

Management of City Traffic, using Wireless Sensor Networks with Dynamic Model

by

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Abstract

Road network of a region is of a paramount importance in the overall development. Management of road traffic is a key factor for the city authority and reducing the road traffic congestion is a significant challenge in this perspective. In this thesis, a Wireless Sensor Network (WSN) based road-traffic monitoring scheme with dynamic mathematical traffic model is presented that will not necessarily include all adjacent intersections of a block; rather the important major intersections of a city. The objective of this scheme is to reduce the congestion by re-routing the vehicles to better performing road-segments by informing the down-stream drivers through broadcasting the congestion information in a dedicated radio channel. The dynamic model can provide with the instantaneous status of the traffic of the road-network. The scheme is a WSN based multi-hop relay network with hierarchical architecture and composed of ordinary nodes, Cluster-Head nodes, Base Stations, Gateway nodes and Monitoring and Control Centers (MCC) etc. Through collecting the traffic information, MCC will check the congestion status and in defining the congestion, threshold factors have been used in this model. For the congested situation of a road-segment, a cost function has been defined as a performance indicator and estimated using the weight factors (importance) of these selected intersections.

This thesis considered a traffic network with twelve major intersections of a city with four major directions. Traffic arrivals in these intersections are assumed to follow Poisson distribution. Model was simulated in Matlab with traffic generated through Poisson Random Number Generator and cost function was estimated for the congestion status of the road-segments over a simulation period of 1440 minutes starting from midnight. For optimization purpose we adopted two different approaches; in the first approach, performance of the scheme was evaluated for all threshold factor values iteratively one at a time, applying a threshold factor value to define threshold capacities of all the road-segments; traffic was generated and relative cost has been estimated following the model specifications with the purpose of congestion avoidance. In the second approach, different values of threshold factor have been used for different road segments for determining the optimum set-up, and exhaustive search technique has been applied with a smaller configuration in order to keep computations reachable. Simulation results show the capacity of this scheme to improve the traffic performance by reducing the congestion level with low congestion costs.

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Contents

1	Introduction	1
1.1	Background	1
1.2	Motivation and Objective	2
1.3	Thesis Contribution	5
1.4	Thesis Outline	6
1.5	List of Publications	6
2	State of the Art	7
2.1	Introduction	7
2.2	Formal Analytical Methods	7
2.2.1	Mathematical Models with Wireless Sensor Networks (WSNs) . .	8
2.2.2	Dynamic Mathematical Models	11
2.2.3	Mathematical Models with Other Perspectives	12
2.2.4	Other Methods	17
2.3	Use of Genetic Algorithm	18
2.4	Optimizing Area-Specific Traffic	20
2.5	Use of Poisson Distribution	21
2.6	Use of Petri Nets	22
2.7	Non-Analytical-based Methods	23
2.8	Conclusion	25
3	System Model	26
3.1	Introduction	26
3.2	Road Traffic Network	27
3.3	System Architecture	28
3.3.1	Traffic Light System	29
3.3.2	Traffic Monitoring Data Movement	30

3.3.3	Assumption of Classical Poisson Process	31
3.3.4	Other Assumptions	31
3.4	City Vehicular traffic Model	32
3.4.1	The Vehicular Model	33
3.4.2	Estimating Cost function	35
3.5	Conclusion	39
4	Simulation Results	41
4.1	Introduction	41
4.2	Monte-Carlo Method	42
4.3	Single Threshold Approach	42
4.3.1	Sensitivity Analysis	45
4.4	Distributed or Brute Force Approach	48
4.5	Conclusion	56
5	Conclusion and Future Works	65
5.1	Conclusion	65
5.2	Future Works	67
A	Comparison of the research work of [1] and our proposed model	73

List of Tables

2.1	Notations used in [2]	12
3.1	Total City Costs by Threshold factors with Control Scheme	38
4.1	Total City Cost comparison by Threshold factors for small sample size	44
4.2	City Costs by Threshold factors with large samples	44
4.3	Distances among different directions of 2 set of Mean arrival rates	51

List of Figures

2.1	Traffic congestion caused by (a) different paths (b) a broken vehicle . . .	9
2.2	Selected road network and directions in [2]	10
2.3	Operation of the threshold-tuning algorithm in [3]	13
2.4	Snapshot of the underlying lattice of the model in [4]	15
2.5	Flowchart of Imperialist Competitive Algorithm (ICA) in [5]	16
2.6	The designed fuzzy control system in [6]	17
2.7	Cell Transmission Model Basic Building Block in [7]	18
2.8	The Conceptual Circular Structure of CTSCRG Problem	19
2.9	Basic flow chart of the Genetic Algorithm in [8]	20
2.10	ITCS Architecture proposed in [9]	22
2.11	Green Light phase-transitions in [10]: (a)8-phases (b)6-phases (c)2-phases	23
2.12	A traffic network with nine intersections in [10]	24
2.13	The block diagram of the urban traffic network control system in [10] . .	24
3.1	Symbolic map of selected intersections (not neighbours)	27
3.2	System Architecture for proposed Traffic Monitoring Network	29
3.3	Twelve (12) cycles of Green Light with specific pair of directions	30
3.4	Hourly Mean Arrival Rate (λ) for all road types	34
3.5	Hourly Mean Arrival Rate (λ) separately all road types	34
4.1	Total City Cost-by threshold factor (No Control vs with Control)	43
4.2	Difference in Total City Cost for No Control vs with Control	45
4.3	Av. Cost (all thr.) comparison (No Control vs with Control)	46
4.4	Difference of Average Cost (No Control minus With Control)	47
4.5	Ideal City Cost for No Control vs with Control	48
4.6	Av. Traffic (all thr.) for No Control vs with Control	49
4.7	Av. Cost (all thresholds) for High and Low λ	49

4.8	Ideal City Cost-High vs Low λ	50
4.9	Av Traffic (all thresholds) for High vs Low λ	50
4.10	Av. Cost (all thresholds) for High and Low weight (normal λ and θ . . .	51
4.11	Ideal City Cost for High and Low weight	52
4.12	Total City Cost by Threshold Factor for High and Low weight	52
4.13	Av. Cost - High and low θ	53
4.14	Ideal City Cost- High and low θ	54
4.15	Av. Traffic (all thresholds) for High vs Low θ	55
4.16	Total Costs - No Control vs with Control for each permutation set	56
4.17	Comparison of costs- with and without control (set-1 and 2)	57
4.18	Comparison of costs- with and without control (sets-3 and 4)	58
4.19	Total Cost for each permutation set with Control	58
4.20	Total Cost for No Control situation for each permutation set	59
4.21	Total Costs for some selected permutation sets (1 and 2) with Control . .	59
4.22	Total Costs for some selected permutation sets (3 and 4) with Control . .	60
4.23	Total Cost-difference (No Control vs with Control)	60
4.24	Difference of costs- with and without control (set-1 and 2)	61
4.25	Difference of costs- with and without control (set-3 and 4)	61
4.26	Total City Traffic (with Control) for each permutation set	62
4.27	City Traffic by permutation sl. (with Control)-set 1 and 2	62
4.28	City Traffic by permutation sl. (with Control)-set 3 and 4	63
4.29	Difference in City Traffic (No Control vs with Control)	63
4.30	Aggregate Traffic by Road segment for No Control vs with Control . . .	64

List of Acronyms

AL: Approaching Lane

AQM: Active Queue Management

ATLC: Adaptive Traffic Light Control

CA: Cellular Automata

COP: Controlled Optimization of Phases

EDEA: Enumerative Delay Estimation Approach

ER: Escape Rate

FNNM: Fuzzy Neural Network Model

FPGA: Field-Programmable Gate Array

GA: Genetic Algorithm

GDP: Gross Domestic Product

GM: Grey Model

GTHA: Greater Toronto and Hamilton Area

ICA: Imperialist Competitive Algorithm

ISN: Intersection Sensor Node

ITS: Intelligent Transportation Systems

MCC: Monitoring and Control Centre

MET: Mean Elapsed Time

MUC: Multiple User Class

PSO: Particle Swarm Optimization

RED: Random Early Detection

RL: Reinforcement Learning

STPN: Synchronized Timed Petri Net

TPN: Timed Petri Net

TRED: Traffic Random Early Detection

USN: Upstream Sensor Node

VANET: Vehicular Ad Hoc Network

WSN: Wireless Sensor Network

List of Symbols

- θ_{id} : Non-compliance factor, the % of arrival rate effective in the d^{th} direction of i^{th} intersection in a congested situation
- β_{id} : Deterministic departure rate of vehicles from the d^{th} direction of i^{th} intersection
- ϕ_{id} : Excess traffic in the d^{th} direction of i^{th} intersection
- $\lambda_{id}(t_h)$: Hourly mean arrival rate in the d^{th} direction of i^{th} intersection
- κ_{id} : Continuous congestion counter in the d^{th} direction of i^{th} intersection
- c_{id} : Maximum capacity (number of vehicles) of a road-segment in d^{th} direction of i^{th} intersection
- d**: Index of direction
- E**: Expected value
- i**: Index of intersection
- I**: Indicator function
- $J(l)$: Cost of Congestion with threshold matrix “l”
- l_{id} : Threshold capacity of a road-segment in the d^{th} direction of i^{th} intersection!
- $L_{id}(t_k)$: Green Light Indicator in the d^{th} direction of i^{th} intersection at the discrete time point t_k (1 for ON, 0 for OFF)
- N**: Total Number of Intersections
- P**: Probability
- p_{id} : Quantity of traffic arrival (following Poisson Distribution) in the d^{th} direction of i^{th} intersection during the sample period t_k to t_{k+1}
- T**: Iteration period used in this model (1 minute in current simulation)
- t_k : Discrete time point at $k = 0, 1, 2, 3, \dots$
- t_{k+1} : Discrete time point $k = 0, 1, 2, 3, \dots$

$\mathbf{t}_{k-\gamma}$: Starting time point of continuous congestion (discrete), where $\gamma \geq 12 * T$

$\mathbf{V}(\mathbf{X})$: Variance

$\mathbf{w}$: Weight

$(\overline{X})$: Mean value of X

$\mathbf{x}_{id}(t_k)$: Number of vehicles in the d^{th} direction of i^{th} intersection at time t_k

$\mathbf{x}_{id}(t_{k+1})$: Number of vehicles in the d^{th} direction of i^{th} intersection at the discrete time point t_{k+1}

Chapter 1

Introduction

1.1 Background

The road network in a city and the quality of road transportation system significantly impacts the economic growth of a region and facilitates communication and trade. With the growth of population, the transportation sector also dictates an increased share in the overall economy. As a matter of fact, according to the Transportation Research Board of USA, the transportation expense is equal to 11 percent of the national GDP, 19 percent of total household spending goes in this sector and about 11 million people, (8 percent of the U.S. labor force) are dependent on this sector [11].

Although road transportation is a means of development in large cities, but on the other hand, it has the environmental impacts like noise, pollution in many cities; and congestions in the road network is a considerable headache to the city authorities. Motor vehicles on the road have become one of the main sources of pollutant in the urban areas and causing air quality deterioration in some big cities. Issue of city traffic and urban environment coordination development have become a main research area in the 21st century [12].

Due to the fact of steep growth trend in the volume of traffic, all the large cities are working hard to face the challenge to optimize the management of the road traffic. Several branches of professionals and researchers have focused their attention to this field; Intelligent Transportation Systems (ITS) is a part of this process. The idea of ITS was conceived in the 1980s by the transportation experts with the aim of exploiting the

advancements in the computing and communications sector in the road transportation sector. ITS involves engaging information technology and innovative services for the improvement of the transportation system and generate a positive contribution towards the economic and social advancements. In a larger context, transport strategies of an urban area focus to enhance different aspects like energy efficiency, environmental performance, lifestyle, safety and security of road transport, passenger and freight mobility.

Toronto City Summit Alliance report 2010 revealed that, during 1986 and 2006, in the Greater Toronto and Hamilton Area (GTHA) road traffic congestion reduced average peak period traffic speed by 25%; commuting time increased by 52%; greenhouse gas emission from vehicles increased by 56%; and direct annual costs of congestion (i.e. lost time to drivers) grew to more than \$3 billion per year, while the drag on the economy grew to more than \$2 billion per year (Toronto City Summit Alliance, 2010) [13].

The number of vehicles is increasing constantly in all levels of geographic entities. More than 700 million vehicles are registered worldwide, of all types and designations, more and more vehicles and road transportation means being produced each year. Such increase led to the reach of motor saturation limit on many roads, especially in the economically developed countries [14]. The increased number of road vehicles in large cities, caused by the increase of population and other factors may cause road congestion and traffic delay which can hinder the economic and social advancements of the area; poor road infrastructures degrades the situation significantly. Traffic congestion may slow down the delivery of services, affecting the economic growth and cause health issues like mental depression, stress etc.

