results showed that, the developed control system improved the vehicles flow at all 5 intersections in the network.

(3) Percentages of the differences between the developed and the existing systems in terms of the frequencies of utilization cycles during 15 minutes' period between 21:30 and 21:45 are presented in Figure 119. These percentages were calculated based on the results presented in Figures 103. Number of cycles at intersections No. 2350 (X1, Y), No. 2400 (X, Y) and No. 3400 (X, Y-1) increased by 6.4%, decreased by 5.7% at intersection No. 1400 (X, Y1). Remained constant at intersection No. 2500 (X-1, Y). The results showed that, the developed control system improved the number of cycles at 3 intersections, which means shorter cycles and probably shorter waiting times. In addition, the existing system performed better than the developed system at one intersection (No. 1400 (X, Y1)).

But the developed control system has no effect on the last intersection (No. 2500 (X-1, Y)).

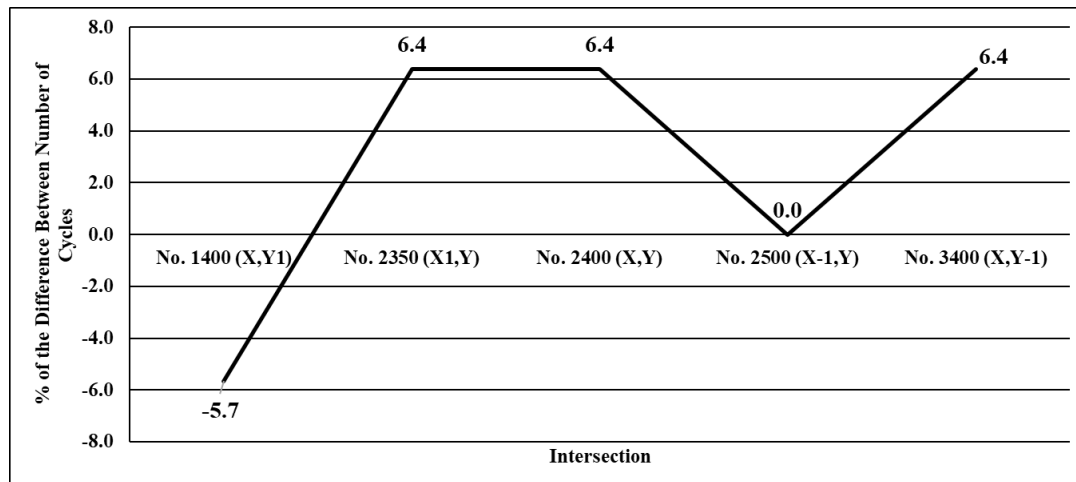


Figure (119)

The Percentage Differences Between the Developed System and the Existing One in Terms of Frequencies of Utilization Cycles During 15 Minutes' Period Between 21:30 and 21:45

6.3.5. Summary of the Analysis

Three cases appeared by summarizing the results. First case showed that the amount of traffic passing through some of the phases has increased and the time required for the vehicles to pass through these phases has decreased when comparing the developed system with the existing condition. This case appeared during the period 6:45 to 7:00 at the E' and W' phases for intersection No. 1400 (X, Y1), the S' and W' phases for intersection No. 2350 (X1, Y) and the S' and E' phases for intersection No. 2400 (X, Y). During the period 14:15 – 14:30, the first case appeared at the N' phase for intersection No. 1400 (X, Y1), the N' and E' phases for intersection No. 2350 (X1, Y), the S' and E' phases for intersection No. 2400 (X, Y) and the S' phase for intersection No. 3400 (X, Y-1) while during the period 21:30 – 21:45, the first case appeared at the S' phase for intersection No. 1400 (X, Y1), the S' and W' phases for intersection No.

2350 (X1, Y), the E' for intersections No. 2400 (X, Y) and No. 3400 (X, Y-1). In other words, these phases utilized unnecessary green times by the existing control system. The developed system adjusted such wasted green times based on the traffic flow.

The second case showed that the amount of traffic passing through the various phases and the time required for the vehicles to pass through these phases have increased with the developed system compared with the current situation. The second case appeared during the period 6:45 to 7:00 at the S' and N' phases for intersection No. 1400 (X, Y1), the N' phase for intersection No. 2350 (X1, Y), the N' and W' for intersections No. 2400 (X, Y) and No. 3400 (X, Y-1) and all phases for intersection No. 2500 (X-1, Y). During the period 14:15 – 14:30, this case appeared at the S', E' and W' phases for intersection No. 1400 (X, Y1), the S' for intersection No. 2350 (X1, Y), the N' and W' phases for intersection No. 2400 (X, Y), the S', N' and E' phases for intersection No. 2500 (X-1, Y), and the E' and W' phases for intersection No. 3400 (X, Y-1). During the period 17:15 – 17:30, the second case appeared at the N', E', and W' phases for intersection No. 1400 (X, Y1), the S' and N' phases for intersection No. 2350 (X1, Y), the S', N', E' and W' phases for intersections No. 2400 (X, Y), No. 2500 (X-1, Y) and No. 3400 (X, Y-1). During the period 21:30 – 21:45, the second case appeared at the N', E', and W' phases for intersections No. 1400 (X, Y1) and No. 2500 (X-1, Y), the N' phase for intersection No. 2350 (X1, Y), the S', N', and W' phases for intersection No. 2400 (X, Y), and the S', N', and W' phases for intersection No. 3400 (X, Y-1). This case means that the phases need less green time than what was given by the existing control system and the developed system used this green time based on the traffic situation of these phases and used this time to increase the number of vehicles passing through these phases to shorten the vehicle queues and shorten the waiting times.

The last case showed that the amount of traffic passing the remaining phases' rather than phases mentioned previously at all periods has decreased along with the green time needed to dissipate the vehicles from the intersections. This indicates that the existing system consumes more green time than necessary to accommodate such traffic.

6.4. Results and Performance of the Network

The traffic situation of each signal phase in an intersection within a network influence the traffic situation of the phase of the next intersection throughout a specific direction. For example the network of the intersections shown in Figure 48, the S' phase of the intersection No. 3400 (X, Y-1) is affecting the S' phase of the intersection No. 2400 (X, Y) which in turn is affecting the S' phase of the intersection No. 1400 (X, Y1), respectively. This is in addition to the effects of the N' and E' phases of the intersection No. 3400 on the S' phase of the intersection No. 2400, and the effects of the N' and E' phases of the intersection No. 2400 on the S' phase of the intersection No. 1400, respectively. Similarly, other phases affected the surrounding intersections phases. The results of the intersections and their effects on the surrounded intersections are presented in this section.

The performance of the developed control model in a specific direction of the network are evaluated in terms of number of vehicles passing through the various phases of the intersections in a specific direction and in terms of the utilization of phases green times. Thus, a measure of performance is obtained by calculating the percentages of the summation of the differences between number of vehicles, as obtained by the developed and existing systems, passing sequential phases in a specified direction.

Another measure of performance is obtained by calculating the percentages of the summation of the differences in the utilization of phase green times between the developed system and the existing condition.

6.4.1. Results and performance of period 6:45 – 7:00

The number of vehicles passing the S' phase of the intersection No. 3400 (X, Y-1) decreased by 14 vehicles, increased by 10 vehicles at intersection No. 2400 (X, Y), and increased by 19 vehicles at intersection No. 1400 (X, Y1) between 6:45 to 7:00 as shown in Figure 120. The first measure of performance is obtained by calculating the percentages of the total differences between number of vehicles passing the sequential S' phases in the South direction. Total differences between the number of vehicles passing through the South direction is equal to 15 vehicles (calculated as; $-14 + 10 + 19$). That means, the number of vehicles passing through the South direction is increased by 1.3% ($(15 \times 100) / 1192$). In addition, the utilization of green times of the S' phases of the intersection No. 3400 (X, Y-1) decreased by 215 sec., decreased by 38 sec. at intersection No. 2400 (X, Y), and increased by 11 sec. at intersection No. 1400 (X, Y1) as shown in Figure 121. Another measure of performance is obtained by calculating the percentages of the total differences in the utilization of the S' phase green times between the developed system and the existing condition. The total difference between the green time through the South direction is equal to -242 sec. (calculated as; $-215 - 38 + 11$). That means, the green time needed to dissipate the traffic at South direction is decreased by 20.2% ($(-242 * 100) / 1200$). The results of the increases in the number of vehicles and the decreases in the utilized green time to dissipate the traffic at South direction showed that, the developed control system improved the traffic flow and the green time at the current direction. It is obviously clear that it performed better than the existing one.

The number of vehicles passing the N' phase of the intersection No. 1400 (X, Y1) increased by 18 vehicles, increased by 19 vehicles at intersection No. 2400 (X, Y), and increased by 88 vehicles at intersection No. 3400 (X, Y-1) as shown in Figure 120. Total differences between the number of vehicles passing through the North direction is 125 vehicles (calculated as; $18 + 19 + 88$). That means, number of vehicles passing through the North direction increased by 46.3% ($((125 \times 100)/270)$). Moreover, the utilization of green times of the N' phases of the intersection No. 1400 (X, Y1) increased by 12 sec., increased by 32 sec. at intersection No. 2400 (X, Y), and increased by 54 sec. at intersection No. 3400 (X, Y-1) as shown in Figure 121. The total difference between the green time through the North direction is 98 sec. (calculated as; $12 + 32 + 54$). That means, the green time needed to dissipate the traffic at North direction is increased by 39.7% ($((98 * 100)/ 247)$). The increases of the number of vehicles passing through the North direction, and the increases of the green time needed to dissipate the traffic flow showed that, the developed control system improved the traffic flow at North direction. That means, the developed control system performed better than the existing one. But the developed control system had a negative influence on the green time of the North direction which means that the existing control system performed better than the developed one on the current case.

The number of vehicles passing the E' phase of the intersection No. 2350 (X1, Y) decreased by 31 vehicles, increased by 18 vehicles at intersection No. 2400 (X, Y), and increased by 28 vehicles at intersection No. 2500 (X-1, Y) as shown in Figure 120. Total differences between the number of vehicles passing through the East direction is equal to 15 vehicles (calculated as; $-31 + 18 + 28$). That means, number of vehicles passing through the East direction is increased by 1.4% ($((15 \times 100)/1094)$). Additionally, the utilization of green times of the E' phases of the

intersection No. 2350 (X1, Y) decreased by 273 sec., decreased by 11 sec. at intersection No. 2400 (X, Y), and increased by 16 sec. at intersection No. 2500 (X-1, Y) as shown in Figure 121. The total difference between the green time through the East direction is equal to -268 sec. (calculated as; $-273 - 11 + 16$). That means, the green time needed to dissipate the traffic at East direction is decreased by 22% ($((-268 * 100)/ 1222)$). The results of the increasing number of vehicles and decreases the utilized green time to dissipate the traffic at East direction showed that, the developed control system improved the traffic flow and the green time at this direction. It is obviously clear that the developed control system performed better than the existing one.

The number of vehicles passing the W' phase of the intersection No. 2500 (X-1, Y) increased by 59 vehicles, increased by 134 vehicles at intersection No. 2400 (X, Y), and increased by 13 vehicles at intersection No. 2350 (X1, Y) as shown in Figure 120. Total differences between the number of vehicles passing through the East direction is 206 vehicles (calculated as; $59 + 134 + 13$). That means, the number of vehicles passing through the West direction increased by 21.7% ($((206 \times 100)/ 949)$). Moreover, the utilization of the green times of the W' phases of the intersection No. 2500 (X-1, Y) increased by 41 sec., increased by 80 sec. at intersection No. 2400 (X, Y), and decreased by 27 sec. at intersection No. 2350 (X1, Y) as shown in Figure 121. The total difference between the green time through the West direction is 94 sec. (calculated as; $41 + 80 - 27$). That means, the green time needed to dissipate the traffic at West direction is increased by 13% ($((94 * 100)/ 729)$). The increases of the number of vehicles passing through the West direction, and the increases of the green time needed to dissipate the traffic flow showed that, the developed control system improved the traffic flow at West direction and had better performance than the existing one. At the same time, the

developed control system had a negative influence at the green time of the West direction which means that the existing control system performed better than the developed one in the current case.

From previous results, the amount of vehicle passing through four directions has clearly increased. The utilization of the green times for the vehicles to pass through network directions decreased in two directions and increased in other two directions. To summarize, the developed control system performing based on the actual traffic situation.

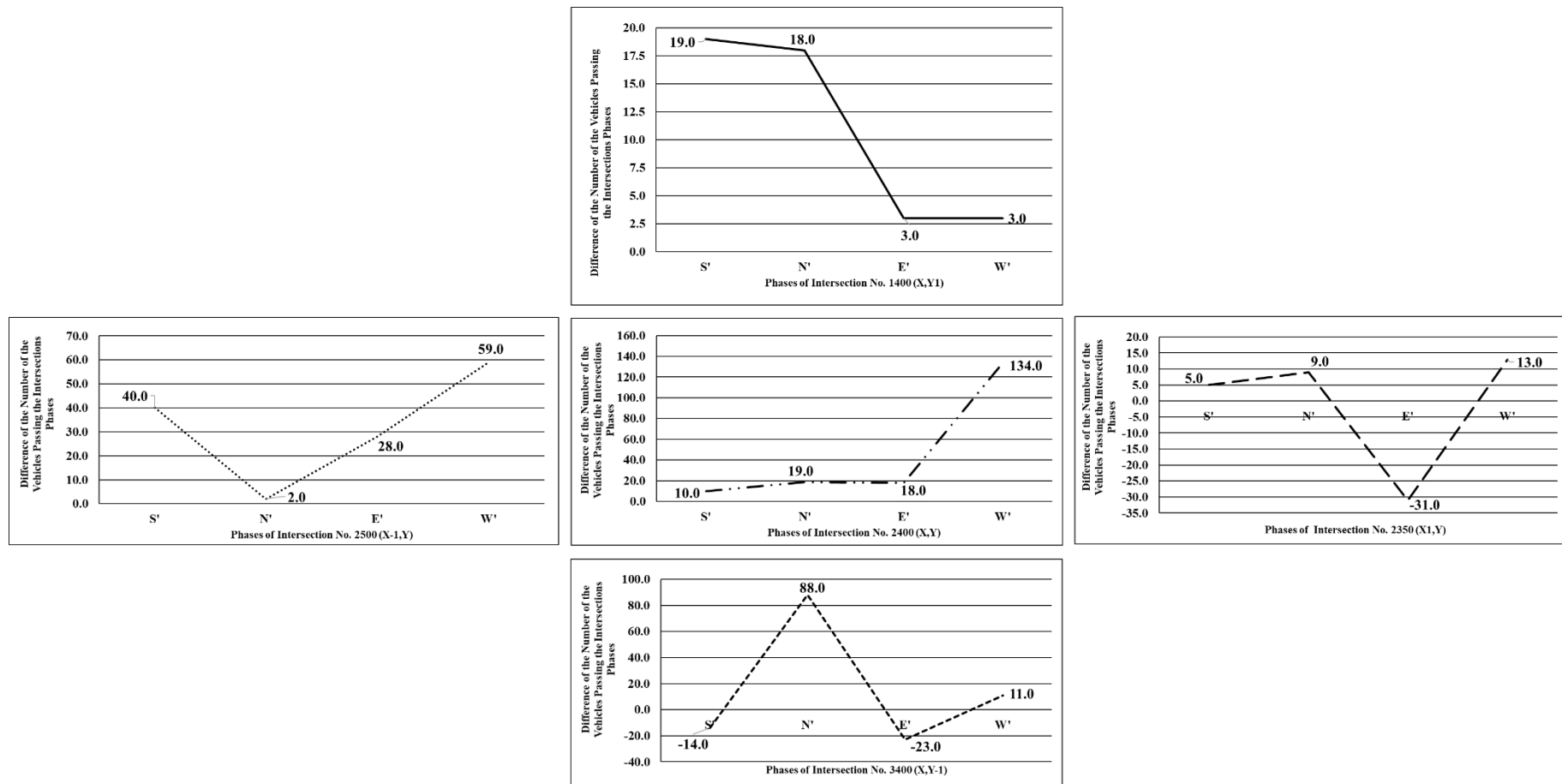


Figure (120)

Differences in the Traffic Passing the Various Signal Phases Between the Developed System and the Existing Condition for a Tested Case Between 6:45 and 7:00

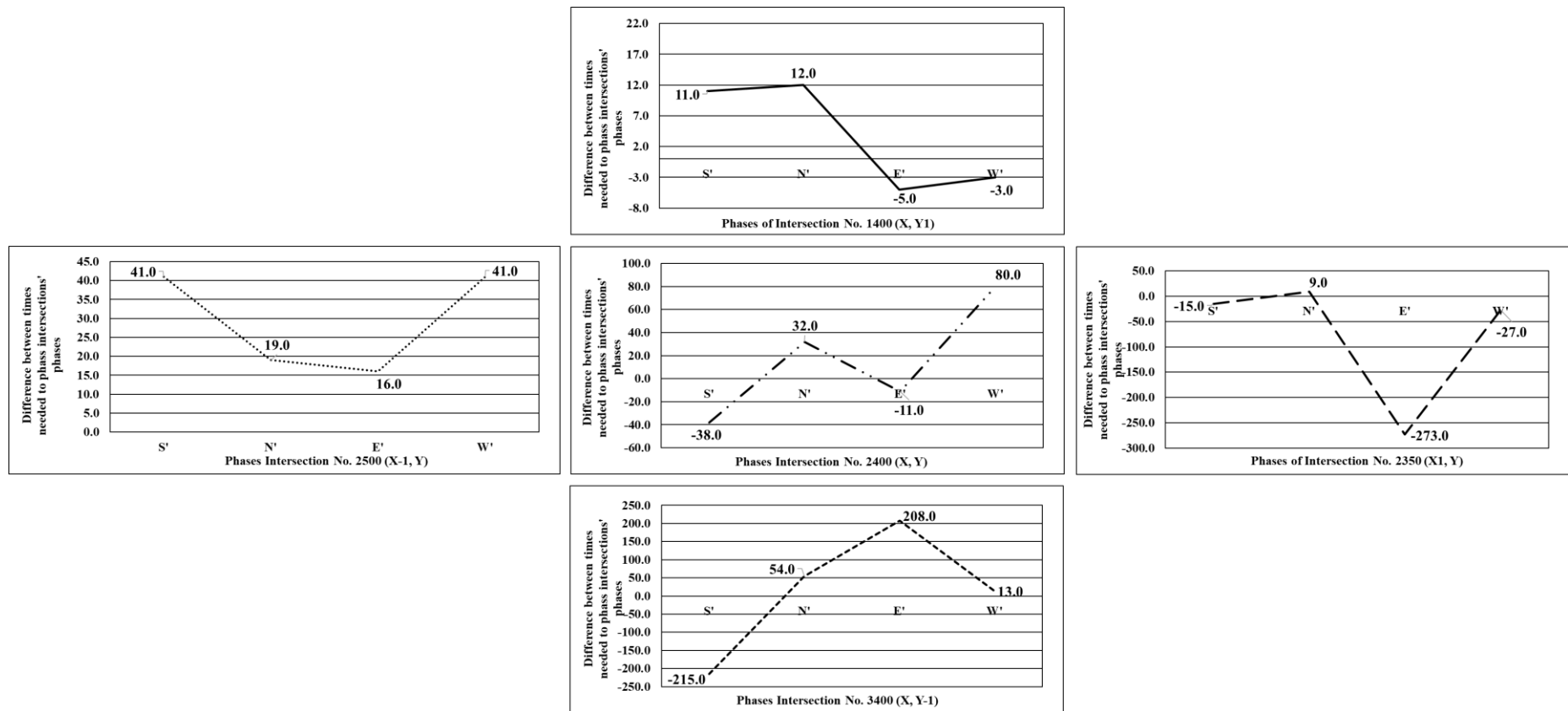


Figure (121)

Differences in the Total Green Time Utilization Between the Developed System and the Existing Condition to Dissipate the Traffic at Various Intersections Between 6:45 and 7:00

6.4.2. Results and performance of period 14:15 – 14:30

The number of vehicles passing the S' phase of the intersection No. 3400 (X, Y-1) increased by 64 vehicles, increased by 15 vehicles at intersection No. 2400 (X, Y), and increased by 74 vehicles at intersection No. 1400 (X, Y1) between 14:15 to 14:30 as shown in Figure 122. The first measure of performance was obtained by calculating the percentages of the total differences between number of vehicles passing the sequential S' phases in the South direction. Total differences between the number of vehicles passing through the South direction is 153 vehicles (calculated as; $64 + 15 + 74$). That means, number of vehicles passing through the South direction is increased by 29.5% ($((153 \times 100)/519)$). In addition, the utilization of green times of the S' phases of the intersection No. 3400 (X, Y-1) decreased by 125 sec., decreased by 84 sec. at intersection No. 2400 (X, Y), and increased by 29 sec. at intersection No. 1400 (X, Y1) as shown in Figure 123. Another measure of performance was obtained by calculating the percentages of the total differences in the utilization of the S' phase green times between the developed system and the existing condition. The total difference between the green time through the South direction is -180 sec. (calculated as; $-125 + (-84) + 29$). That means, the green time needed to dissipate the traffic at South direction is decreased by 26.8% ($((-180 * 100)/ 670)$). Previous results showed that, number of vehicles passing through the South direction is increased while the green time needed to dissipate the traffic is decreased. The developed control system improved the traffic flow and the green time at the South direction. That means, the developed control system performed better than the existing one.

The number of vehicles passing the N' phase of the intersection No. 1400 (X, Y1) increased by 221 vehicles, increased by 25 vehicles at intersection No. 2400 (X, Y), and decreased by 20 vehicles at intersection

No. 3400 (X, Y-1) as shown in Figure 122. Total differences between the number of vehicles passing through the North direction is equal to 226 vehicles (calculated as; $221 + 25 - 20$). That means, number of vehicles passing through the North direction is increased by 22.5% ($((1226 \times 100)/1004)$). Moreover, the utilization of green times of the N' phases of the intersection No. 1400 (X, Y1) decreased by 62 sec., increased by 42 sec. at intersection No. 2400 (X, Y), and remained constant at intersection No. 3400 (X, Y-1) as shown in Figure 123. Total difference between the green time through the North direction is equal to -20 sec. (calculated as; $-62 + 42 + 0$). That means, the green time needed to dissipate the traffic at North direction is decreased by 3.1% ($((-20 * 100)/ 639)$). As in South direction, the developed control system improved the number of vehicles passing through the North direction and the green time needed to dissipate the traffic by increasing the vehicle flow and decreasing the green time. That means, the developed control system performed better than the existing one.