Optimized Traffic management is a crucial aspect to a city authority as it significantly dictates in the overall productivity and the economic growth of a region and also brings a distinct effect on the standard of life. It's absence will result in traffic congestion in the city and as a consequence, frustration of mind will be accumulated in the city dwellers and economic growth may be risked to be hindered.

1.2 Motivation and Objective

In last twenty years, there have been numerous research performed in the field of Intelligent Transportation Systems (ITS). One of the main objectives in these research works

is to make the road transportation system smooth and reduce the level of congestion. In this connection of reducing congestion on the road, different studies focussed on different aspects and used different approaches like involving the Wireless Sensor Networks (WSN) in this field, improving the performance of the traffic light system, using mathematical models to optimize the traffic; some of the studies used different sophisticated algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Fuzzy logic etc to optimize the traffic and reduce congestion.

Xiao Laisheng et al. presented a dynamic mathematical model for predicting the road traffic congestion using WSN [1] and after identifying congestion, control measure of redirecting the traffic to other lanes have been proposed. However this study does not address the direction aspects of a road in case of congestion. Major intersections of an area have been considered for the study; however, the prioritization scheme among the intersections is not incorporated in the model.

Several research have been conducted on adaptive traffic light control system for optimizing road traffic; some of the works include [2], [15], and [16]. The paper [16] does not have any dynamic mathematical traffic model and although [2] proposed a dynamic mathematical model with addressing the direction issues; however it also does not address the prioritization aspect among the intersections; it included all the intersections of a block or city. Similarly [15] also focussed on decentralizing the management of traffic lights between adjacent intersections using a static WSN. In reality all adjacent intersections of a block may not be of importance to the city authority, rather they have to take special care for reducing congestion in the major (important) road intersections.

So, as an overall observation, it is noticed that most of the studies in this road traffic control discipline focussed on a block of adjacent intersections; few of them adopted mathematical models, most of which are not dynamic model. In addition to that in most of the studies, the ‘direction’ aspect of the traffic is not taken into consideration while congestion in an intersection does not necessarily mean all directions are congested of that intersection. Also re-directing the traffic in case of congestion, needs to be done with a bottom-up approach; not in the top-down approach. Here, the term ‘*top-down approach*’ means some decision (e.g. to detour) being imposed from the traffic-authority on the vehicle drivers which not necessarily be suitable for them; on the other hand ‘*bottom-up approach*’ is referred to the process of initiation of a decision by the driver

themselves based on information regarding the road-situation provided by the traffic authority which may create frustration among the drivers of the vehicles.

In order to address these research-gaps in the road traffic management field, we have proposed a dynamic mathematical traffic model that will not necessarily include all the neighboring intersections of a block or the city; rather they are dispersed major intersections of the city. This dynamic model can provide with the instantaneous status of the traffic of the road-network. In estimating the cost function (penalty for congestion) the importance, termed as ‘weight’ of the directions¹ of all intersections have been used which are crucial factor in the prospect of optimized management in our model. Traffic from all eight directions are taken into consideration in our model for estimating the congestion status. Re-direction of traffic is handled in a bottom-up attitude where drivers of the upstream vehicles will have the freedom to choose which direction to detour and on what intersection; in order to avoid congestion, while periodically they are being provided with the congestion-information ahead of time before reaching the congested point. In this model, after detecting congestion, the monitoring-system will broadcast the congestion-information through a dedicated radio channel in order to achieve the goals of reducing congestion, increasing the network throughput and decrease the delay. On hearing the congestion-information of the down-stream path of their own destinations, the drivers of the upstream-vehicles will have enough time and scope to decide the route to detour to a better performing road-segment in order to avoid congestion and reduce delay on the road. Thus the man-machine interaction is assumed to contribute to the reduction of congestion, improve the traffic performance and enhance the optimal use of road-resources.

Our proposed model provides a solution for the city to reduce the level of congestion and optimize the existing resources without further investment for the expansion of road infrastructures. The scheme can monitor the important major road intersections in the city that tend to easily blocked; and it can periodically check the status of traffic (congestion level). It will be able to attract the attention of the city authority and the drivers on the road to the congestion status of the specific points of interest.

¹different directions of an intersection is referred as road-segments in the discussion in this thesis

1.3 Thesis Contribution

In order to reduce congestion in the road-network, expansion of road infrastructures may not be a sustainable solution to the city authority because of several issues like budget constraints, space constraints, high cost or the degradation of the environmental standards. As an alternative way, city has to consider the possible ways to optimize the existing transportation facilities and reduce the congestion level on the road. Our proposed model provides a solution for the city to reduce the level of congestion and optimize the existing resources without further investment for the expansion of road infrastructures. The proposed traffic monitoring scheme can monitor the major (important) road intersections in the city that are easily blocked. In order to avoid or at least reduce congestion in the road-network, we have developed the cost function using the prioritization scheme with the compliance of the importance of the selected intersections and their directions as well. The scheme will be able to attract the attention of the city authority and the drivers on the road to the congestion status of the specific points of interest. The system will periodically check the congestion status of the monitoring area. After detecting congestion, it will broadcast the congestion-information through a radio channel targeting the vehicle-drivers in order to achieve the goals of reducing congestion, increasing the network throughput and decrease the delay. This is a dynamic cost effective congestion control model; cost effective in the sense of importance of the intersection and the direction of the lanes. Here, we tried to deal with the worst case scenario for the non-neighboring intersections which are dispersed in different locations of the city.

If the city planners think of the option of expanding road-width in some sections of the road, or increasing the number of lanes in some locations, they will need to know which intersection is most affected by the congestion issue. This model will be able to help the city by identifying the culprit - which intersection of road the road network is the most worst-one, that needs improvement by using our prioritized cost function.

The contribution of this thesis as a whole can be summarized in the following:

- Development of a dynamic mathematical traffic model that can generate the instantaneous status of the traffic of the road-network (selected dispersed major intersections) of a city.
- Design of a scheme which will periodically check the congestion status of the mon-

itoring area and after detecting congestion, broadcast the congestion-information through a dedicated radio channel to inform the target audience (drivers of the upstream-vehicles) in order to improve road-traffic performance by achieving the goals of reducing congestion, increasing the network throughput and decrease the delay.

- Design of a scheme which enables upstream drivers to detour to a better performing road segment in case of congestion on their way, in order to avoid congestion and reduce delay on the road.
- Design of a model which provides a solution for the city to reduce the level of congestion and optimize the existing resources without further investment for the expansion of road infrastructures.
- Development of a cost function as a performance indicator of the road-traffic, using the prioritization scheme with the importance of the selected road intersections and their directions for the purpose to reduce congestion in the road-network.

1.4 Thesis Outline

The remainder of this Thesis is organized as follows: Chapter 2 contains the State of the Art where details review of related works have been presented. Chapter 3 explains the System Architecture of our model. In Chapter 4, we will demonstrate the simulation results of our proposed model and Chapter 5 will contain the conclusion and future works proposed. Additional information have been kept in the Appendix 1 containing some details comparison of the research work of [1] and our proposed model.

1.5 List of Publications

- Mustazibur Rahman, Nasir Uddin Ahmed and Hussein T. Mouftah, ‘City Traffic Management Model using Wireless Sensor Networks’, in Proc. 27th CCECE, May 2014 (Paper accepted for publication).
- Mustazibur Rahman, Nasir Uddin Ahmed and Hussein T. Mouftah, ‘Traffic Optimization in WSN-based Intelligent Transportation System’. Poster session presented at: 3rd Annual NSERC DIVA Workshop; 2013 Nov 12-13, Ottawa, Canada.

Chapter 2

State of the Art

2.1 Introduction

In this chapter we examine existing works relevant to road traffic management. It is worth mentioning that the subject of traffic management or congestion control is a vast discipline of research; so, making a comprehensive survey of the available work is outside the scope of this thesis.

In this chapter we will present the review of existing research works in the discipline of road traffic optimization. They will be categorized on the basis of used methods or techniques and scope of the study etc. Thus they will be divided into the groups of formal analytical methods i.e. mathematical models use, models using Wireless Sensor Networks (WSNs), genetic algorithm, area-specific traffic optimization, use of poisson distribution, petri nets, and non-formal analytical-based methods i.e. studies not focusing much on mathematical models and the finally, the conclusion.

2.2 Formal Analytical Methods

Different studies have used different techniques for optimizing road traffic, some of them adopted mathematical models. Few studies with the mathematical models have engaged the wireless sensor networks (WSNs), some of the studies have used dynamic models in their propositions while some used other perspectives. For the optimization of road traffic, some studies have also adopted other methods like Fuzzy Logic, Neural Network etc.

2.2.1 Mathematical Models with Wireless Sensor Networks (WSNs)

X. Laisheng et al. proposed a traffic flow congestion control model based on grey forecasting process which will monitor the important roads of a city which easily get congested. The traffic flow forecasting model is developed with the use of Adaptive GM (1, 1) model. One may know that in grey systems theory, GM(n,m) denotes a grey model, where 'n' is the order of the difference equation and 'm' is the number of variables. Thus, GM(1,1) refers to the First Order, One Variable Grey Model. The traffic model generates time series data by using the raw data collected by the WSN and along with time, it keeps updating the data through replacing the oldest data by the latest one, which is the speciality of the Adaptive GM Model [1].

The congestion control algorithm TRED (Traffic Random Early Detection) proposed in this paper, has been adopted from the concept of computer network's AQM (Active Queue Management) algorithm RED (Random Early Detection). It first calculates the average length of traffic queue and categorizes the situation of an intersection into one of the three stages of congestion, namely (i) Normal (No congestion), (ii) Non-compulsory (average queue length is between minimum-threshold, and maximum-threshold) and (iii) Compulsory stage. Depending on the stage (probability of scheduling vehicles) it opts for the source side traffic to be redirected. In the 1st case, no action is taken and in the 2nd case scheduling the source side traffic to other lanes with the mark probability P_a has been recommend and in the last case of a serious congestion, redirection to other lanes is a must for eliminating congestion. This paper displayed some reason graphically for the occurrence of the traffic congestion on the road in Figure 2.1.

Indeed, this model is based on the algorithm of ad-hoc network traffic where approximation of large number is okay but in case of road traffic it is very different in nature; and also it is a very old algorithm which has been modified a lot even for the network traffic and now is of almost no use. The network traffic does not face any intersection or traffic signals while the road traffic has to pass through them in large numbers; also the number of network packets pass through a Router is significantly large than the volume of traffic (number of vehicles) in an intersection. In addition to that, this model did not pay attention to the direction aspects of a road in case of congestion. An intersection may have lanes from all eight (8) directions and although some directions become congested, not necessarily all the direction's traffic are affected by that congestion and thus

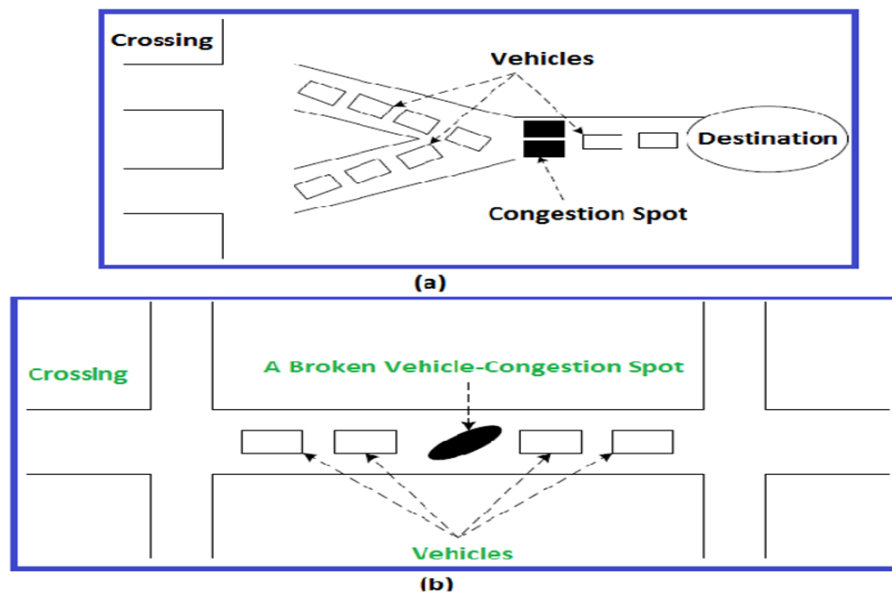


Figure 2.1: Reasons of Traffic congestion shown in [1], (a) different paths (b) a broken vehicle

do not need to be re-directed to another lane. The lack of direction issue may make this model too much generalized and also inefficient for an intersection. Another aspect is the top-down approach, adopted in this model while the bottom-up approach could be brought forward where, after receiving the congestion information, drivers could make informed-decision considering all kind of information like the distance of the destination, congestion status and possible waiting time of alternative paths etc. Also the prioritization among the intersection in respect of congestion avoidance is not addressed by this model. Lack of any simulation result of the proposed system also is an issue for the further need of research.