The number of vehicles passing the E' phase of the intersection No. 2350 (X1, Y) increased by 68 vehicles, increased by 116 vehicles at intersection No. 2400 (X, Y) and at intersection No. 2500 (X-1, Y) as shown in Figure 122. Total differences between the number of vehicles passing through the East direction is 300 vehicles (calculated as; $68 + 116 + 116$). That means, the number of vehicles passing through the East direction is increased by 2.2% ($((27 \times 100)/1232)$). Additionally, the utilization of green times of the E' phases of the intersection No. 2350 (X1, Y) decreased by 194 sec., decreased by 24 sec. at intersection No. 2400 (X, Y), and increased by 90 sec. at intersection No. 2500 (X-1, Y) as shown in Figure 123. The total difference between the green time through the East direction is -128 sec. (calculated as; $-194 - 24 + 90$). That means, the green time needed to dissipate the traffic at East direction is decreased by 11.6%

$((-128 * 100) / 1104)$. The results showed that the developed control system improved the traffic through East direction by increasing the number of vehicles passing through and decreasing the green time needed to dissipate the traffic. That means, the developed control system performed better than the existing one.

The number of vehicles passing the W' phase of the intersection No. 2500 (X-1, Y) decreased by 11 vehicles, increased by 63 vehicles at intersection No. 2400 (X, Y), and decreased by 25 vehicles at intersection No. 2350 (X1, Y) as shown in Figure 122. Total differences between the number of vehicles passing through the East direction is equal to 27 vehicles (calculated as; $-11 + 63 - 25$). That means, number of vehicles passing through the West direction is increased by 2.2% $((27 \times 100) / 1232)$. In addition, the utilization of green times of the W' phases of the intersection No. 2500 (X-1, Y) decreased by 101 sec., increased by 11 sec. at intersection No. 2400 (X, Y), and decreased by 194 sec. at intersection No. 2350 (X1, Y) as shown in Figure 123. The total difference between the green time through the West direction is equal to -284 sec. (calculated as; $-101 + 11 - 194$). That means, the green time needed to dissipate the traffic at West direction is decreased by 23.8% $((-284 * 100) / 1193)$. Previous results showed that, the number of vehicles passing through the West direction is increased while the green time needed to dissipate the traffic is decreased. The developed control system improved the number of traffic and the green time at the West direction. That means, the developed control system performed better than the existing one.

From the previous results, the amount of vehicle passing through the four directions has clearly increased. In addition, the utilization of the green times for the vehicles to pass through network directions decreased in all four directions.

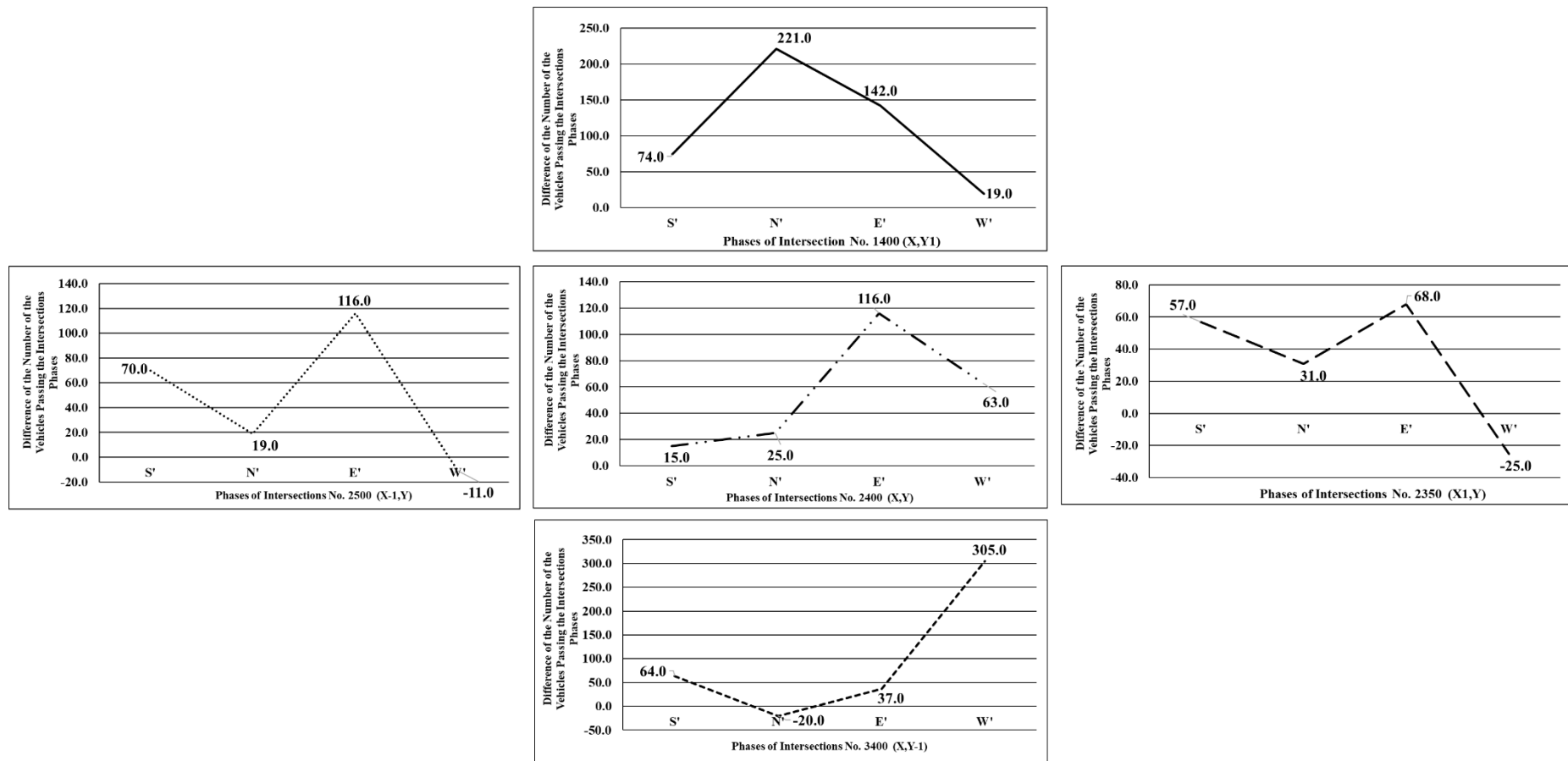


Figure (122)

Differences in the Traffic Passing the Various Signal Phases Between the Developed System and the Existing Condition for a Tested Case Between 14:15 and 14:30

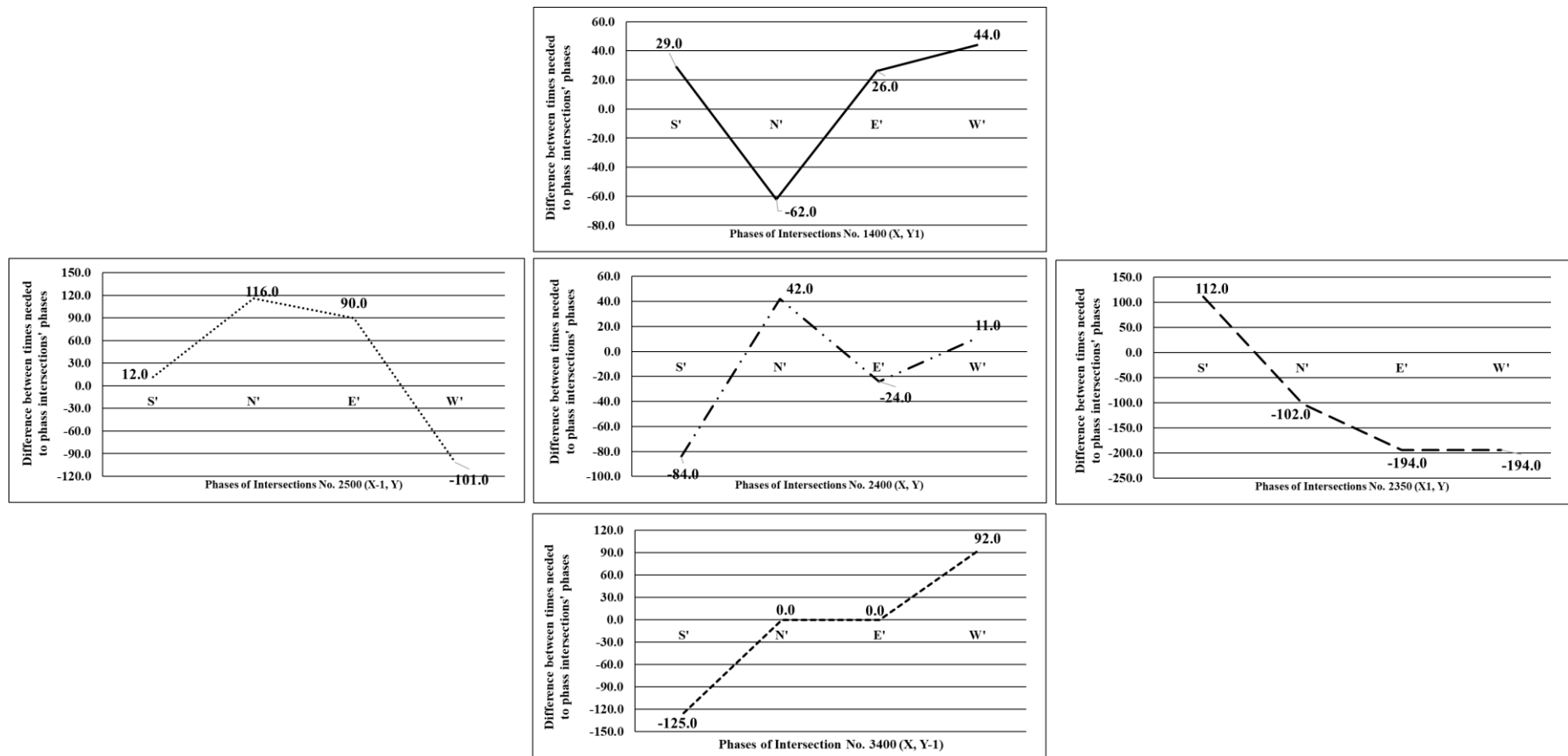


Figure (123)

Differences in the Total Green Time Utilization Between the Developed System and the Existing Condition to Dissipate the Traffic at Various Intersections Between 14:15 and 14:30

6.4.3. Results and performance of period 17:15 – 17:30

The number of vehicles passing the S' phase of the intersection No. 3400 (X, Y-1) increased by 36 vehicles, increased by 27 vehicles at intersection No. 2400 (X, Y), and decreased by 18 vehicles at intersection No. 1400 (X, Y1) between 17:15 to 17:30 as shown in Figure 124. The first measure of performance was obtained by calculating the percentages of the total differences between number of vehicles passing the sequential S' phases in the South direction. Total differences between the number of vehicles passing through the South direction is 45 vehicles (calculated as; $36 + 27 - 18$). That means, number of vehicles passing through the South direction is increased by 4.4% ($((45 \times 100)/1033)$). Moreover, the utilization of green times of the S' phases of the intersection No. 3400 (X, Y-1) increased by 48 sec., increased by 21 sec. at intersection No. 2400 (X, Y), and decreased by 29 sec. at intersection No. 1400 (X, Y1) as shown in Figure 125. Another measure of performance was obtained by calculating the percentages of the total differences in the utilization of the S' phase green times between the developed system and the existing condition. The total difference between the green time through the South direction is 40 sec. (calculated as; $48 + 21 - 29$). That means, the green time needed to dissipate the traffic at South direction is increased by 5.7% ($((40 * 100)/705)$). The results showed that, the number of vehicles passing through the South direction is increased as well as the green time needed to dissipate the traffic. That means, the developed control system improved the vehicle flow at this direction but had a negative influence on the green time needed to dissipate the traffic. As a result, the developed control system performed better than the existing system by increasing the vehicle flow whereas the existing system performed better than developed one by decreasing the green time.

The number of vehicles passing the N' phase of the intersection No. 1400 (X, Y1) increased by 109 vehicles, increased by 7 vehicles at intersection No. 2400 (X, Y), and increased by 47 vehicles at intersection No. 3400 (X, Y-1) as shown in Figure 124. Total differences between the number of vehicles passing through the North direction is equal to 163 vehicles (calculated as; $109 + 7 + 47$). That means, number of vehicles passing through the North direction is increased by 27.5% ($((163 \times 100)/592)$). In addition, the utilization of green times of the N' phases of the intersection No. 1400 (X, Y1) increased by 73 sec., increased by 16 sec. at intersection No. 2400 (X, Y), and increased by 32 sec. at intersection No. 3400 (X, Y-1) as shown in Figure 125. The total difference between the green time through the North direction is equal to 121 sec. (calculated as; $73 + 16 + 32$). That means, the green time needed to dissipate the traffic at North direction is increased by 25% ($((121 * 100)/482)$). The increases of the number of vehicles passing through the North direction, and the increases of the green time needed to dissipate the traffic flow showed that, the developed control system performed better than the existing one by increasing the traffic flow. But the developed control system had a negative influence at the green time which means that the existing control system performed better than the developed one.

The number of vehicles passing the E' phase of the intersection No. 2350 (X1, Y) decreased by 122 vehicles, increased by 34 vehicles at intersection No. 2400 (X, Y) and increased by 48 vehicles at intersection No. 2500 (X-1, Y) as shown in Figure 124. Total differences between the number of vehicles passing through the East direction is -40 vehicles (calculated as; $-122 + 34 + 48$). That means, number of vehicles passing through the East direction is decreased by 2.7% ($((-40 \times 100)/1255)$). In addition, the utilization of green times of the E' phases of the intersection No. 2350 (X1, Y) decreased by 194 sec., increased by 28 sec. at

intersection No. 2400 (X, Y), and increased by 37 sec. at intersection No. 2500 (X-1, Y) as shown in Figure 125. The total difference between the green time through the East direction is -129 sec. (calculated as; $-194 + 28 + 37$). That means, the green time needed to dissipate the traffic at East direction is decreased by 12.9% ($(-129 * 100) / 1004$). The previous results showed that the green time needed to dissipate the traffic through East direction and the number of vehicles passing through the direction are decrease. That means, the influence of the developed control system is negative on East direction and the existing control system performed better than the developed one.

The number of vehicles passing the W' phase of the intersection No. 2500 (X-1, Y) increased by 24 vehicles, increased by 62 vehicles at intersection No. 2400 (X, Y), and decreased by 130 vehicles at intersection No. 2350 (X1, Y) as shown in Figure 124. Total differences between the number of vehicles passing through the East direction is -44 vehicles (calculated as; $24 + 62 - 130$). That means, number of vehicles passing through the West direction is decreased by 3.5% ($(-44 \times 100) / 1255$). Moreover, the utilization of green times of the W' phases of the intersection No. 2500 (X-1, Y) increased by 20 sec., increased by 50 sec. at intersection No. 2400 (X, Y), and decreased by 194 sec. at intersection No. 2350 (X1, Y) as shown in Figure 125. The total difference between the green time through the West direction is -124 sec. (calculated as; $20 + 50 - 194$). That means, the green time needed to dissipate the traffic at West direction is decreased by 12.6% ($(-124 * 100) / 982$). The results showed that the green time needed to dissipate the traffic through West direction and the number of vehicles passing through the direction are decreased. That means, the influence of the developed control system is negative on West direction and the existing control system performed better than the developed one.

From previous results, the amount of vehicle passing through the four directions has increased at two directions and decreased at the other two. While, the utilization of the green times for the vehicles to pass through network directions decreased in two directions and increased in the other two.

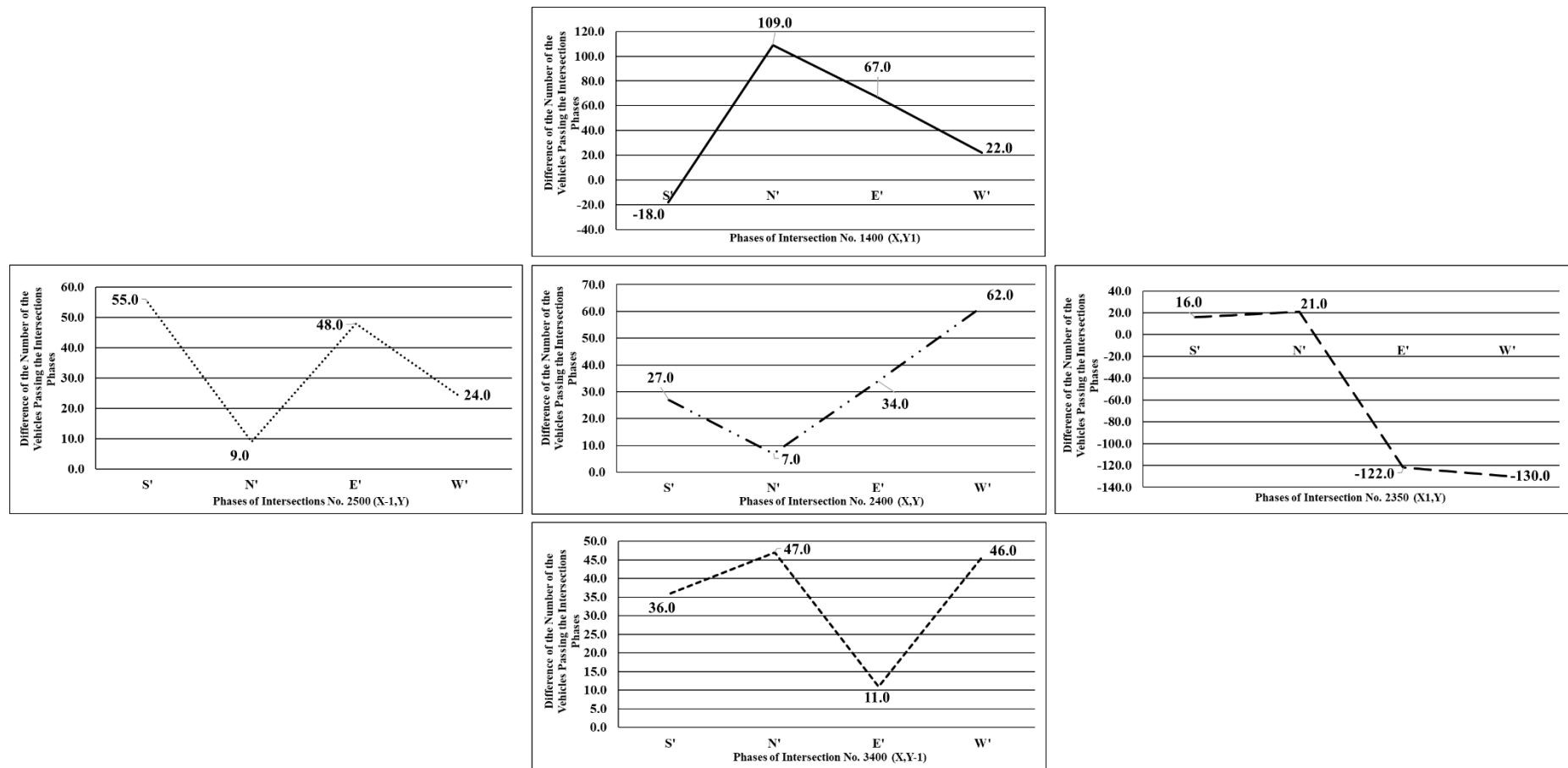


Figure (124)

Differences in the Traffic Passing the Various Signal Phases Between the Developed System and the Existing Condition for a Tested Case Between 17:15 and 17:30

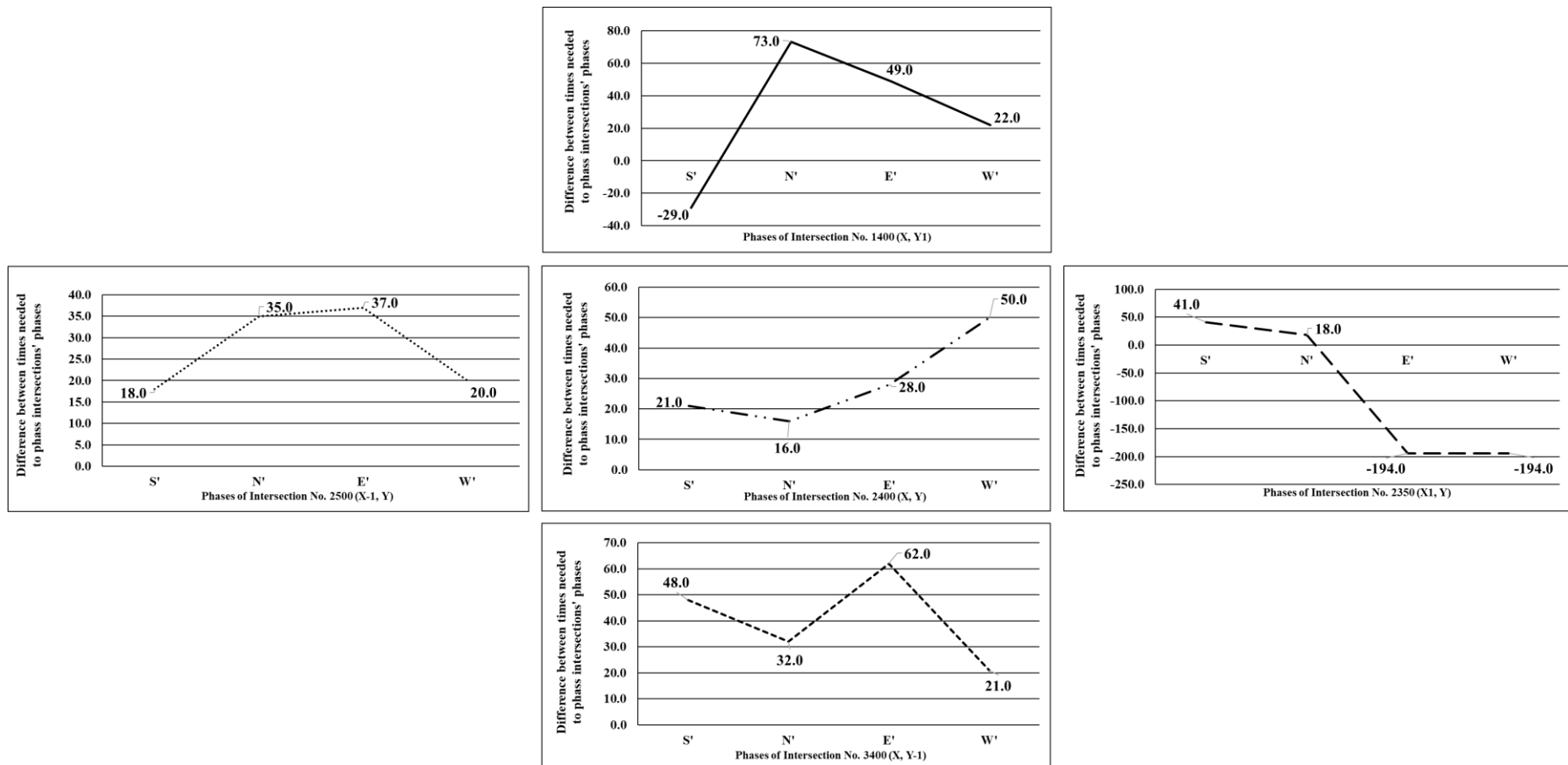


Figure (125)