Moreover, top-down approach has been adopted in this model while the bottom-up approach could be brought forward. The scheduler is proposed to redirect the traffic to another lane which may cause disappointment to some drivers because of increased length of detour path. In order to fill this gap we have proposed a true dynamic model which can address this issue properly. The only approximation used in our model is our assumption of the arrival is Poisson process but it is not the homogenous ordinary Poisson process, rather the time-varying Poisson process. In our model we have proposed

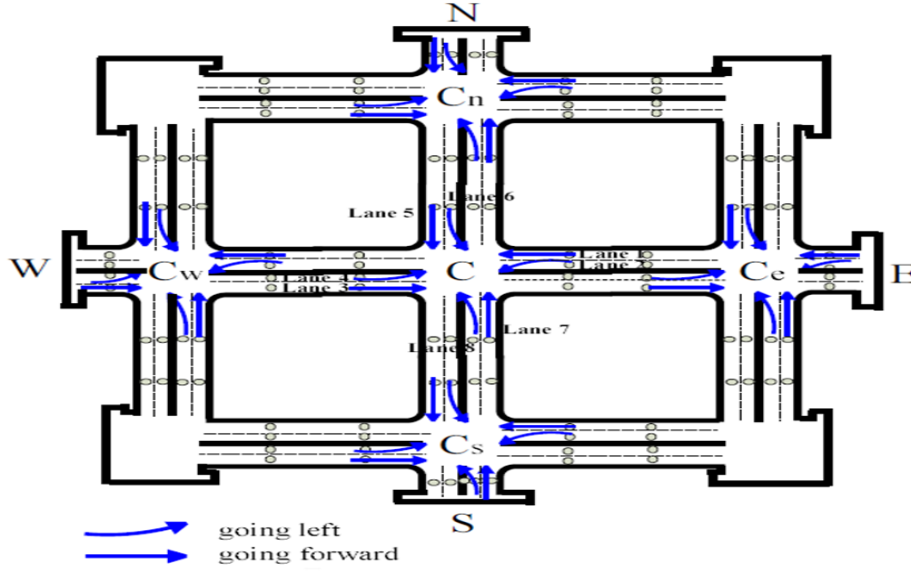


Figure 2.2: Selected road network and directions in [2]

the bottom-up approach, where the driver will choose the direction and the intersection where they will adopt the detour in order to avoid the congestion as the congestion status of the road-network will be broadcasted to all the drivers by radio system. Also, the issue of rescheduling the ‘source side traffic’ by the proposed system [1] will also face a big question; it will not be feasible if that lane (traffic to be redirected) is also congested. On the other hand, the drivers will have freedom of more than one option to choose the direction and the intersection to turn in order to reach the desired destination if they are aware of the congestion status of the intersections and directions towards their destination, in case the immediate lane is congested. Appendix 1 can be viewed for details of the analysis of the afore-said research work.

In [17], B. Zhou et al. mainly focused on optimizing the intervals of green lights in fixed sequences of traffic lights without considering the traffic flow characteristics and special traffic circumstances. The same authors have done some indepth work [2] for adaptive traffic light control system for multiple intersections using real-time traffic data collected by a wireless sensor network (WSN). The authors have developed couple of algorithms: Real-time Traffic Data Detection, Green Light Sequence Determination, ‘Light Length Determination’ algorithm etc. The first algorithm-estimates traffic volume, wait-

ing time, number of stops, traffic flow characteristic, hunger level, blank circumstance and special circumstance. In determining which case should be assigned the next green light, the second algorithm determines which of the 12 cases should obtain green light in the next second (t) in each intersection and for how long. The Light length determination algorithm uses local traffic volume and traffic condition from neighbor intersections. This paper has presented dynamic model to achieve 3 objectives: 1) increase the network throughput, 2) decrease the average delay and 3) average number of stops. To formulate the problem, the authors defined the following notations and assumed constant speed in all vehicles and same type of sensor nodes as in Table 2.1.

Zhou et al. considered a traffic network (Figure 2.2) with five intersections of four-directions (east, west, north, and south); one central intersection C and four minor intersections (C_e, C_w, C_n, C_s). Each direction has four lanes, two are approaching lanes (AL) (left and forward), two are leaving lanes which also are ALs of corresponding neighbor intersection [2]. Each AL is controlled by a traffic light which offers two signals, red for stop and green for go. It proposed 12 cases to rotate the green light in a pair of lanes in each case. When a vehicle enters the AL, the upstream sensor node (USN) detects its type, ID and length of vehicle ($L_{vehicle}$) and sends the detected data, such as the arrival rate, to the intersection sensor node (ISN) which detects the departure rate and number of vehicles is calculated using the following differential equation:

$$TVL(v, r, t) = \max\{TVL(v, r, t - 1) + AR(v, r, t) - DP(v, r, t), 0\} \quad (2.1)$$

In total, the authors have used 13 different equations in this paper for achieving their purposes.

In a similar work like this [2], Faye, Sébastien et al. developed distributed adaptive traffic light control algorithm [15] for decentralizing the management of traffic lights between adjacent intersections using a static WSN.

2.2.2 Dynamic Mathematical Models

The authors of [3] also presented traffic light control algorithm based on stochastic optimization. This paper used stochastic optimization for tuning the thresholds (Figure 2.3) which are used for the configuration of the traffic lights with the objective of maximizing

Table 2.1: Notations used in [2]

$P = \{1, 2, 3, \dots, 12\}, k \in P$	$L = \{1, 2, 3, \dots, 8\}, r \in L$
v : element of $set\{C, C_e, C_w, C_n, C_s\}$.	T : total time period.
Dst: distance between adjacent intersections.	
$AR(v, r, t)$: number of arrival vehicles in r of v at t .	
$DP(v, r, t)$: number of departure vehicles in r of v at t .	
$WTL(v, r, t)$: total vehicles' waiting time in r of v at t .	
$TV L(v, r, t)$: number of vehicles in r of v at t .	
$NSL(v, r, t)$: number of vehicles' stops in r of v at t .	

traffic flow. It categorizes congestion into 3 categories as low, medium, and high. The same authors modified their work later as [18] in order to use reinforcement learning (RL) algorithm with function approximation for traffic signal control. In this work, they succeeded to come out from the dependency on queue lengths and elapsed times at each lane and reduce computational complexity.

2.2.3 Mathematical Models with Other Perspectives

In the paper titled ‘Simulation and optimization of traffic in a city’, Marco Wiering et al. mainly focused on minimizing car waiting times in their Java based Simulator GLD, where their proposed RL (reinforcement learning) algorithm learns waiting times before traffic lights, and uses these estimates to set the traffic light configuration [19]. The GLD simulator is a grid based Infrastructures. An infrastructure consists of roads and nodes. A road connects two nodes, and can have several lanes in each direction. A node is either a junction (with traffic light) or an edge-node. An infrastructure is occupied by vehicles and traffic lights. Vehicles (Car) enter the edge-nodes in a certain rate at each time step and with an assigned destination (another edge-node). At a junction, a car decides to which lane it should go next according to its driving policy. Once a car has entered a lane, it cannot switch lanes.

For optimization, this paper has used value functions. $Q(s, l)$ is a value of a car in state s in the queue and light l set to red/green; a state is defined as $s = [p, d]$ where p is the car's position in the infrastructure and d is the destination address. A value function

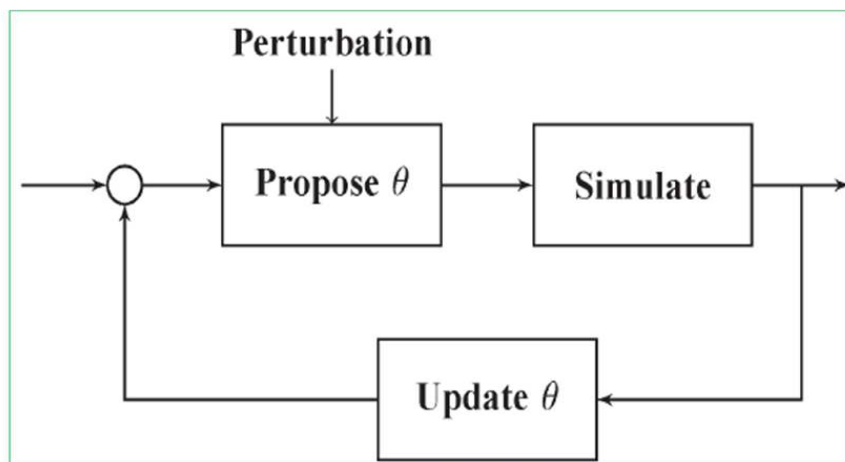


Figure 2.3: Operation of the threshold-tuning algorithm in [3]

is defined as:

$$Q(s, red) = R(s, s) + \gamma V(s) = 1 + \gamma V(s) \quad (2.2)$$

$$Q(s, green) = \sum_{s'} P(s, s') (R(s, s') + \gamma V(s')) \quad (2.3)$$

where $P(s, s')$ is the transition probability that the car goes to a next state s' which can also be s in case of congestion since the car will have to wait even in front of green light. The study used discounting factor $\gamma < 1$ which trades off immediate costs versus long-term costs and makes the Q-functions finite. Then $V(s)$ is defined as:

$$V(s) = P(green|s)Q(s, green) + P(red|s)Q(s, red) \quad (2.4)$$

where $P(l|s)$ with $l \in \{red, green\}$ is defined as the probability the light is on red/green when the car is in state s . Here, $V(s)$ estimates the average time a car has to wait until its destination address without knowing the traffic light decision. By definition $V(s) = 0$, if s is the cars destination address (and the car will be removed from the infrastructure).

For all cars the waiting time for a red light will be longer than the waiting time for a green light. Thus each car will have an advantage to set its light to green, based on its waiting time for red minus its waiting time for green. For each traffic node if the sum is estimated for all gains of cars standing in the queue for the traffic light, an optimal local

decision can be reached if traffic configuration A is chosen that sets the light to green for traffic lights i maximizing the cumulative gain:

$$A_j^{opt} = \frac{max}{A_j} \sum_{i \in A_j} \sum_{s \in queue_i} (Q(s, red) - Q(s, green)) \quad (2.5)$$

E. Brockfeld et al. have adopted stochastic optimization method and used the cellular automaton model for vehicular traffic in city networks. It considered city network as a simple square lattice geometry (Figure 2.4) and treated all streets and intersections equally, i.e., there are no dominant streets [4]. They used the geometric characteristics of the network (distance between intersections) to determine the duration of the traffic light cycles and tried to optimize the capacity of the road-network through the cycle times. The authors of this study focussed on global traffic light control strategies; specifically, synchronized traffic lights. In order to allow a more flexible traffic light control, they enhanced the existing city traffic model proposed and modified by Chowdhury and Schadschneider by adding a parameter in the model. This time offset parameter is assigned to every intersection in order to avoid simultaneous switching of the traffic lights and finally they have implemented a two-dimensional green wave with the help of this parameter. This work does not use any dynamic model though.

But in the research work of this thesis, we have considered a different type of road network, where the intersections are not neighbours and also we have adopted the weight-assignment process for different intersections in proportion to their importance to the City. Our model is a dynamic model and we developed the cost function (or penalty function) based on these weights which are proportionate to the importance of the directions and the intersections in order to optimize the traffic of a city.

A mathematical traffic flow model has been adopted in [5], where the traffic network of nine adjacent intersections is optimized. In their model, an “ER (Escape Rate)” factor is used for the traffic’s optimization purpose, which is estimated for each intersection. Moreover, their study is based on the Imperialist Competitive Algorithm (ICA); the flowchart is displayed in Figure 2.5. The idea of this optimization is - the weaker imperialists lose their colonies to more powerful empires and after loosing all colonies, the imperialist itself becomes a colony of others and thus only one powerful empire will be left. However, this model is based on intersections’ static information which may not

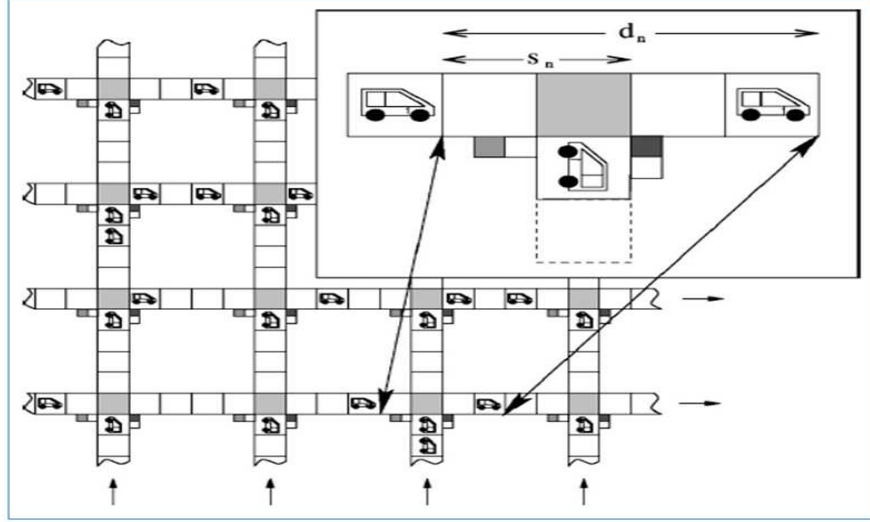


Figure 2.4: Snapshot of the underlying lattice of the model in [4]

be suitable for a dynamic traffic model. In addition, in an intersection they did not consider traffic coming from all the possible eight directions for the simplification purpose (considered only the major four directions). As a result, this model can not address the real time traffic properly. Also it takes care of the adjacent nine (9) intersections in one block; but in reality, all the intersections of a block or a city may not be important to the city authority in order to smoothen the city traffic situation. On the other hand, our proposed model will not consider all the intersections of the city, rather all the important major intersections; and in order to estimate the cost function, the importance of the intersections (weight factor used in our model) are crucial factor in the prospect of optimization in our model. Moreover, in each selected intersection in our model, traffic from all eight directions are taken into consideration for estimating the congestion and redirection of traffic for the purpose of smoothing the city traffic.

Yang et al. proposed mechanisms of Traffic control based on feedback control strategy for isolated intersections¹ to reduce average intersection delay and queue length. By running Field applications, they succeeded to reduce intersection average delay by 13.2%

¹Isolated Intersection: the Intersection at least 1.6km from the nearest upstream signalized intersection according to HCM, 2000.

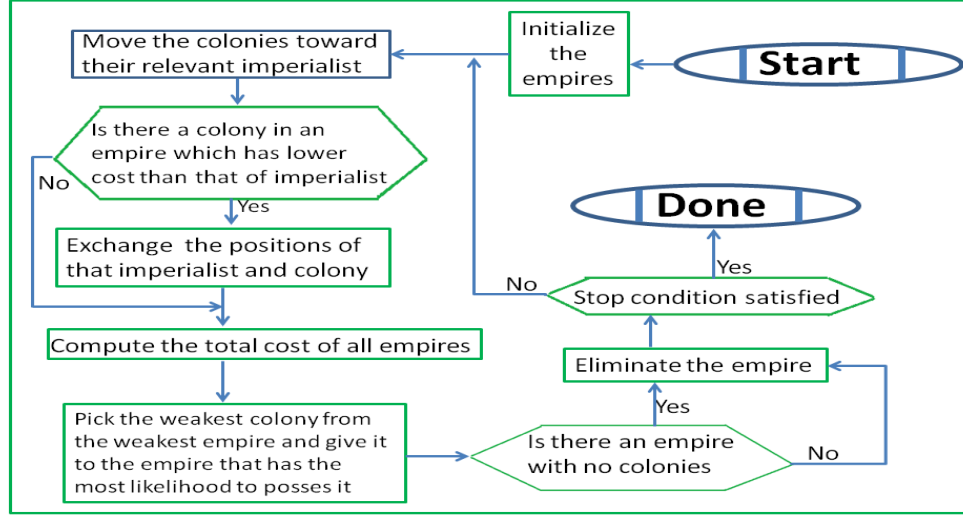


Figure 2.5: Flowchart of Imperialist Competitive Algorithm (ICA) in [5]

and maximum queue length by 100 meters in rush hours [20]. Intersection reserve capacity and degree of saturation were the direct control objectives in this study. It admits that for extending this strategy to multiple intersections, signal offset and other control parameters have to be included in the model.

In [16], without proposing any dynamic mathematical model, this research work attempted to optimize traffic light cycle time in order to optimize the road traffic. It used genetic algorithms (GAs), cellular automata (CA)-based traffic simulator, and Beowulf cluster as hardware to test the system. Inside the GA optimization process, traffic simulator creates new vehicles and this study uses the mean elapsed time² (MET) for optimization, while this factor may vary significantly in the real world. This paper developed the deterministic traffic simulator and compared the result with the result of stochastic non-deterministic optimization technique. In the simulation process, it used the origin-destination probability matrix for the vehicles, which does not seem to be very realistic since in reality, vehicles may change the route frequently during the travel time depending on the congestion status of the road. Also [21] proposed algorithm for scheduling automated traffic in a vehicular testbed.

²Mean time at the network: difference between the arrival and departure time of a vehicle (in the simulator environment)

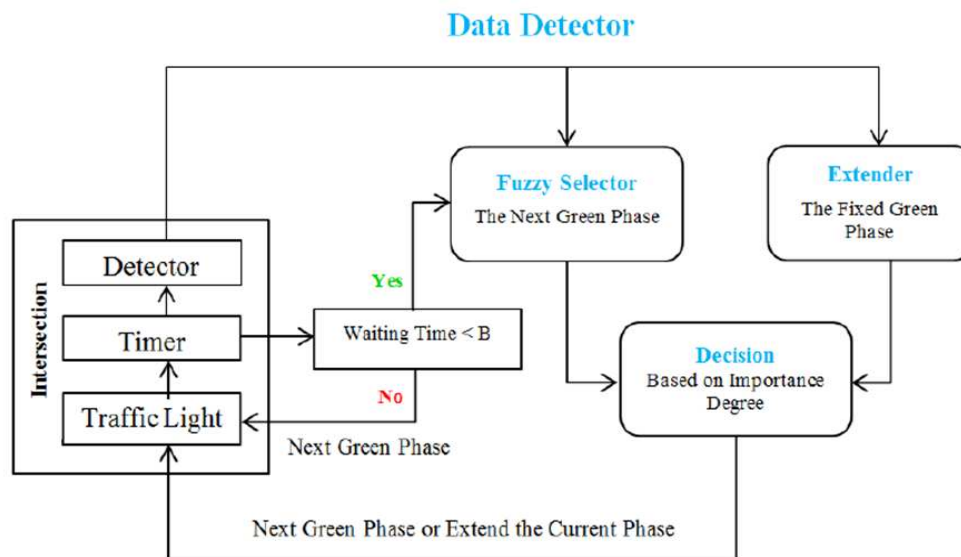


Figure 2.6: The designed fuzzy control system in [6]

2.2.4 Other Methods

Some researchers have used other methods i.e. Fuzzy Logic, Neural Network Etc. in order to resolve the traffic optimization issue in their research works. In a 2013 IEEE publication titled as “*Design and Simulation of A Fuzzy Controller for A Busy Intersection*”, Shahraki et al. have proposed an improvement in the traffic light system. This study has designed a traffic light control system based on fuzzy logic in order to reduce traffic waiting time and congestion on an intersection with two-way streets and left and right turn options [6]. They have defined three modules as stages: next green phase selector, green phase extender, and the decision stage. Considering different directions of a typical intersection this study has defined three phases for a green light. In the decision making process, it considers the following inputs ‘Length of Queue Num’ (number of vehicles behind a red light), ‘Length of Link Num’ (number of vehicles on a link between two intersection), ‘Length of arrival’ (average number of arrivals in green light) and ‘Waiting time’ (in red light). The module titled ‘decision stage’ makes decisions, based on the received inputs from the other two modules whether to change the green phase or to extend the duration of the green light of the current phase depending on the urgency, which is estimated on the values of the inputs. The output of this system is the indicator of the severity of the traffic condition of a specific link; i.e. the worse traffic

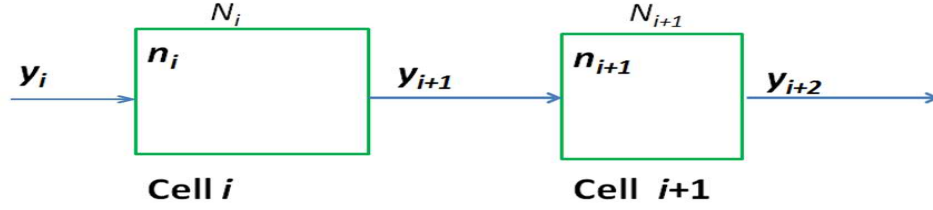


Figure 2.7: Cell Transmission Model Basic Building Block in [7]

gets the higher value and thus higher urgency for the related phase to be served. So, a higher value phase either gets the next green light or if it is already green, it's duration gets extended. Figure 2.6 displays their designed fuzzy control system.

G. Tong, et al. in [22] used the fuzzy neural network model(FNNM) strategy for predicting the traffic flow of real time traffic control systems. Gokulan et al. have proposed [23] a distributed multi agent-based traffic-signal control scheme using fuzzy logic. A thorough overview of traffic signal control strategies has been presented in [24]. The authors of [25] proposed an intelligent system for urban traffic control based on neural network and fuzzy expert system and implemented in VLSI.

2.3 Use of Genetic Algorithm

The authors of the paper Combined traffic signal control and route guidance: Multiple user class traffic assignment model versus discrete choice model showed the comparison of performance of the two models - Multiple User Class Traffic Assignment (MUC) Model and Discrete Choice Model by combining Hybrid Genetic Algorithm with cellular automata simulation to calculate travel time and optimize signal setting plan. They represented Traffic flow dynamics by Cell Transmission Model displayed in Figure 2.7. The same authors emphasized on the aspects presented by Claudio Meneguzzo i.e. the circular structure, practical relevance, and the definition of Combined Traffic Signal Control and Route Guidance (CTSCRG) problem in the discussion of their paper [7]. The circular structure of the interactions among flow-responsive signal control and user route choice is shown in Figure 2.8.

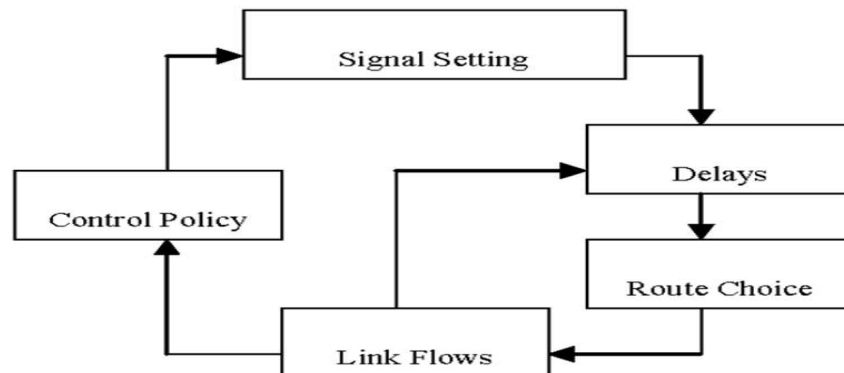


Figure 2.8: The Conceptual Circular Structure of Combined Traffic Signal Control and Route Guidance (CTSCRG) Problem [7]

In this paper, the authors have estimated perception error, which is a function of current travel time and can be represented by randomized travel time, following stochastic user equilibrium. They found important influence of the perception error of the drivers on numerical results related to traffic assignment.

R. Koggalage et al. Proposed a methodology of handling city traffic with the focus of traffic management by rearranging the traffic flow to minimize the interruption to the continuous traffic. They developed a software tool using Flow Control Mechanisms, Genetic Algorithms and Graph Theory in order to dynamically suggest improved traffic plans [8]. They expect the software tool to consider a large city map with details of all the junctions, roads and other useful information and provide the user a predefined city traffic plan to minimize the number of interruptions for the vehicle flow by taking into consideration of various parameters that are needed in practical situations. They have modeled road structure as a graph and then Genetic Algorithm (Figure 2.9) and Graph Theory are applied to find a better solution. Although with some sample data this tool was capable of suggesting a better solution but it has to be realized that theoretical junction status and the real-time is significantly different.

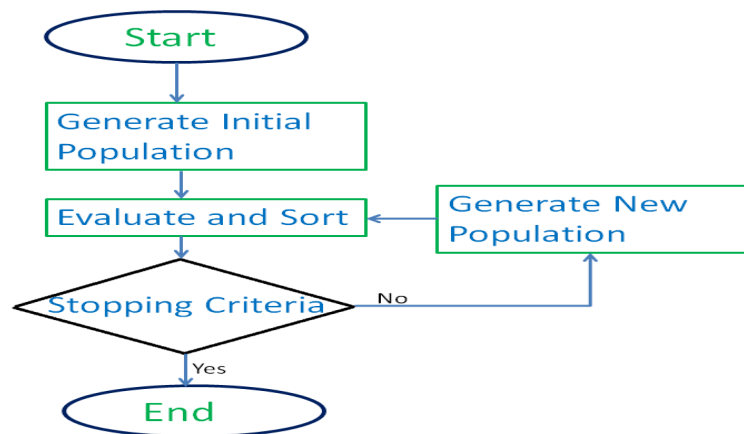


Figure 2.9: Basic flow chart of the Genetic Algorithm in [8]

2.4 Optimizing Area-Specific Traffic

In order to improve the maintenance of vehicular traffic in India, Jain et al. proposed a traffic light management system, [26] where an intersection's traffic light duration will be determined based on the information provided by the four (4) neighboring intersections. In this system, a weight is assigned to every direction depending upon the current number of vehicles and after every green light, this new data is sent to the neighboring nodes in direction of the green light. According to this weight received from all four neighboring intersections, each node's traffic lights will be turn on or off for each direction at that particular instance of time. They proposed to collect Speed, Final destination and Current route of the vehicle by information sharing through data dissemination techniques in VANETs; which does not seem to be easy to implement.