Differences in the Total Green Time Utilization Between the Developed System and the Existing Condition to Dissipate the Traffic at Various Intersections Between 17:15 and 17:30

6.4.4. Results and performance of period 21:30 – 21:45

The number of vehicles passing the S' phase of the intersection No. 3400 (X, Y-1) increased by 13 vehicles, increased by 3 vehicles at intersection No. 2400 (X, Y), and increased by 63 vehicles at intersection No. 1400 (X, Y1) between 21:30 to 21:45 as shown in Figure 126. The first measure of performance was obtained by calculating the percentages of the total differences between number of vehicles passing the sequential S' phases in the South direction. Total differences between the number of vehicles passing through the South direction is 79 vehicles (calculated as; $13 + 3 + 63$). That means, number of vehicles passing through the South direction is increased by 12.5% ($((79 \times 100)/632)$). In addition, the utilization of green times of the S' phases of the intersection No. 3400 (X, Y-1) increased by 19 sec., increased by 3 sec. at intersection No. 2400 (X, Y), and decreased by 9 sec. at intersection No. 1400 (X, Y1) as shown in Figure 127. Another measure of performance was obtained by calculating the percentages of the total differences in the utilization of the S' phase green times between the developed system and the existing condition. The total difference between the green time through the South direction is 13 sec. (calculated as; $19 + 3 - 9$). That means, the green time needed to dissipate the traffic at South direction is increased by 1.8% ($((13 * 100)/ 723)$). The increases of the number of vehicles passing through the South direction, and the increases of the green time needed to dissipate the traffic flow showed that, the developed control system performed better than the existing one by increasing the traffic flow. However, the developed control system had a negative influence at the green time which means that the existing control system performed better than the developed one.

The number of vehicles passing the N' phase of the intersection No. 1400 (X, Y1) increased by 30 vehicles, increased by 4 vehicles at intersection No. 2400 (X, Y), and increased by 121 vehicles at intersection

No. 3400 (X, Y-1) as shown in Figure 126. Total differences between the number of vehicles passing through the North direction is 155 vehicles (calculated as; $30 + 4 + 121$). That means, number of vehicles passing through the North direction is increased by 19% ($((155 \times 100)/818)$). The utilization of green times of the N' phases of the intersection No. 1400 (X, Y1) increased by 16 sec., increased by 5 sec. at intersection No. 2400 (X, Y), and increased by 65 sec. at intersection No. 3400 (X, Y-1) as shown in Figure 127. The total difference between the green time through the North direction is 86 sec. (calculated as; $16 + 5 + 65$). That means, the green time needed to dissipate the traffic at North direction is increased by 18% ($((86 * 100)/ 480)$). As well as in previous direction, number of vehicles passing the North direction and the green time needed to dissipate the traffic increased by the developed control system. That shows, the developed control system improved the traffic at North direction, which means that the developed control system performed better than existing. At the same time, the developed control system had a negative influence on the green time which shows that the existing control system performed better than the developed one.

The number of vehicles passing the E' phase of the intersection No. 2350 (X1, Y) decreased by 77 vehicles, increased by 9 vehicles at intersection No. 2400 (X, Y) and increased by 50 vehicles at intersection No. 2500 (X-1, Y) as shown in Figure 126. Total differences between the number of vehicles passing through the East direction is -18 vehicles (calculated as; $-77 + 9 + 50$). That means, number of vehicles passing through the East direction is decreased by 1.2% ($((-18 \times 100)/1502)$). Moreover, the utilization of green times of the E' phases of the intersection No. 2350 (X1, Y) decreased by 166 sec., decreased by 6 sec. at intersection No. 2400 (X, Y), and increased by 37 sec. at intersection No. 2500 (X-1, Y) as shown in Figure 127. The total difference between the green time

through the East direction is -135 sec. (calculated as; $-166 - 6 + 37$). That means, the green time needed to dissipate the traffic at East direction is decreased by 13% ($(-135 * 100) / 1040$). The results showed that the green time needed to dissipate the traffic through East direction and the number of vehicles passing through the direction are decreased. That means, the influence of the developed control system is negative on the East direction and the existing control system performed better than the developed one.

The number of vehicles passing the W' phase of the intersection No. 2500 (X-1, Y) increased by 22 vehicles, increased by 127 vehicles at intersection No. 2400 (X, Y), and increased by 14 vehicles at intersection No. 2350 (X1, Y) as shown in Figure 126. Total differences between the number of vehicles passing through the East direction is 163 vehicles (calculated as; $22 + 127 + 14$). That means, number of vehicles passing through the West direction is increased by 15.2% ($(163 \times 100) / 1068$). In addition, the utilization of green times of the W' phases of the intersection No. 2500 (X-1, Y) increased by 20 sec., increased by 116 sec. at intersection No. 2400 (X, Y), and decreased by 140 sec. at intersection No. 2350 (X1, Y) as shown in Figure 127. The total difference between the green time through the West direction is -4 sec. (calculated as; $20 + 116 - 140$). That means, the green time needed to dissipate the traffic at West direction is decreased by 0.4% ($(-4 * 100) / 990$). Previous results showed that, number of vehicles passing through the West direction is increased while the green time needed to dissipate the traffic is decreased. The developed control system improved the number of traffic and the green time at the West direction by increasing the traffic flow and decreasing the green time. That means, the developed control system performed better than the existing one.

From previous results, the amount of vehicle passing through three directions has increased, however it decreased at the last direction. The

utilization of the green times for the vehicles to pass through network directions decreased in two directions and increased in the other two.

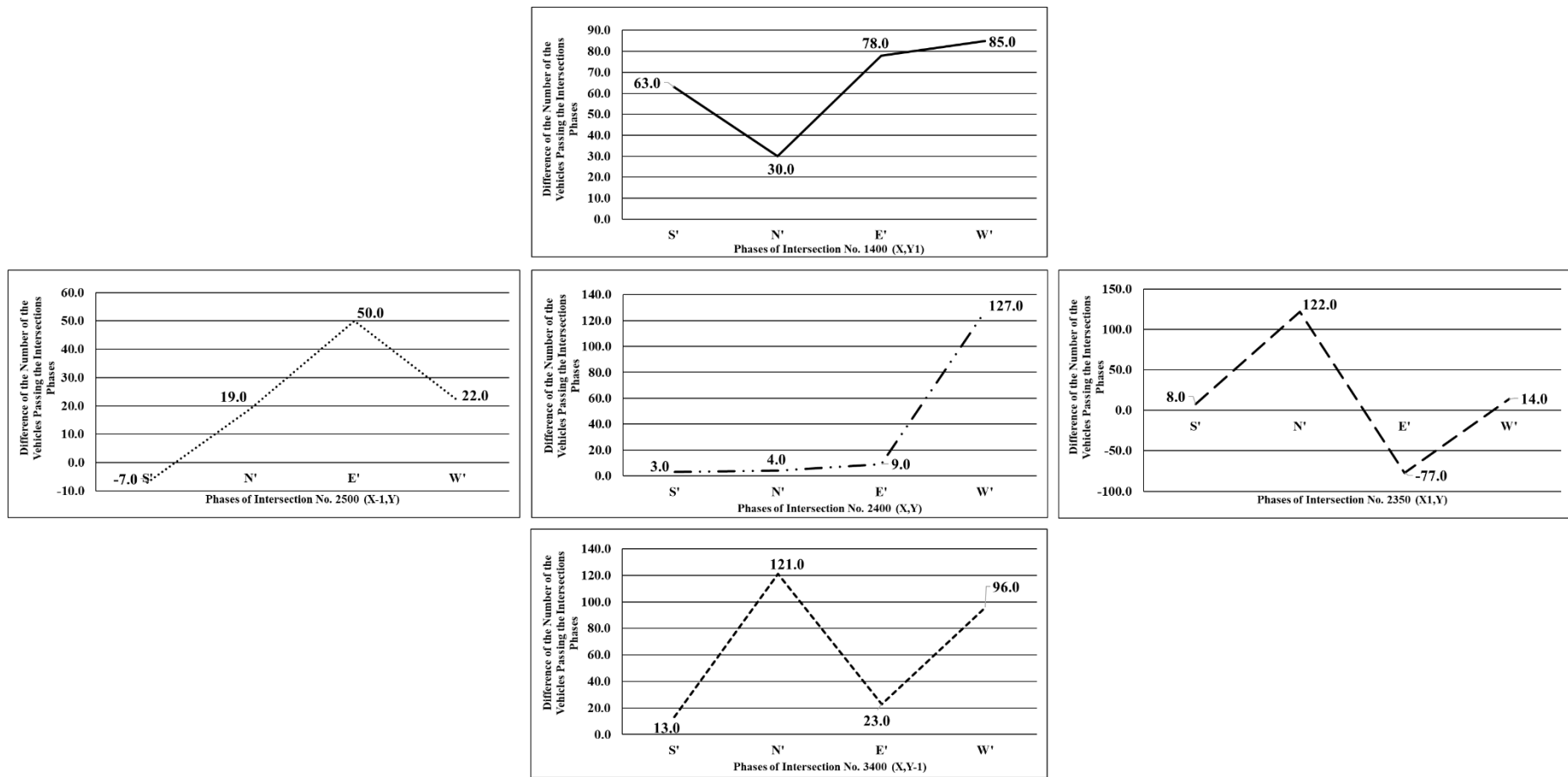


Figure (126)

Differences in the Traffic Passing the Various Signal Phases Between the Developed System and the Existing Condition for a Tested Case Between 21:30 and 21:45