Hong Dai et al. in [27] presented a hierarchical architecture for urban traffic control and traffic guidance system in China with adaptive signal timing scheme using mathematical model for minimizing delay and congestion. This paper suggests the signal timing parameters should be regulated in a week interval according to statistical intersection delays. The authors of [28] and [14] focussed on optimization of area-specific urban traffic.

2.5 Use of Poisson Distribution

In the research paper [29] titled ‘A Novel Intelligent Traffic Light Control Scheme’, Cheng Hu and Yun Wang have proposed a mathematical model to improve the traffic light control system in order to reduce the average waiting time on a road intersection, where traffic is generated following the Poisson distribution. In the proposed approach, an intersection termed in this report as ‘road cross’ is modeled first with mathematical equations, treating the lanes as queues, vehicles as data packets; 12 states are defined for the traffic light for that specific intersection. According to the adopted PI algorithm in this study, weights are assigned to each of the states considering all relevant factors of the mathematical equations which include both upstream and downstream traffic information. The green light is switched on by rotation among these 12 states, based on the calculated weights of the states; i.e. if any state attains higher weight than the current state, then next ‘green turn’ will be switched to that state after completion of the assigned green time for the current state. (or The switching of the green light among these 12 states is decided based on their calculated weights; i.e. if any state attains higher weight than the current state, then next ‘green duration’ will be switched to that state after completion of the assigned ‘green time’ for the current state.) It ensures that each state will get a minimum amount of green time. In order to avoid state starvation³, red light duration of each lane is taken into consideration by utilizing an ageing method.

In the research work ‘*Traffic flow model for vehicular network*’ Nafi et al. have attempted to modify the queuing model and apply it for road traffic which follows Poisson distribution in order to estimate various traffic flow parameters under a fixed cycle traffic light system [30]. They established some mathematical relationship among various parameters where a road segment is considered as a service station with fixed cycle traffic signal system. They developed the mechanism to estimate the total delay over the period of one red phase and also other parameters such as average number of vehicles at any time in the system, or in the queue etc. They have simulated the traffic model in Matlab.

³If some serial lane’s upstream is always empty and its downstream is always full, certain traffic light states may not be tuned for a long time - this situation leads to state starvation.

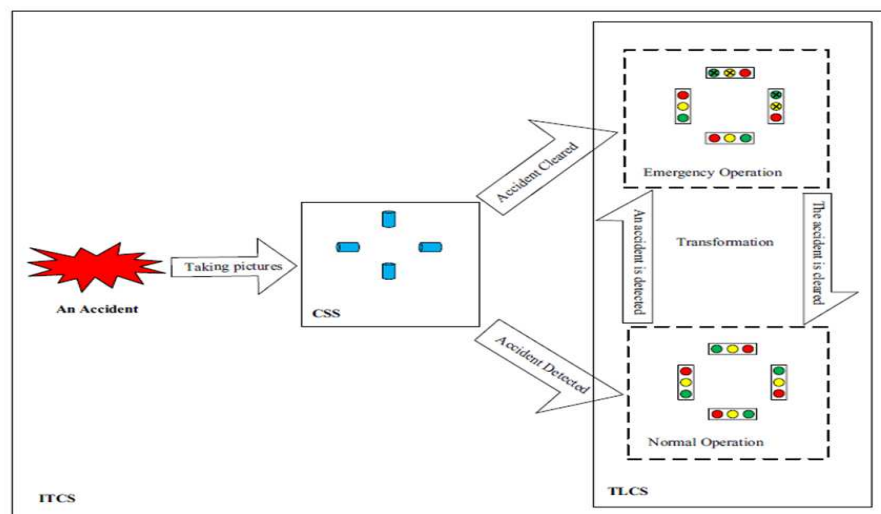


Figure 2.10: ITCS Architecture proposed in [9]

2.6 Use of Petri Nets

L. Qi et al. proposed and simulated a traffic control system (ITCS) for accident prevention and providing emergency response using Time Petri nets (TPN)s, Synchronized Petri nets (SPN)s and camera surveillance mechanism (Figure 2.10). This scheme has 2 subsystems: camera surveillance subsystem (CSS) and traffic light control subsystem (TLCS). The CSS uses surveillance camera to sense and detect the accident synchronously; and then according to the information of the accident, TLCS applies the appropriate measures in order to prevent the potential secondary accidents by establishing the cooperation between cameras and the traffic lights [9]. The authors have adopted reachability tree method to demonstrate the functionality of the model to enforce the traffic transition phases and verify their important properties.

Yi-Sheng et al. used the master-slave configuration to model urban traffic lights system using the synchronized timed Petri net (STPN). This paper focuses on using the STPN to model different schemes for urban traffic lights control system with eight-phase, six-phase and two-phase (Figure 2.11). The Authors have considered an urban traffic network with nine intersections (Figure 2.12) and divided the intersections into 3 categories: (1) main road intersection (marked as A); (2) minor road intersection (marked as B); (3) tertiary road intersection (marked as C).

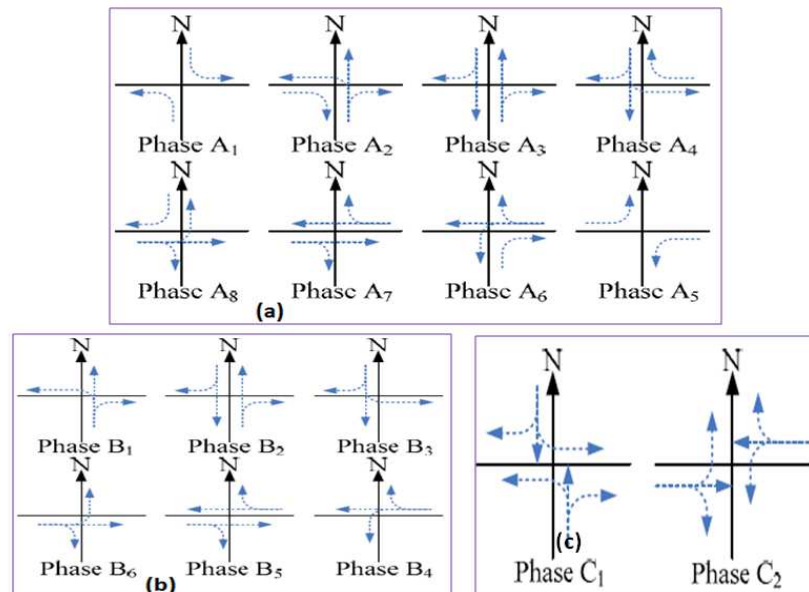


Figure 2.11: Green Light phase-transitions in [10]: (a)8-phases (b)6-phases (c)2-phases

Figure 2.13 displays a block diagram of the urban traffic network control system proposed in this study. Different timers have been included in this control system; a global timer will synchronize all events/transitions firing time and others to determine the status of the traffic lights. Coordinating the traffic lights of the nine intersections is the primary function of the master STPN model [10].

2.7 Non-Analytical-based Methods

Some research works have been performed to optimize road traffic relying on non-analytical-based methods. Yi et al. performed research on the topic of adaptive traffic signal control system and proposed a modified approach for over-saturated isolated intersections in an article titled ‘Improved Signal Control for Over-saturated Intersection’. They proved the deficiency of the existing short term traffic prediction based algorithms like COP (Controlled Optimization of Phases) by illustrating the fact that as these algorithms assign ‘green time’ to a phase considering only the volume of traffic and ignoring

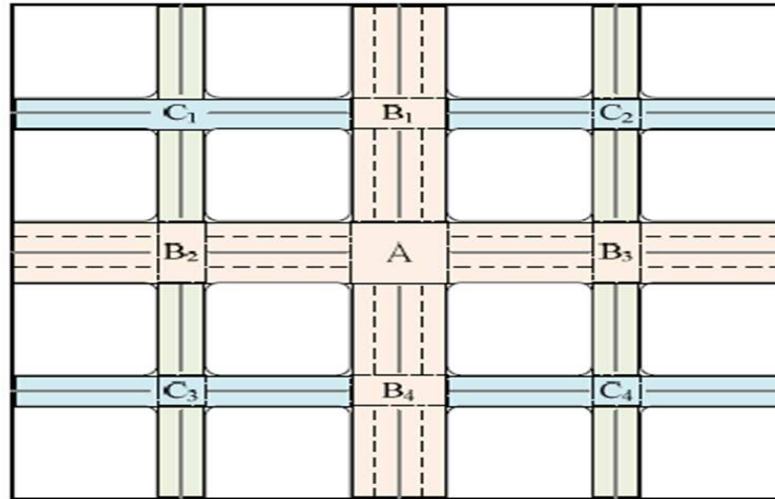


Figure 2.12: A traffic network with nine intersections in [10]

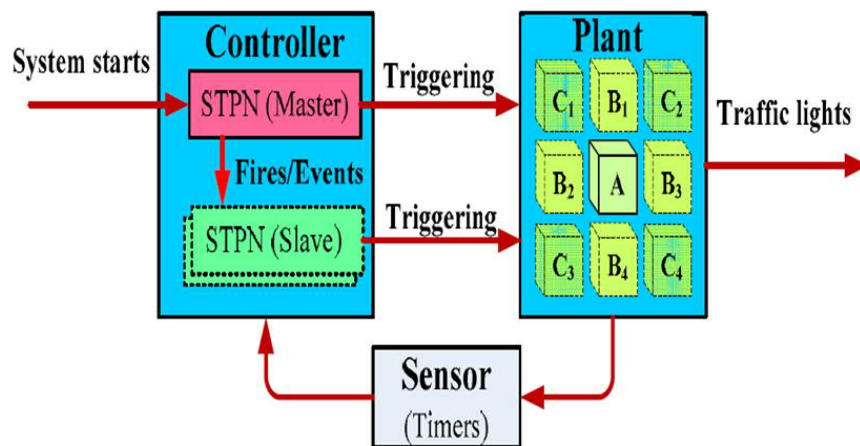


Figure 2.13: The block diagram of the urban traffic network control system in [10]

historical data, a phase with small volume of traffic may be skipped all the way and become stuck for very long time. They proposed an improved model EDEA (Enumerative Delay Estimation Approach) for the over-saturated intersections in order to overcome these deficiencies [31]. In their formulated model, they have added some additional factors in their equation including the ‘initial delay’ item for the phase selection process. They have presented the simulation result and proved their model to perform better than the existing signal control systems. The main contribution of this study was to improve short term traffic prediction method and delay estimation in system optimization.

T. Nadeem et al. developed TrafficView, under the e-Road project to provide the vehicles drivers with road traffic information for helping in situations like foggy weather, or finding an optimal route in a trip several miles long [32]. The authors of the paper [33] applied agent-based control concept for networked systems of control theory in traffic and transportation management. The authors in [34], proposed a scheme to use logic control in FPGA for Intelligent Traffic Control System. The authors of [35] presented a novel approach towards traffic congestion identification based on vehicle trajectories. Similar works have been performed in [36] and [37].

2.8 Conclusion

In this chapter we presented relevant studies parallel to our work. The main focus of the research works and their methods of optimization were the points of interest in this discussion. Several advantages and disadvantages of each research work and its technique described are also illustrated above. We will discuss the system model in the next chapter, how it is implemented and how it works will also be included.

Chapter 3

System Model

3.1 Introduction

This chapter outlines our proposed road traffic monitoring scheme, its components, how it is implemented and how it works. The discussion will include the road traffic network used in this study, system architecture of the proposed scheme, adopted traffic light system, movement of the traffic monitoring data, assumption of classical poisson process for traffic data, other assumptions, mathematical terms of the city vehicular traffic model and estimating the cost function and finally conclusion.

There are number of problems to use the wired devices for monitoring road traffic in a city environment where continuous expansion is obvious. Traffic congestion has dynamic features due to different time and different place. It is not appropriate to install wired traffic monitoring equipment in fixed locations for those systems with dynamic features. Wireless sensor networks is an information monitoring and transmitting network that can be applied to traffic flow monitoring and forecasting system [1]. In this thesis, we have proposed a traffic monitoring network based on wireless sensor network that is applicable to all types of city environment. In this connection, we have proposed a dynamic mathematical traffic model which can provide with the instantaneous status of traffic of the road-network and estimate the performance through a cost function.

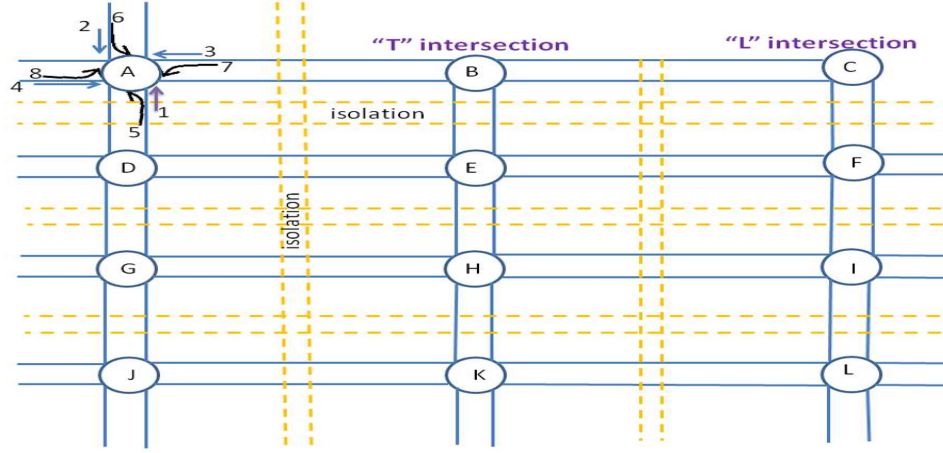


Figure 3.1: Symbolic map of selected intersections (not neighbours)

3.2 Road Traffic Network

This research work considered important or major intersections of a city. Since the idea of ‘important intersection’ may vary from city to city, depending on several factors like population, geographical size of the city, socio-economic infrastructure and so many other factors; the issue of defining and quantifying the major intersections will finally depend on the specific city authority at the time of implementation. As a representative mid-sized city, this thesis considered a traffic network with twelve major (important) intersections across the city with eight (8) directions of four major directions: north, south, west, and east, and four minor turning directions: north-west, south-east, south-west, and north-east (the symbolic map and the direction aspects are shown in Figure 3.1). All the intersections are assumed to have traffic arrivals following Poisson Distribution as they are dispersed intersections at different locations in a city (i.e. they are not necessarily neighbours). At maximum, an intersection may have lanes from all these above 8 directions and some intersection may have lanes from less number of directions but at least from 2 directions which makes it as an ‘L’ or ‘T’ junctions.

In general traffic includes both pedestrians and the vehicles but for the simplicity of the model, our focus is kept limited only to the movement of the vehicles on the road. The traffic monitoring scheme proposed in this study uses WSNs to monitor city transport vehicles and is indeed applicable to all types of city environment. The system can monitor the important road intersections in the city that are easily blocked; and it can

periodically check¹ the status of traffic (congestion level). In order to avoid congestion in the road-network, we have developed the cost function using the prioritization scheme with the compliance of the importance of the selected intersections and their directions as well. After detecting congestion, it will broadcast the congestion-information through a dedicated radio channel to inform the target audience (drivers of the upstream vehicles) in order to achieve the goals of reducing congestion, increasing the network throughput and decrease the delay.

3.3 System Architecture

This proposed traffic monitoring scheme will use the WSNs to capture data from important road intersections in the city. This data will be gathered to a Cluster-Head node from the surrounding ordinary nodes and be passed to a Base Station which will complete multi-hop relay transmission to a Gateway node. Gateway nodes will convert wireless signals into wired signals and send the combined data to the Monitoring and Control Centre (MCC) by using the internet. The MCC database will combine data from all the road-network elements and periodically analyse the data and evaluate the status of traffic (congestion level) in all major intersections; if congestion is detected, it will broadcast the information of the congested nodes through a radio channel so that the target audience can take appropriate decision for Detour.

When a vehicle enters the AL (approaching lane), the upstream sensor node (USN) detects its type, ID and length of vehicle and sends the detected data, such as the arrival rate, to the intersection sensor node (ISN) which detects the departure rate. The system architecture is illustrated in Figure 3.2.

¹The duration of this period will vary considering several factors like time of the day (rush hour, slack hour etc), type of city (large, medium, small), type of road-network and other factors. Therefore, it is left out from this discussion for the phase of real-time implementation by the city authority, implementing the scheme.

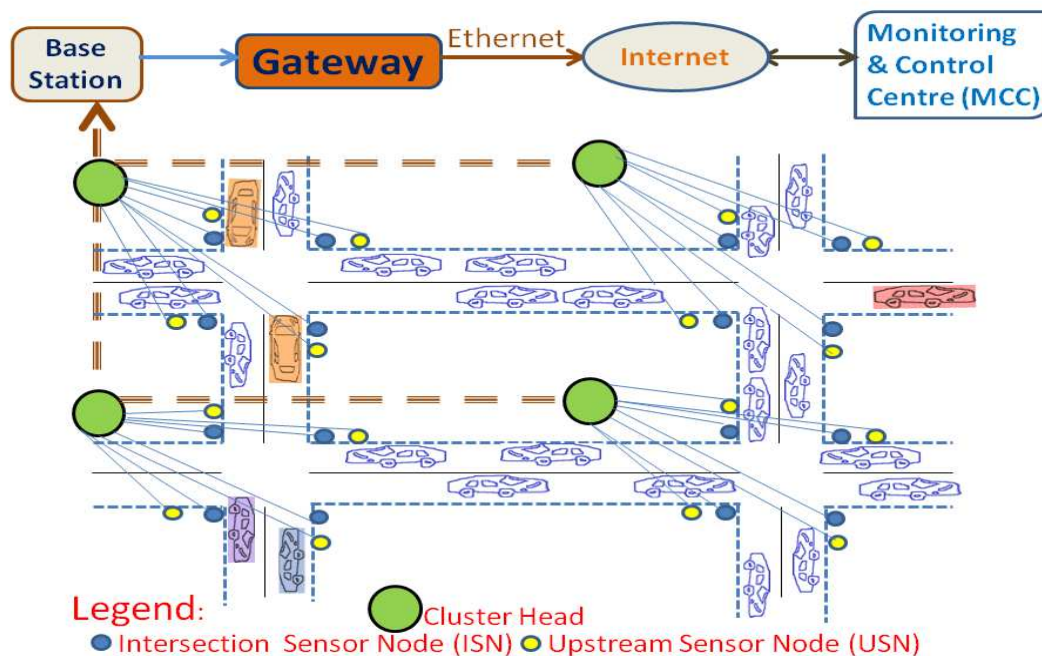


Figure 3.2: System Architecture for proposed Traffic Monitoring Network

3.3.1 Traffic Light System

In order to keep the computation simpler, we assumed the Traffic lights at each Road Intersection to be managed by the city in a static fashion, although ATLC (Adaptive Traffic Light Control) is already in use in several cities around the globe. The green light is assumed to revolve within 12 cycles² to display green light for controlling the intersections (Figure 3.3). These 12 cases rotate the green light in an intersection for twelve non-colliding pair of lanes sequentially during an iteration period of this scheme [2]. It is to be noted that before implementation of these green-light sequences, discussion might be needed about the acceptability of some of these cases like case 3, 5, 6 and 10 in the light of the law perspectives in the developed countries like Canada.

²Traffic light cycle rotates in a finite sequence of states of green and red iteratively for a fixed period of time (each iteration period of this scheme).

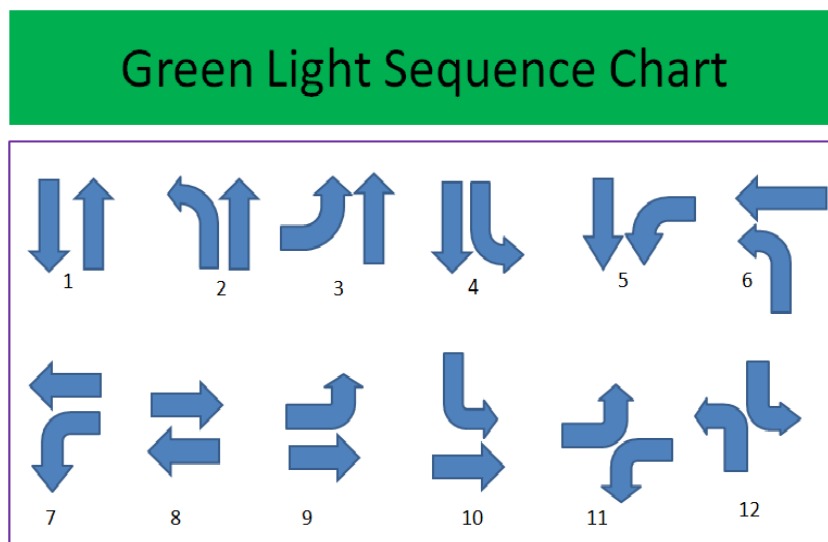


Figure 3.3: Twelve (12) cycles of Green Light with specific pair of directions

3.3.2 Traffic Monitoring Data Movement

Proposed Traffic monitoring scheme is a WSN based multi-hop relay network with hierarchical architecture [1]. It is composed of ordinary nodes, Cluster-Head nodes, Base Stations, Gateway nodes and Monitoring and Control Centers (MCC) etc. Ordinary nodes complete traffic data acquisition. Cluster-Head nodes gather data from the surrounding ordinary nodes and send the data to the base stations who complete multi-hop relay transmission. Base Stations further send the data to the Gateway nodes who complete the conversion between wireless signals and wired signals and realize internet access. The MCC completes the comprehensive data processing and upon detection of congestion, redirects the source side traffic to better running lane/direction by broadcasting the info of the congested nodes to the target audience. In calculating the congestion level on each direction of the important intersections MCC compares the current traffic volume with the threshold number of vehicles. When congestion is detected, the system will broadcast the required info to the target audience (who are registered to the Scheme) using the radio system.

3.3.3 Assumption of Classical Poisson Process

We assumed that the intersections chosen for this study are dispersed across the whole city and they are neither necessarily neighbors nor related to each other. In addition to that as they are major intersections of a city (moderately big sized), the number of traffic arrivals ($x(t_k)$ where $k \in 0, 1, 2, 3, \dots$) in general can be categorized as large in volume and for the non-overlapping intervals, these numbers ($x(t_k, t_{k+1})$, and $x(t_{k+3}, t_{k+4})$) are independent. The inter arrival-times are independent and obey the exponential distribution ($\exp \lambda$). Thus, the traffic arrivals in these intersections follow poisson distribution since the 2 main criteria for this probability distribution (events to be independent and large in size) are observed here.

In general, a random variable X is said to be a Poisson random variable with parameter $\lambda > 0$ if for $n \in \{0, 1, 2, \dots\}$, and $P\{X = n\} = e^{-\lambda} \frac{\lambda^n}{n!}$ of a probability distribution whose mean and variance are identical, i.e. $(\bar{X}) = V(X) = \lambda$. In this thesis we have assumed the Poisson Random Process (not the Poisson Random Variable), where $\{X(t), t \in J\}$ and $\lambda(t) = E(X(t))$. $P\{X(t) = n\} = \frac{e^{-\lambda(t)} (\lambda(t))^n}{n!}$. Therefore the traffic arrival rate in these intersections is expected to behave as a stochastic process and follow Poisson Distribution. The Hourly mean arrival rates (λ_h), are illustrated in Figure 3.4.

3.3.4 Other Assumptions

- The departure rate is considered to be deterministic since the road network and the green-light sequences are assumed to be deterministic aspects, but during the 24 hours time of a day if the traffic becomes low or ‘None’, then the determinability of the Departure rate will not hold.
- We assumed randomness of traffic from different directions.
- Effects of pedestrians and bicycles are not considered in our discussion.
- Fixed-length or static green-light system is assumed for this study. But indeed most of the city intersection’s duration of green lights is adaptively maintained. In future, if someone is interested, research can be done with the adaptive green light duration with the proposed model.

3.4 City Vehicular traffic Model

The following City Vehicular traffic Model is proposed in this current research works. The items involved in this model are the WSN, it's sensor nodes, the MCC, Intersections of road networks and vehicles, traffic lights in the intersections, the drivers of the vehicles etc.

Features of the Model

- It's a dynamic mathematical model.
- Choosing the right threshold factor α_s is a control in this model which is to be done by the city authority.
- This model presents the status of traffic at intersections (selected ones in a city) at any instance of time.
- It's an instantaneous process.
- City responsible can observe or monitor if any time, congestion is developing at some Intersection.
- It's a Man-Machine interaction model.
- Drivers of vehicles are expected to understand the language and instructions.
- Traffic is assumed to be Non-homogeneous.
- Dynamics of vehicles are not considered in this model (No mechanical aspects are considered).
- Weight (w) is proportionate to the importance of the road-segment.
- Choosing the right non-compliance factor θ is also a control here.