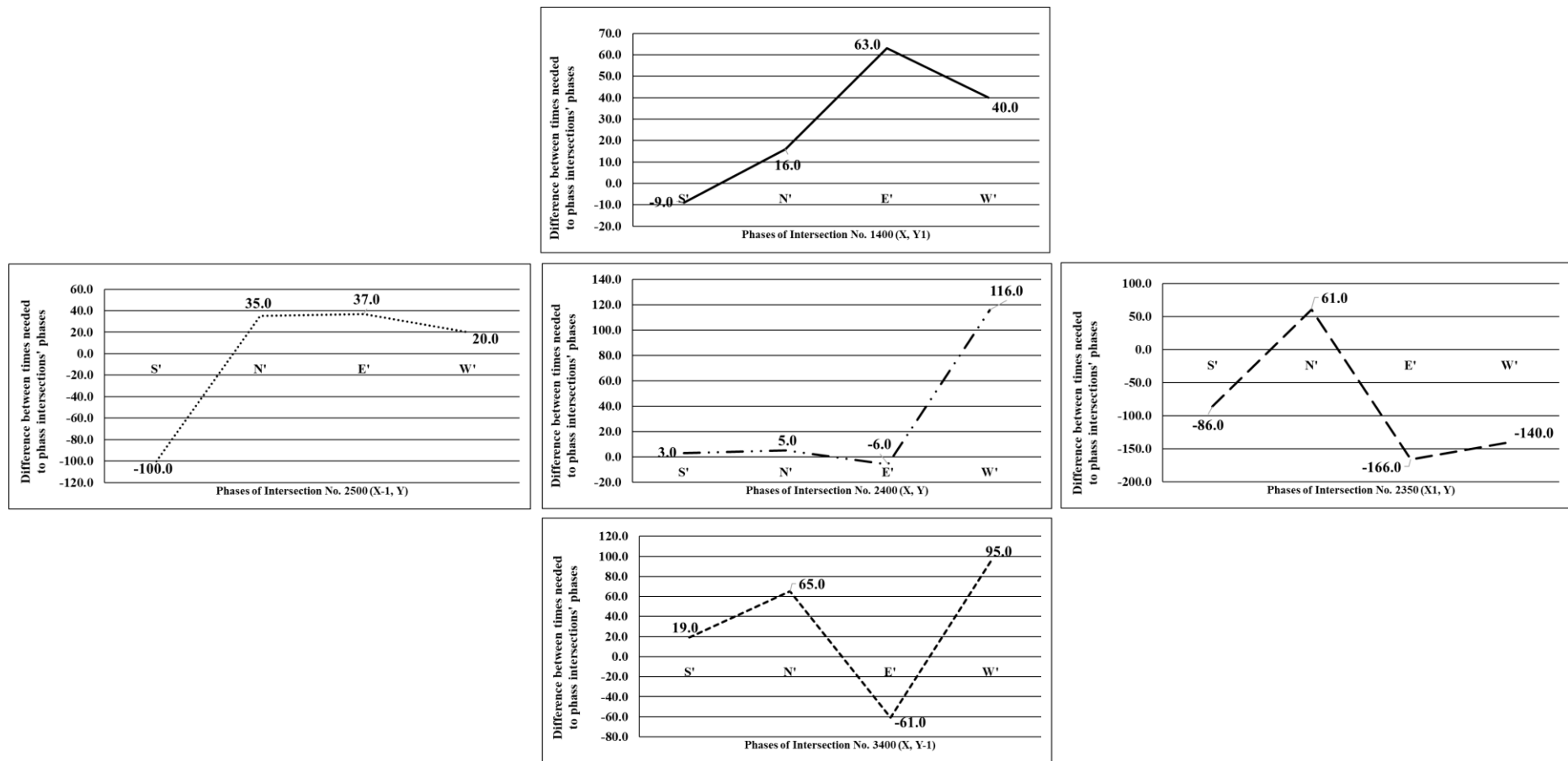


Figure (127)

Differences in the Total Green Time Utilization Between the Developed System and the Existing Condition to Dissipate the Traffic at Various Intersections Between 21:30 and 21:45

By summarizing the results, three cases appeared. First case showed that the number of vehicles passing through some directions increased and the green time needed to pass through these directions decreased when comparing the developing system with the existing condition. That appeared during the period 6:45 to 7:00 at South and East directions through the network. However, during the period 14:15 – 14:30, the first case appeared at all four directions (South, North, East, and West) within the network, while it is appeared during the period 21:30 to 21:30 at West direction only. That means, these directions are given more time than needed by using the existing system, and the developed system reduced the time loss for that direction based on the traffic flow. The developed system improved the traffic situation by increasing the number of vehicles passing through these directions in order to reduce the queue length. The overall results may lead to reduction of waiting and delay times.

The second case showed that the number of vehicles and the green time needed to pass through some directions increased. The second case appeared during the period 6:45 to 7:00 at North and West directions through the network. During the period 17:15 – 17:30, this case appeared at South and North directions within the network, while it is appeared during the period 21:30 to 21:45 at South and North directions. That means, these directions are given less time than needed using the existing system. But the developed system increased the green time based on the traffic flow and queue length. That increased the number of vehicles passing through these directions.

The last case showed that the number of vehicles and the green time needed to pass through other directions decreased. This case appeared during the period 17:15 to 17:30 at East and West directions. During the period 21:30 to 21:45, the third case appeared at East direction. That

means, the existing control system performed better than the developed one.

6.5. Summary of the Results

The previous results are summarized in this section for the individual intersections and for the network.

6.5.1. Overall intersections results

The tested network considered for the evaluation of the developed control system consisted of a grid of five intersections. Each intersection consisted of four phases. These added to a total of 20 phases in the network. Table 22 presents the simulated results of the developed system when compared with the existing system for the number of vehicles passing the various intersections' phases and the time needed for the vehicles to pass through these intersections during four considered periods.

Table (22)

Number of Vehicles and Green Time Indicators' Required to Pass the Grid Intersections' Phases by the Developed System when Compared with the Existing Condition

Period	Results	Intersection No. 1400 (X, Y1)				Intersection No. 2350 (X1, Y)				Intersection No. 2400 (X, Y)				Intersection No. 2500 (X-1, Y)				Intersection No. 3400 (X, Y-1)			
	Phases	S'	N'	E'	W'	S'	N'	E'	W'	S'	N'	E'	W'	S'	N'	E'	W'	S'	N'	E'	W'
6:45 - 7:00	No. of vehicle passing intersections' phases	↑	↑	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↓	↑	↓	↑
	Time needed to pass the vehicles through intersections' phases	↑	↑	↓	↓	↓	↑	↓	↓	↓	↑	↓	↑	↑	↑	↑	↑	↓	↑	↑	↑
14:15 - 14:30	No. of vehicle passing intersections' phases	↑	↑	↑	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↑	↓	↑	↓	↑	↑
	Time needed to pass the vehicles through intersections' phases	↑	↓	↑	↑	↑	↓	↓	↓	↓	↑	↓	↑	↑	↑	↑	↓	↓	-	↑	↑
17:15 - 17:30	No. of vehicle passing intersections' phases	↓	↑	↑	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Time needed to pass the vehicles through intersections' phases	↓	↑	↑	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
21:30 - 21:45	No. of vehicle passing intersections' phases	↑	↑	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↑
	Time needed to pass the vehicles through intersections' phases	↓	↑	↑	↑	↓	↑	↓	↓	↑	↑	↓	↑	↓	↑	↑	↑	↑	↑	↓	↑
* ↑ Increasing indicator, ↓ Decreasing indicator, - No change indicators																					

The results of the developed system for periods 6:45 – 7:00 and 14:15 – 14:30 showed that 55% ($\frac{11 \text{ phases}}{20 \text{ total phases}} * 100$) of the network phases exhibited increases in both number of passing vehicles and the green time relative to the performance of the existing system. Furthermore, 35% of the network phases exhibited increases in the number of passing traffic, but they showed decreases in the green time. However, 10% of the network phases showed decreases in both the number of passing traffic and the green time. Five percent of the network phases showed decreases in the number of passing vehicles and an increase in green time. As can be seen, the developed control system improved the traffic flow at 90% of the network phases during the periods 6:45 to 7:00 and 14:15 to 14:30 which means that the developed control system performed better than the existing one. In addition, it improved the green time by 40% of the network phases during the same periods. But the developed control system had a negative impact on the green time by 30% on the network phases. The explanation is that the green time distributed by the existing control system is not based on the traffic situation, while the developed control system increased the green time based on the actual traffic situation as needed.

Results for the period 17:15 – 17:30 showed that 85% of the network phases exhibited increases in both the number of passing traffic and green times. However, 15% of the network phases showed decreases in both parameters. As can be seen, the developed control system improved the traffic flow at 85% of the network phases which means that the developed control system performed better than the existing one. In addition, it improved the green time by 40% of the network phases during the same periods. But the developed control system had a negative impact on the green time by 30% of the network phases. Since the green time decreased

and the number of vehicles increased that means, the developed control system performed better than the existing one.

Furthermore, results taken from the period 21:30 – 21:45 showed that 65% of the network phases resulted in increases in both the passing traffic and the green time. Whereas, 25% of the network phases showed an increase in the passing traffic and a decrease in green time. For this same period, 10% of the network phases showed decreases in both the number of passing vehicles and the green time. From results, the developed control system improved the traffic flow at 90% of the network phases. That indicate, the developed control system performed better than the existing one. In addition, the developed control system improved the green time by 25% of the network phases. But it had a negative impact on the green time by 75% of the network phases. In general, the developed control system improved the traffic flow with high percentage which means, it performed better than existing one.

From the previous analysis, $85\% \left(\frac{(11+6) \text{ phases}}{20 \text{ total phases}} * 100 \right)$ of the phases in the network showed increases in the traffic passing through phases during 6:45 – 7:00, 14:15 – 14:30, and 17:15 – 17:30 periods, when comparing the developed control system and the existing condition, while 90% of the phases in the network showed increases during the period 21:30 – 21:45. That means, the developed control system performed better than the existing one.

The results of the developed system for the total number of vehicles passing intersections' phases and the number of cycles during the earlier four specified periods are shown in Table 23 (section 6.2).

Table (23)

**Total Number of Vehicles Passing a Grid of Five Intersections and
Number of Cycles Needed to Dissipate them During Specified Periods
by the Developed System Compared with the Existing Condition**

Period	Results	Intersection No. 1400 (X, Y1)	Intersection No. 2350 (X1, Y)	Intersection No. 2400 (X, Y)	Intersection No. 2500 (X-1, Y)	Intersection No. 3400 (X, Y-1)
6:45 - 7:00	% Total number vehicles passing intersection	↑	↓	↑	↑	↑
	% Number of cycle time	↑	↑	↑	↑	↑
14:15 - 14:30	% Total number vehicles passing intersection	↑	↑	↑	↑	↑
	% Number of cycle time	↓	↑	↓	↑	-
17:15 - 17:30	% Total number vehicles passing intersection	↑	↓	↑	↑	↑
	% Number of cycle time	↓	↑	↓	-	↑
21:30 - 21:45	% Total number vehicles passing intersection	↑	↑	↑	↑	↑
	% Number of cycle time	↓	↑	↑	-	↑
* ↑ Increasing indicator, ↓ Decreasing indicator, - No change indicator						

From Table 23, one may say that 80% of the intersections showed improvements in the traffic passing the various intersections during the periods between 6:45 and 7:00 and between 17:15 and 17:30, respectively. On other hand, all the network intersections showed improvements in the traffic passing the intersections during the periods between 14:15 and 14:30 and between 21:30 and 21:45. Similarity, all the intersections showed increases in the number of cycles during the period 6:45 – 7:00. That meant that the developed system shortened and accelerated the cycles through specified periods. In other words, greater number of cycles were utilized to dissipate the traffic during the earlier period. This means shorter waiting time and probably lesser delays. Forty percent of the intersections showed increases in number of cycles during the periods 14:15 – 14:30 and 17:15 – 17:30, while 20% did not show any changes in number of cycles during these periods. Furthermore, 60% of the intersections showed increases in the number of cycles during the period 21:30 – 21:45. From

the results, the developed control system improved the number of cycles through the different periods, which means that the developed control system distributed the green time based on the traffic situation. That met by decreasing the green time loss at some phases and increasing the green times at other phases to increase the traffic flow and the number of cycles. Increasing number of cycles means shorter cycles and probably shorter waiting time and delay time.

Table 24 presents the differences in numbers of vehicles passing the various phases for each tested intersection between the developed system and existing conditions along with the green times necessary to pass through these phases during the following four tested periods: 6:45 to 7:00, 14:15 to 14:30, 17:15 – 17:30 and 21:30 to 21:45.

For the period 6:45 to 7:00, the total number of vehicles passing the various phases with the existing conditions is 5660 vehicles, and it is 6071 vehicles with the developed system (Figures: 56, 58, 60, 62 and 64). The difference in the total number of vehicles passing the various phases through the network increased by 411 vehicles ($6071 - 5660$), i.e. an increase of 7.3% ($((411*100)/5660)$). The total green times necessary to pass through these phases is 4905 sec. with the existing conditions, and it is 4854 sec. with the developed system (Figures: 57, 59, 61, 63 and 65). The difference in the total green time necessary to pass through the various phases decreased by 51 sec. ($4854 - 4905$), i.e. a decrease of 1.0% ($((-51*100)/4905)$).