3.4.1 The Vehicular Model

Following dynamic equation is to determine the quantity of traffic and the congestion status of the road traffic in the selected major intersections of a city:

$$\begin{aligned}
 x_{id}(t_{k+1}) = & x_{id}(t_k) + I_1(x_{id}(t_k) < l_{id})p_{id}([t_k, t_{k+1}), \lambda_{id}(t_h)) \\
 & + I_2(c_{id} \geq x_{id}(t_k) \geq l_{id})p_{id}([t_k, t_{k+1}), \theta_{id}, \lambda_{id}(t_h)) \\
 & - \beta_{id}(t_{k+1} - t_k)I_3(x_{id}(t_k) > 0, L_{id}(t_k) = 1)
 \end{aligned} \tag{3.1}$$

Set of Important Intersections $Z \in N\{i = 1, 2, 3, \dots, N \text{ and } d = 1, 2, 3, \dots, n_i\}$. Here, 'x' is the number of vehicles in d^{th} direction at i^{th} intersection where 'i' is the index of intersection and $i=1,2,\dots,N$ and 'd' for the direction, where $d=1,2,\dots,n_i$; and t_k is the discrete points in time where, $k= 1,2,3,\dots,1441$ minutes (end of the day). I_1, I_2, I_3 are indicator functions; I_1 indicates if the traffic of previous time point (t_k), is less than the threshold capacity (l_{id}), I_2 evaluates if the traffic is equal to, or greater. In these two cases, traffic arrival (p_{id}) vary; in the 2nd case, it's reduced and becomes a function of the non-compliance factor θ_{id} , time and mean arrival rate $\lambda_{id}(t_h)$ while in the 1st case non-compliance factor θ_{id} , doesn't have any impact. The 3rd indicator function (I_3) checks if the road-segment has any traffic at the time of green-light, where L_{id} is the traffic-light indicator with value of 1 for green light and 0 for red light.

Notes about the equation

- Above equation estimates Number of vehicles at i^{th} intersection, towards the d^{th} direction; where $i=1,2,\dots,N$ and $d=1,2,\dots,n_i$ at discrete points in time, t_{k+1} , $k= 0,1,2,3,\dots,t_{end}$ (end of the day) and $\theta \in (0, 1)$.
- here $x_{id}(t_{k+1})$ is the number of vehicles in the d^{th} direction of i^{th} intersection at the discrete time point t_{k+1} .
- here $x_{id}(t_k)$ is the number of vehicles in the d^{th} direction of i^{th} intersection at time t_k .
- c_{id} is the capacity or length (expressed in number of vehicles) of the road-segment in the d^{th} direction of i^{th} intersection (i.e. maximum number of vehicles it can hold).

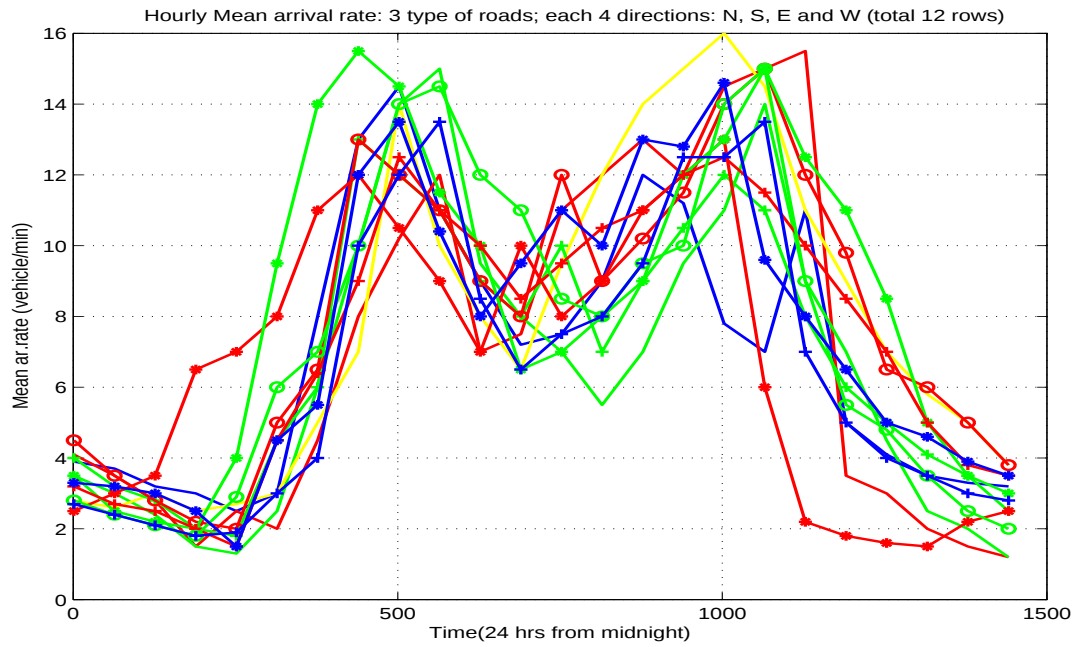


Figure 3.4: Hourly Mean Arrival Rate (λ) for the whole Day for 3 types of road and each with 4 major directions (12 different road-segments)

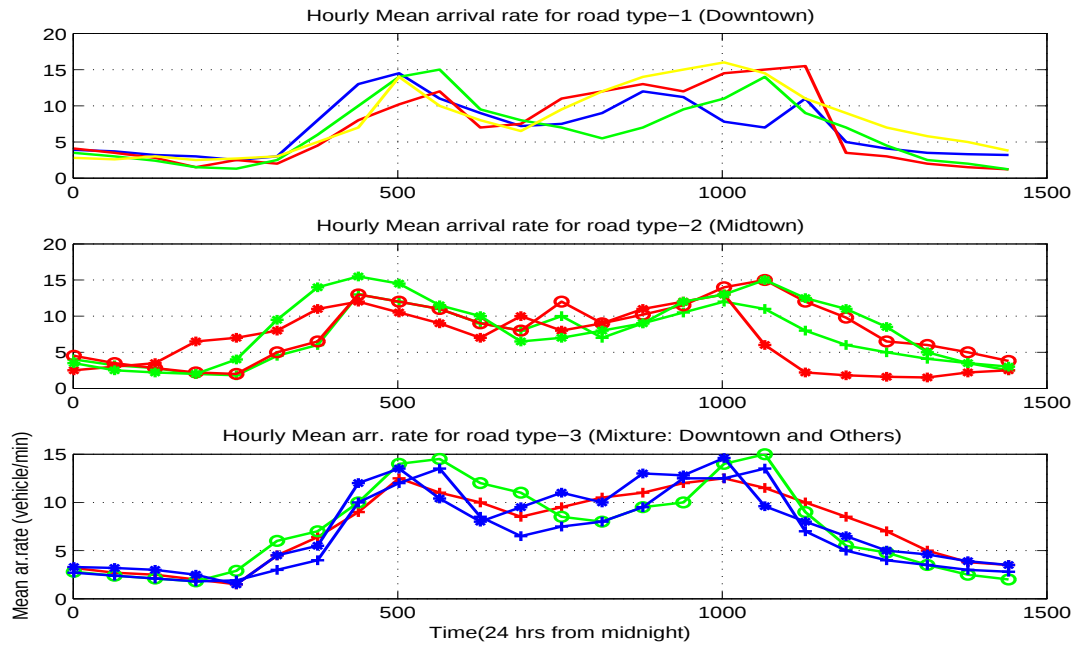


Figure 3.5: Hourly Mean Arrival Rate for 3 different types of roads during the whole Day (24 hours from midnight)

- here l_{id} is the threshold capacity of the road-segment in the d^{th} direction of i^{th} intersection! Indeed, it's a vector of thresholds and $d=1,2,\dots, n_i$ and $l_{id} = \alpha_s * c_{id}$; α_s is the threshold factor chosen for simulation from the set of threshold-factor values, by the city authority and a control in this proposed model.
- p_{id} is the amount of traffic arrival (following Poisson Distribution) in the d^{th} direction of i^{th} intersection during the sample period t_k to t_{k+1} and $\lambda_{id}(t_h)$ is the mean arrival rate per unit time (which stays same in each hour). The Hourly mean arrival rates, are illustrated in Figure 3.4.
- θ_{id} is Non-compliance factor, which is also a control here. When the d^{th} direction of i^{th} intersection becomes congested, the monitoring system will broadcast the congestion information in the dedicated radio channel and the down-stream drivers are expected to re-route to a better performing route in order to avoid the congested situation. As a result, the arrival rate in the congested road-segment is expected to be reduced by the Non-compliance factor θ_{id} .
- β_{id} is the deterministic departure rate of vehicles from the d^{th} direction of i^{th} intersection.
- $L_{id}(t_k)$ is the Green Light Indicator; i.e. if the green light is ON, in the d^{th} direction of i^{th} intersection at the discrete time point t_k .

3.4.2 Estimating Cost function

The weighted congestion cost of the entire traffic system is given by the equation:

$$J(l) = E\left(\sum_{k=1}^{t_{end}} \sum_{i=1}^N \sum_{d=1}^{n_i} [w_{id} I_1(x_{id}(t_k) \geq l_{id}) + \kappa_{id}(t_{k-\gamma}, t_k) * (\phi_{id})(t_k) * w_{id} I_2(x_{id}(t_{k-\gamma}) \geq l_{id}, L_{id}(t_{k-\gamma}, t_k) = 1)]\right) \quad (3.2)$$

- In the above equation two indicator functions (I_1 and I_2) have been used to evaluate the congested status of road traffic. I_1 evaluates if the initial congestion occurred and I_2 checks if the continuous congestion has formed. Congestion is defined if the amount of traffic in the d^{th} direction of i^{th} intersection, counts equal or larger than the threshold capacity of the lane i.e. $x_{id}(t_k) \geq l_{id}$. This situation of traffic congestion will activate the first indicator function (I_1) above.

- If the congestion persists for more than the duration of a green-light cycle period ³ in the d^{th} direction of i^{th} intersection, then continuous congestion is defined; which will activate the second indicator function (I_2) above. In other words, if a lane stays continuously congested between two or more light-cycles during the discrete time points $t_{k-\gamma}$ to t_k , where $\gamma \geq 12 * T$, the value of Continuous congestion counter is $\kappa_{id} = \gamma$, otherwise $\kappa_{id} = 0$. As a compensation process, cost is estimated by multiplying κ_{id} with the excess traffic ϕ_{id} at t_k and the weight w_{id} according to the value (either zero or one) of the second indicator function (I_2).
- Indeed, the second indicator function (I_2) evaluates 3 different statements: first, if the d^{th} direction of i^{th} intersection is congested at the discrete time t_k , secondly, if the congestion is existing continuously between two or more light-cycles during the discrete time points $t_{k-\gamma}$ to t_k , where $\gamma \geq 12 * T$, and finally if the traffic light was green during the period of $t_{k-\gamma}$ to t_k .
- Purpose is to minimize cost $J(l)$ by choosing the right threshold value “l” so that $J(l)$ is minimized.
- The primary goal of this work is to develop a methodology for optimized control of city traffic by reducing the congestion level and delay in driving and improve (optimize) the throughput of the road-network.
- Traffic light cycle: the finite sequence of states e.g., green and red light runs iteratively within 12 cases (Figure 3.3).

The proposed model is better illustrated by Example 1.

Example 1 (Total cost) *We already saw the weighted congestion cost equation of the entire traffic control system in eq. 3.2. Following Table 3.1 shows little details of the items of the total city cost calculation. Twelve rows indicate cost for the twelve selected intersections and bottom row is the Total cost (city cost) estimated through the summation of all the 12 rows. Each column is related to a value of Threshold factor (7 of them chosen in this study) which in real-life application stage, has to be chosen by the city authority. Each item (cost of intersection) in a row is indeed calculated by adding costs for all the 8 directions of that i^{th} intersection. Cost for each direction (d^{th}) is calculated*

³12 iteration periods of the static traffic light sequence assumed in this study

according to the above equation: when length of traffic of a road segment reaches or exceeds the threshold capacity, congestion is detected and as a compensation process cost is imposed and calculated by adding the weight (w_{id}) depending on the positive value of the first indicator function. When the congestion continues from one time instance for a whole traffic light cycle period (12 iteration periods or $12 * T$), the second indicator function becomes active and the increased penalty is added to the cost by adding the second term of the above equation by multiplying the time of continuous congestion $\kappa_{id}(t_{k-\gamma})$, (where $\gamma \geq 12 * T$) with the quantity of excess traffic ($\phi_{id}(t_{k-\gamma})$) and the weight (w_{id}). This process is simulated for the period of 24 hours (1440 minutes); at each iteration period ($T=1$ minute in the current simulation), the cost is estimated and costs are added for all the iterations, and the cost in the following Table 3.1 applies for the total iteration period i.e. 24 hours cost.