For the period 14:15 to 14:30, the total number of vehicles passing the various phases at the existing conditions is 6283 vehicles, and it is 7669 vehicles with the developed system (Figures: 68, 70, 72, 74 and 76). The difference in the total number of vehicles passing the various phases through the network increased by 1386 vehicles ($6283 - 7669$), i.e. an

increase of 22.1% $((1386 * 100) / 6283)$. The total green times necessary to pass through these phases is 5147 sec. with the existing conditions, and it is 4945 sec. with the developed system (Figures: 69, 71, 73, 75 and 77). The difference in the total green time necessary to pass through the various phases decreased by 202 sec. $(5147 - 4945)$, i.e. a decrease of 4.0% $((-202 * 100) / 5147)$.

The results' analysis of the tested network during the periods 6:45 to 7:00 and 14:15 to 14:30, showed increases in the total number of vehicles passing the various phases, and decreases in the total green times necessary to pass through these phases when the developed system was compared with current conditions. In other words, the developed control system improves the network performance by increasing the traffic flow and reducing the total green time.

For the period 17:15 to 17:30, the total number of vehicles passing the various phases with the existing conditions is 6981 vehicles, and it is 7352 vehicles with the developed system (Figures: 80, 82, 84, 86 and 88). The difference in the total number of vehicles passing the various phases through the network increased by 371 vehicles $(6981 - 7352)$, i.e. an increase of 5.3% $((371 * 100) / 6981)$. The total green times necessary to pass through these phases is 4877 sec. with the existing conditions, and it is 5051 sec. with the developed system (Figures: 81, 83, 85, 87 and 89). The difference in the total green time necessary to pass through the various phases increased by 174 sec. $(4877 - 5051)$, i.e. an increase of 3.6% $((174 * 100) / 4877)$.

For the last period 21:30 to 21:45, the total number of vehicles passing the various phases with the existing conditions is 6345 vehicles, and it is 7148 vehicles with the developed system (Figures: 92, 94, 96, 98 and 100). The difference in the total number of vehicles passing the various phases

through the network increased by 803 vehicles ($6345 - 7148$), i.e. an increase of 12.7% ($((803 * 100) / 6345)$). The total green times necessary to pass through these phases is 4928 sec. with the existing conditions, and it is 4935 sec. with the developed system (Figures: 93, 95, 97, 99 and 101). The difference in the total green time necessary to pass through the various phases increased by 7 sec. ($4928 - 4935$), i.e. an increase of 0.1% ($((7 * 100) / 4928)$).

Analysis of the results of the tested network during the periods 17:15 to 17:30 and 21:30 to 21:45, showed increases in the total number of vehicles passing the various phases, and in the total green times necessary to pass through these phases when the developed system was compared with current conditions. In other words, the developed control system improved the network performance by increasing the traffic flow but did not improve the total green time which may increase the waiting times and delays.

Table (24)

Differences Between the Developed System and the Existing Condition in Terms of Number of Vehicles Passing the Intersections and the Time Consumed to Cross Them

Period	Intersection	Intersection No. 1400 (X, Y1)				Intersection No. 2350 (X1, Y)				Intersection No. 2400 (X, Y)				Intersection No. 2500 (X-1, Y)				Intersection No. 3400 (X, Y-1)				Summation
	Results	S'	N'	E'	W'	S'	N'	E'	W'	S'	N'	E'	W'	S'	N'	E'	W'	S'	N'	E'	W'	
6:45 - 7:00	Difference of No. of vehicle passing intersections' phases (vehicles)	19	18	3	3	5	9	-31	13	10	19	18	134	40	2	28	59	-14	88	-23	11	411
		2.6%	20.1%	3.3%	5.8%	1.7%	7.4%	-25.6%	2.8%	6.3%	26.7%	3.9%	36.8%	12.5%	26.7%	5.4%	45.3%	-4.9%	81.0%	-2.6%	3.0%	
	Difference of time needed to pass the vehicles through intersections' phases (seconds)	11	12	-5	-3	-15	9	-273	-27	-38	32	-11	80	41	19	16	41	-215	54	208	13	-51
		1.8%	19.2%	-3.5%	-2.7%	-4.6%	6.4%	-64.5%	-6.4%	-20.2%	27.7%	-3.0%	37.9%	13.4%	27.7%	3.7%	43.6%	-55.1%	82.4%	67.0%	10.3%	
14:15 - 14:30	Difference of No. of vehicle passing intersections' phases (vehicles)	74	221	142	19	57	31	68	-25	15	25	116	63	70	19	116	-11	64	-20	37	305	1386
		31.3%	42.7%	49.8%	27.3%	45.7%	11.5%	18.7%	-8.2%	15.2%	38.5%	23.9%	17.5%	17.3%	14.5%	31.4%	-2.0%	34.9%	-4.7%	8.1%	53.5%	
	Difference of time needed to pass the vehicles through intersections' phases (seconds)	29	-62	26	44	112	-102	-194	-194	-84	42	-24	11	12	116	90	-101	-125	0	110	92	-202
		14.7%	-16.9%	11.1%	41.5%	59.6%	-48.0%	-39.2%	-39.2%	-48.2%	33.9%	-5.9%	3.0%	5.5%	84.9%	42.8%	-30.7%	-41.7%	0.0%	43.9%	45.8%	
17:15 - 17:30	Difference of No. of vehicle passing intersections' phases (vehicles)	-18	109	67	22	16	21	-122	-130	27	7	34	62	55	9	48	24	36	47	11	46	371
		-2.7%	31.1%	23.1%	16.7%	5.6%	5.8%	-17.4%	-26.9%	15.9%	11.1%	8.6%	14.5%	25.2%	24.4%	11.9%	7.1%	18.4%	26.7%	1.6%	7.6%	
	Difference of time needed to pass the vehicles through intersections' phases (seconds)	-29	73	49	22	41	18	-194	-194	21	16	28	50	18	35	37	20	48	32	62	21	174
		-8.5%	32.2%	24.2%	17.6%	19.4%	7.4%	-43.4%	-43.4%	16.5%	11.6%	9.1%	15.0%	5.6%	30.4%	14.4%	9.8%	19.3%	27.7%	22.9%	10.3%	
21:30 - 21:45	Difference of No. of vehicle passing intersections' phases (vehicles)	63	30	78	85	8	122	-77	14	3	4	9	127	-7	19	50	22	13	121	23	96	803
		26.5%	6.3%	32.0%	161.1%	6.5%	43.1%	-15.5%	3.0%	1.8%	5.6%	1.4%	33.0%	-5.6%	30.4%	14.4%	9.8%	6.3%	44.6%	2.7%	16.3%	
	Difference of time needed to pass the vehicles through intersections' phases (seconds)	-9	16	63	40	-86	61	-166	-140	3	5	-6	116	-100	35	37	20	19	65	-61	95	7
		-3.0%	6.1%	31.8%	30.6%	-40.4%	26.0%	-37.1%	-31.2%	2.6%	6.4%	-2.0%	34.0%	-30.8%	30.4%	14.4%	9.8%	7.1%	45.7%	-21.8%	47.9%	

The total number of vehicles passing the various phases during the four periods for each of the five intersections is statically tested using paired t-test to determine if there is a significant difference between the results of the developed system and those obtained by the existing conditions. Table 25 presents the differences between the developed system and the existing condition in term of the total number of vehicles passing the various phases of the five intersections through four periods. The table shows significant differences for the four phases since the P-values are less than 0.05. In other words, the developed control system improves the traffic flow by increasing the total number of vehicles passing the various phases of the five intersections through the considered four periods. That means, the developed control system performed better than the existing one.

Similarly, the total green times necessary to pass the phases during the four periods for each of the five intersections is tested using paired t-test to determine whether the differences between the results of the developed system and those obtained by the existing conditions are significant or not. Table 26 presents the paired differences between the developed system and the existing condition in term of the total green times necessary to pass through these phases. The only significant difference shown for N' phases with P-value of 0.032, whereas all the remaining phases show P-values of more than 0.05.

Table (25)

Paired t- test Between the Developed System and the Existing Condition in Term of the Total Number of Vehicles Passing the Various Phases

Phase				Paired Differences				t	df	Sig. (2-tailed)	
				Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
							Lower				Upper
S	Pair 1	Exisiting - Developed	-26.80000	28.79437	6.43862	-40.27618	-13.32382	-4.162	19	.001	
N	Pair 1	Exisiting - Developed	-45.05000	58.29821	13.03588	-72.33440	-17.76560	-3.456	19	.003	
E	Pair 1	Exisiting - Developed	-29.75000	63.26708	14.14695	-59.35991	-14.009	-2.103	19	.049	
W	Pair 1	Exisiting - Developed	-46.95000	83.64114	18.70273	-86.09526	-7.80474	-2.510	19	.021	

Table (26)

Paired t- test Between the Developed System and the Existing Condition in Term of the Total Green Times Necessary to Pass the Five Intersections

Phase				Paired Differences				t	df	Sig. (2-tailed)	
				Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
							Lower				Upper
S	Pair 1	Existing_1 - Developed_1		17.80000	73.28718	16.38751	-16.49946	52.09946	1.086	19	.291
N	Pair 1	Existing_1 - Developed_1		-23.80000	46.04071	10.29502	-45.34772	-2.25228	-2.312	19	.032
E	Pair 1	Existing_1 - Developed_1		10.40000	116.48465	26.04676	-44.11649	64.91649	.399	19	.694
W	Pair 1	Existing_1 - Developed_1		-.30000	89.70308	20.05822	-42.28233	41.68233	-.015	19	.988

6.5.2. Overall network results

The sample network consisted of four directions S', N', E' and W'. Each direction consisted of three intersections. The results of the increasing or decreasing indications of the percentage differences in passing traffic through the network directions between the developed system and the existing condition along with the indication of necessary green time to dissipate this traffic during various specified 15 minutes periods are shown in Table 27.

Table (27)
Increasing and Decreasing Indicators Between the Developed Control System and Existing Condition in Terms of Passing Traffic and the Corresponding Green Time Necessary to Dissipate Such Traffic

Period	Results	Network Direction			
		S'	N'	E'	W'
6:45 - 7:00	% difference of No. in vehicle passing through network direction	↑	↑	↓	↑
	% difference of time needed to pass the vehicles through network direction	↓	↑	↓	↑
14:15 - 14:30	% difference of No. in vehicle passing through network direction	↑	↓	↑	↑
	% difference of time needed to pass the vehicles through network direction	↓	↑	↓	↓
17:15 - 17:30	% difference of No. in vehicle passing through network direction	↑	↑	↑	↓
	% difference of time needed to pass the vehicles through network direction	↑	↑	↓	↓
21:30 - 21:45	% difference of No. in vehicle passing through network direction	↑	↑	↑	↑
	% difference of time needed to pass the vehicles through network direction	↑	↑	↓	↑
* ↑ Increasing indicator, ↓ Decreasing indicator, - No change indicators					

The results for the period between 6:45 and 7:00 showed that the number of vehicles passing through the S' direction has increased and the corresponding green time to dissipate these vehicles through the same directions has decreased. In the N' direction, both the number of vehicles and the corresponding green time needed to pass has increased. The W' direction followed the N' direction in the creasing trend of both parameters. However, both the traffic dissipation and the time needed to allow the corresponding traffic to cross the network from the E' direction have decreased (Table 27). That means, one out of four directions (25%) of the network (S' direction) exhibited an increase in the dissipated number of vehicles and a decrease in the corresponding green time. Two out of four (50%) of the network (N' and W' directions) exhibited an increase in both the dissipated number of vehicles and the corresponding green time. Whereas, one out of four directions (25%) of the network (E' direction)

exhibited a decrease in both the dissipated number of vehicles and the corresponding green time.

The results for the period between 14:15 and 14:30 showed that the number of vehicles passing through the S', E' and W' directions has increased and the corresponding green time to dissipate these vehicles through the same directions has decreased, which means lesser delays. In the N' direction, the number of vehicles has decreased, and the corresponding green time needed to pass has increased (Table 27). That means, three out of four directions (75%) of the network (S', E' and W' directions) exhibited an increase in the dissipated number of vehicles and a decrease in the corresponding green time. One out of four (25%) of the network (N' direction) exhibited a decrease in the dissipated number of vehicles and an increase in the corresponding green time.

The results for the period between 17:15 and 17:30 showed that the number of vehicles passing through the S' and N' directions and the corresponding green time to dissipate these vehicles through the same directions has increased. In the E' direction, the number of vehicles has increased, and the corresponding green time needed to pass has decreased. The W' direction, both the traffic dissipation and the time needed to allow the corresponding traffic to cross the network has decreased (Table 27). That means, one out of four directions (25%) of the network (E' direction) exhibited an increase in the dissipated number of vehicles and a decrease in the corresponding green time. Two out of four (50%) of the network (S' and N' directions) exhibited an increase in both the dissipated number of vehicles and the corresponding green time. Whereas, one out of four directions (25%) of the network (W' direction) exhibited a decrease in both the dissipated number of vehicles and the corresponding green time.

The results for the period between 21:30 and 21:45 showed that the number of vehicles passing through the S', N' and W' directions and the

corresponding green time to dissipate these vehicles through the same directions has increased. In the E' direction, the number of vehicles has increased, and the corresponding green time needed to pass has decreased (Table 27). That means, one out of four directions (25%) of the network (E' direction) exhibited an increase in the dissipated number of vehicles and a decrease in the corresponding green time. Three out of four (75%) of the network (S', N' and W' directions) exhibited an increase in both the dissipated number of vehicles and the corresponding green time.

Chapter 7

Conclusions, Recommendations and Further Research

7.1. Conclusions

7.2. Recommendations

7.3. Further Research

Chapter 7

Conclusions, Recommendations and Further Research

7.1. Conclusions

Fuzzy logic is used to reduce the complexity of control systems. It can be validated by using hardware, software, or a combination of either. A proposed traffic control system was developed based on fuzzy rules and compared with the existing traffic control system in the State of Kuwait. The traffic control system was developed as a smart system through two stages, designing green time distribution models and designing fuzzy rules. Green time models are designed by distributing the green times based on the road specifications (collector, major arterial, and minor arterial roads) for specified number of zones (1, 2, and 3) and the possibility of combination between these zones. Green times could be distributed in different ways under different conditions or specifications, for the maintained number of zones and the possibility of combination between these zones. The developed system is expandable for any other road configurations (T-intersection, roundabout intersection, etc.) and network. In addition, the fuzzy rules are designed by using visual basic and computer-based program (Excel).

The developed control system was applied to the data from five intersections in a grid network, during four different periods of the same day. The results were evaluated by simulating the network and comparing to existing condition. The developed control system improved the performance of the intersections when compared with existing system during both normal and oversaturated conditions when tested under real

time case. The unused green time (time loss) of most single phases specified by the existing system was added to other phases based on queue lengths at each phase. The frequency of the intersection cycles per specified 15 minutes, has increased through the developed control system when compared with the existing control system.

The existing system specifies a fixed green time during each period while the developed control system allocates it based on the traffic situation. The developed control system leads to higher passage of vehicles through various phases. The time needed to dissipate the vehicles through the various phases decreased. The developed system utilized the green time more efficiently compared with the existing system. The green time reduced from some phases where their vehicle queue is short, and this time is added to other phases where the vehicle queue length is longer to increase the traffic flow.

For the intersections, the number of vehicles passing through the intersection' phases and the green time were increased. This means, the application of the developed control system rules increased the total cycle time to the maximum and distributed the green time amongst the four phases based on the actual traffic situation.

In some intersections, the number of vehicles passing through and the green time were increased in some phases, while remained the same in others. This means that the total cycle time of the system increased to the maximum and added extra time to the phases in need.

Even though the green time varies among all intersection, the number of the passing vehicles at most phases was increased. This means, the developed system reduced the time loss from some phases and added the unused time to the phase that needed it to increase the number of vehicles passing through.

The number of cycles varied during the tested periods, since the developed control system specified the cycle time based on traffic situation and vehicle queues. For example, when a phase is characterized having long vehicle queue in a connected intersection of long distance then the system gives this phase extra green time of the full cycle.

As per tested network, the developed control system improved the traffic flow through various vehicle movements within the network directions by distributing the green times based on the traffic situation. In other words, the developed system reduced the wasted time from certain directions and added it to the critical directions where the vehicles queues located at the last zone of the phase. As a result, the developed system reduced the travel time.

As per paired t-test analysis, a significant improvement is shown by the developed control system in terms of the total number of vehicles passing through the various phases of the five intersections through the considered four periods (6:45 – 7:00, 14:15 – 14:30, 17:15 – 17:30 and 21:30 – 21:45). On the other hand, the paired t- test shows a significant improvement between the developed control system and the existing one in N' phases only, while the other phases do not show any significance in term of the total green times necessary to pass through these phases. The conclusion of the t-test shows that the control system achieved the research objective by increasing the total number of vehicles passing through the intersections' phases.

Adaptive control systems such as SCOOT and SCATS are examples of widely available traffic control systems. Detectors' requirements differ with system implementation. In general, SCOOT requires single detector per a signalized phase (Gordon, 2005). Similarly, SCATS utilized one detector for each major phase lane (Gordon, 2005). While the developed

control system requires three detectors per each signalized phase. The location of detectors in SCOOT and SCATS systems is critical, and affecting insufficiently if they are not placed ideally, while the location of detectors in the developed control system is not affecting much if they are not placed ideally.

The operational timing plans of these widely control systems used inclusive cycle length, splits and offsets are continuously reviewed by system automatically, and are modified in small time increments to match usual demands that are measured by the system through the detectors connected to the traffic controllers. While the operational timing plans, inclusive of the green time and the cycle time, are continuously reviewed and modified on a cycle-by-cycle base to match the system modification rules based on the traffic demand. Based on measurements received from the detector, the SCOOT and SCATS determine whether it is better to change the offset, cycle time, or split of phase by a certain time that is specified based on the traffic situation. Both the green times and the cycle time in the developed control system are determined with varying times during each cycle based on the green time distribution models and the queue lengths.

The SCOOT models are unable to handle closely spaced signals due to its detection configuration requirements. While the developed control system is designed to handle far apart intersections.

7.2. Recommendations

It is recommended to test physically on actual ground the developed system to control intersections with specifications matching the ones that it is built for, namely, simple with four perpendicular phases, formed by

the collector, major arterial and minor arterial roads' specifications, three detectors placed at each phase (approach) to obtain actual traffic data, and in a grid network. Changes in variables, such as clearance time, average vehicle length, number of lanes, queue detector location, etc. can be adopted as a new input when running the system.

The developed system can be supported with both soft and hard wares to be marketed for the general use.

7.3. Further Research

The traffic control system of this research was developed based on the collector, major and minor arterial road network. For future work, a new model could be developed by combining this model with other roadway classifications.

The control system can be modified to accommodate emergency situations (vehicle accidents, ambulances in service, etc.) and vehicle acceleration / deceleration. In addition, the green time distribution models can be developed for arterial networks with little modifications required.

Furthermore, the system needs to be tested on the field and on a greater number of signalized intersections within the network.

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ملخص الأطروحة

تعد الإشارة الضوئية من أهم الأجهزة المستخدمة في التقاطعات المرورية للتحكم في حركة السير وتدفق المركبات بطريقة فعالة. ولكنها قد تتسبب في ازدحام مروري إذا لم يتم تنظيمها بشكل فعال. ويتم التحكم في أغلب الاشارات الضوئية من خلال نظم تحكم ثابتة من حيث زمن الدورة أو تحفز من خلال المجسات والتي تدار من خلال البيانات التاريخية عند الاشارات. ومن السهل استخدام نظم التحكم في اشارات التقاطعات المعزولة عندما تكون التقاطعات في حالتها الطبيعية غير المشبعة، أما التقاطعات فوق المشبعة ومن حيث حركة السير فيصعب التحكم فيها. مما يدعو الى انشاء نظم تحكم ديناميكية تناسب حالة المرور اللحظية في التقاطع. لقد تم في هذه الأطروحة انشاء نظام تحكم من خلال استخدام نظام احصائي ذكي فزي (fuzzy) لتطوير أداء الاشارات المرورية من خلال تحسين الحركة المرورية وتقليل زمن رحلة المركبات عبر التقاطعات للتقاطعات البسيطة والرباعية الاتجاهات الموجودة ضمن شبكة تقاطعات مرورية (grid). ويعد النظام الذكي (fuzzy) برمجة لغوية يمكنها أن تتعامل مع المشكلات المرورية المعقدة لتوفير زمن الضوء الأخضر بطريقة ذكية وفق الحالة الحقيقية لحركة السير. والهدف الرئيس من نظام التحكم المنشأ هو تقليل الدورة الزمنية للاشارات وخفض الزمن الضائع عند تحول الاشارة خضراء خلال استخدام نظام التحكم لتحديد الزمن الأخضر لكل اتجاه بناء وفق حالته المرورية. يمر نظام التحكم في أربعة مراحل. وقد تم تصميم نماذج توزيع الزمن الأخضر لاتجاهات التقاطعات ويتم تصنيف الطريق ومواصفاته في المرحلة الأولى من النظام. في المرحلة الثانية تصميم Fuzzy Rules والتي يتم بها تحديد الشروط المستخدمة في نظام التحكم لتحديد زمن الاشارات. وفي المرحلة الثالثة، يتم تشغيل نظام التحكم ومن ثم واعطاء الأوامر التنفيذية لاشارات المرور في المرحلة الرابعة. ومن أجل تنفيذ وتشغيل برنامج التحكم تم الاستعانة في استخدام برنامج Excel و Visual Basic language لتنفيذ وتشغيل برنامج التحكم. تم تطبيق نظام التحكم على نموذج محاكاة لخمس تقاطعات في شبكة مرورية بدولة الكويت لأربعة فترات زمنية مزدحمة مختلفة (6:45-7:00، 14:30-14:15، 17:30-17:15، و 21:30-21:45) من يوم الاثنين الموافق 11 يناير 2016 من خلال استخدام نوع ومواصفات شوارع التقاطعات، متوسط طول السيارة وتدفق السيارات في كل اتجاه. أظهرت النتائج أن أعداد السيارات التي تعبر أغلب اتجاهات التقاطعات زادت بمعدل 7.3% ، 22.1% ، 5.3% و 21.7%. زمن اتجاهات التقاطعات اللازم لعبور السيارات في هذه التقاطعات قد قل بمعدل 1.0% و 4.0% في فترتين زمنيتين، وزاد بمعدل 3.6% و 0.1% في لفترتين الأخرين. كما أن أعداد دوران التقاطعات بقيت كما هي في أغلب التقاطعات مما يعني أن نظام التحكم وزع زمن الاتجاهات بناء على حالة المرور. يمكن تطبيق نظام التحكم على التقاطعات البسيطة والرباعية الاتجاهات والتي تحتوي على مواصفات وخواص الشوارع major collector، arterial، و minor arterial.

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"نمذجة نظام إدارة الحركة المرورية للتقاطعات الفوق المشعبة في الكويت باستخدام التقنية الذكية"

مجلد 1

مخطط بحث لاستكمال متطلبات الحصول على درجة الدكتوراه في الهندسة الميكانيكية

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