As a numerical example: let's consider intersection number 2, there are 8 directions, and at time t_{25} , according to our model, street-lights are green in direction 1 and 2; if the traffic in these two road-segments are $x_{21}(t_{25})=65$ and $x_{22}(t_{25})=45$ respectively and their total capacity c_{21} and c_{22} , are 85 and 55 respectively. For the threshold factor (α) of 70%, threshold capacity (l_{id}) are 60 and 39. According to our model, congestion is defined when traffic of a road-segment exceeds the threshold capacity or becomes equal. In that case, congestion has occurred at direction number 1 of intersection number 2 (since $65 > 60$ i.e. $\text{traffic} \geq \text{threshold}$). As a result cumulative congestion timer κ_{id} will be activated and will be incremented by an iteration period ' $T=1$ ' and the value of excess traffic ($\phi_{id}(t_k)$) in this direction is $(65-60)$ 5. Since the congestion started at this discrete time point of t_{25} , the value of the first indicator function (I_1) for direction number 1 of intersection number 2 will be 1 and the value of I_2 will be 0 as there is no continuous congestion yet.

In our model with static traffic light system, the time-length of the green traffic light sequence cycle is 12. In each of these 12 cases, two non-colliding pair of directions of an intersection get green light during an iteration period. Thus, after every 12 time-intervals (one light-cycle) each direction's light status is repeated and during each cycle a direction gets 3 green times either consecutively or with gaps. According to the adopted static sequence, the afore-said direction number 1 gets green light consecutively at discrete time points t_{25+1} and t_{25+2} , and in the next traffic light-cycle at $t_{25+12}=t_{37}$, if the traffic still remains larger than or equal to the threshold capacity (l_{21}), then continuous congestion is defined. For example, let's assume the amount of traffic at t_{37} is still the same i.e.

Table 3.1: Total City Costs by Threshold factors with Control Scheme

Intersection	thr-1	thr-2	thr-3	thr-4	thr-5	thr-6	thr-7
1	8017.5	6573.8	4648.8	3453.8	3150	2066.3	857
2	12071.3	11815	10385	8291.3	6542.8	5105.5	2942.5
3	12162.5	12162.5	12162.5	11173.8	8600	6186.3	3697.5
4	14596.3	14596.3	13696.3	11152.5	9500	5480	4147.5
5	11127.5	11127.5	11127.5	10915	6855	6284.4	4430.6
6	13828.8	13828.8	10600.6	9765.6	9171.3	7422.5	4526.9
7	15900	15900	14786.9	11970	7945.6	6554.4	4405
8	13333.1	13333.1	13208.1	11932.5	10045.6	6630	2801.3
9	15538.8	15538.8	15538.8	9166.3	11765.6	8947.5	5115.6
10	13241.3	13241.3	13241.3	13241.3	9637.5	9001.8	5336.3
11	12792.5	12792.5	12792.5	11093.8	10019.4	7203.8	5016.3
12	10988.8	11170	9857.5	9507.5	7216.8	5972.5	4401.9
Total (City)	153598.1	152079.4	142045.6	121663.1	100449.5	76854.8	47678.3

$x_{21}(t_{37}) = 65$. In this case, the value of $\kappa_{id}(t_{k-\gamma})$ at this stage becomes $\kappa_{21}(t_{37}) = 12$. As this value has become equal to the length of the traffic light-cycle (12), this fact will activate the second indicator function I_2 to the value of '1'. Thus the cost for this direction number 1 of intersection number 2 will be calculated as $(30*1)+(12*5*30)*1 = 30+1800 = 1830$. This was the cost for a discrete point of time $x_{21}(t_{37})$, but before the t_{37} , the costs for this direction for each time-points t_k will be just the value of the weight $w_{21} = 30$. In the same fashion cost is calculated in our simulation for all the time points of the simulation period of 1440 minutes (24 hours) and adding the costs for all the 8 directions, cost for an intersection is estimated and then combining all the intersections (included in the model), city cost is obtained. The ultimate target is to minimize the cost in order to achieve the optimized management of traffic of a city or a metropolitan area.

Example 2 (Total number of cars) The dynamic mathematical equation 3.1 estimates the congestion status of the road traffic at a discrete point of time. For a numerical example, let's continue with the above example of intersection number 2 and two of its direction's traffic. Among the 8 directions, at discrete time point 25 or t_{25} , traffic in

direction 1 and 2 is found as $x_{21}(t_{25})=65$ and $x_{22}(t_{25})=45$; their respective total capacity c_{21} and c_{22} , are 85 and 55, and threshold capacity (l_{id}) are 60 and 39, using threshold factor⁴ (α_s) 70%. In the next iteration point of time at t_{26} how is the traffic is generated? As the above equation says, it will be the sum of the existing traffic and the new arrival which is assumed to be dependant on the above discussed congestion issue. As we have seen that direction number 1 has already got the congestion during t_{25} , so the first indicator function will be false and thus second major term of the equation won't be effective and the third term will come in use because of the positive value of second indicator function and arrival (using Poisson distribution) will be calculated using the non-compliance factor θ_{id} i.e. $\theta_{21} = 0.20$ and arrival at t_{26} will be $p_{id}([t_k, t_{k+1}), \theta_{id}\lambda_{id}(t_h) = (4 * 1) * 0.2 \simeq 1$, and since at the time t_{26} , this direction has the green light (2nd green-phase within a light cycle) and existing traffic is available, the third indicator function will also have positive value and departure will take place by the amount of $\beta_{id} = 1$. Thus the new quantity of the traffic at t_{26} will be $65+0+1-1=65$. In direction number 2 since there was no congestion and no green light at t_{26} , only first of the 3 indicator function will be positive and thus traffic will be $45+(1*2.5)+(0*2.5*0.2)-(0*2.5) = 47.5 \simeq 48$. In a similar fashion, traffic will be generated in all other directions of this current intersections and then for all other intersections at each point of time.

3.5 Conclusion

In this chapter, we discussed the proposed dynamic model for managing road traffic network in a city with a WSN based monitoring scheme. We assume the WSN elements will perform perfectly and the batteries of the devices will be changed periodically, otherwise the scheme will not be functioning properly. For the purpose of simulation, a road-network of 12 major dispersed intersections have been included in the analysis. Indeed, at the time of implementation, the city authority will have to decide the number of intersections and choose from the city intersections. The scheme will have 4 different levels of entities including sensor nodes in the bottom level at the intersections and upper level entities include Cluster-Head nodes, Base stations, Gateway nodes and the Monitoring and Control Centres. The mathematical model has 2 components, traffic volume and the the cost function as a measure of traffic performance. This scheme instantaneously detects the congestion in the road-traffic and broadcasts the congestion information for

⁴threshold capacity $l_{id} = c_{id} * \alpha_s$; e.g. $85 * 0.7 = 59.5 \approx 60$ as a rounded value

the drivers of the vehicles. We have assumed the poisson distribution for the traffic arrivals, but in some cases, if the conditions for this distribution (independent and large number of events) do not hold, then the result of this model may not be realistic to that specific condition. Also when the traffic monitoring scheme will be in existence, then the first component of traffic will not be needed as the scheme will be getting real-time data and based on that data, system will evaluate the the traffic performance.

Chapter 4

Simulation Results

4.1 Introduction

This chapter outlines the simulation results of our proposed model of road traffic monitoring scheme. The discussion will include the adoption of Monte-Carlo Method, Single Threshold Approach of simulation, sensitivity analysis of the control items in the model, Distributed or Brute Force approach (Separate threshold value for different road segments) of optimization of road-traffic.

In simulating the traffic model, we have used a control of threshold factor (α_s) in order to determine the threshold capacity of each road segment (l_{id}), by multiplying the capacity of the road-segment (c_{id}) and this factor (α_s). In order to achieve the optimized traffic amount for all the selected road segments we simulate the model for different selected values of the set of threshold factors denoted by α_s , where $s=1, 2, 3, \dots, 7$ and $\alpha = \{20\%, 30\%, 40\%, \dots, 80\%\}$. In our quest of getting to the optimal traffic, two different approach have been adopted: the single threshold value approach and distributed approach. In the first approach, one single value of threshold factor has been used for all the road-segments in order to estimate the threshold capacities and the model has been simulated for the whole simulation period of a day (1440 minutes); traffic is generated and relative cost has been estimated according to the model specifications for the purpose of congestion avoidance. Thus the model has been simulated for each the threshold factor values iteratively one at a time. The estimated city costs over the simulation period for all of the threshold factor values have been arranged together in order to compare the performances of the different values. In the second approach, different values

of threshold factor have been used for different road segments; both the approaches are being separately explained with the simulation results in the following.

4.2 Monte-Carlo Method

As the probability distribution of traffic arrivals in the major important intersections is not fully known to us; in order to ensure accuracy in computing the integrals following the Monte-Carlo method we took a large number of samples (1000) for the simulation where we have generated traffic by using the matlab's poisson random number generator at each road-segment level under the selected intersections.

4.3 Single Threshold Approach

In this approach, a single value (α_s) of the set of threshold factor values (α) is used to simulate the model for the whole simulation period of 24 hours and generate the traffic and estimate the costs using our proposed equations (3.1 and 3.2); iteratively all the threshold factor values are used for separate simulations and finally comparison among the costs for each value of (α) is performed. In addition to that, we have estimated the cost for the situation of traffic without the controls of this model in order to compare the performance of this model. Although complete systematic **sensitivity analysis** has not been done, but we tried to investigate the impact of different parameters on the system performance in respect of the congestion cost, we simulated the scheme with varying different parameters used in our model e.g. hourly-mean arrival rate (λ), weight (w), and non-compliance factor (θ) etc. While varying other system-parameters, we used the same data-set of the arrivals for the 24 hours in order to maintain consistency.

Figure 4.1 displays the contribution of the threshold factor in the traffic performance i.e. congestion cost; higher values of threshold can accommodate more traffic to enter a road-segment before the road segment reaches to congestion. This cost has been estimated by the integration of the equation 3.2 over over a period of 24 hours for all the intersections i.e. of the whole city. This figure shows that the highest value of threshold factor ensures the minimum cost i.e. best performance. In order to see the contribution

of the proposed model, we simulate regular situation without the control of this system i.e. allow traffic arrivals without adhering the threshold capacity and see the traffic performance by evaluating the cost curve. Comparison of these 2 cost curves - with and without the proposed control displays that, the cost for the regular situation without the control is clearly higher around the higher values of threshold factor. Up to the value of 50% values of threshold factor, both the phenomenon produce same amount of cost but afterwards the difference between the costs keeps increasing (Figure 4.2) and the amount of cost is significantly lower with our model's proposed control. It was noticed that with small number of samples the difference between these cost curve's are more distinct in the lower values (Table: 4.1) but with large number of samples this difference in the lower values of threshold dies down and both the costs become same (Table: 4.2). Figure 4.2 shows the difference between these two costs.

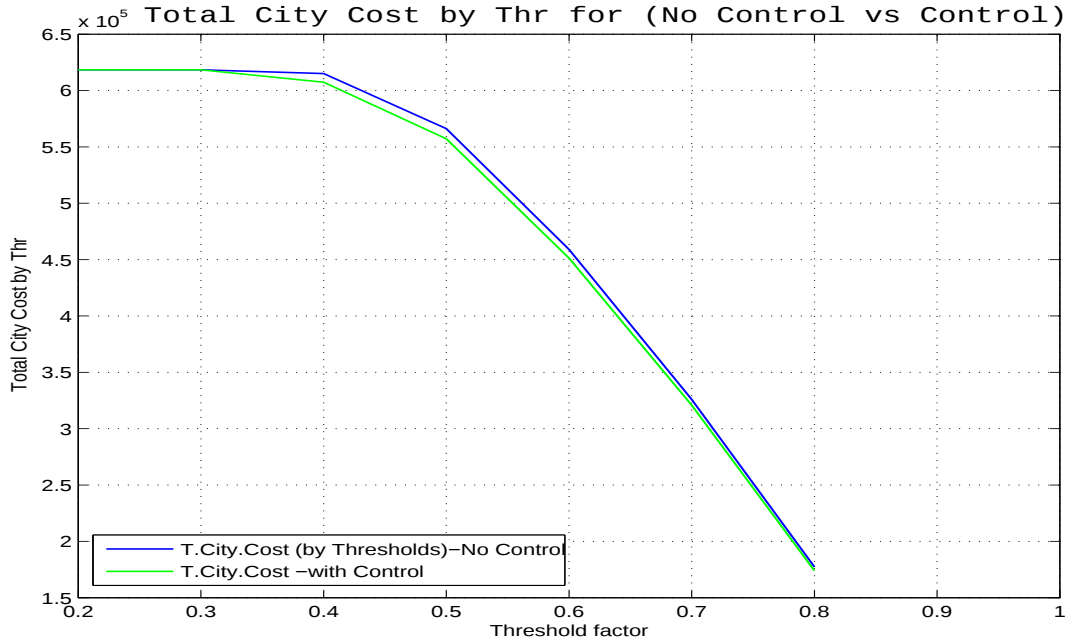


Figure 4.1: Comparison of Total City Cost by Threshold Factor for No Control vs with Control

Figure 4.3 shows the comparison of Average Cost (of all thresholds) for No Control vs with Control over the simulation period of 24 hours; the cost with the proposed control is lower than that of regular situation without control on traffic arrivals. The difference in between these 2 cost curves are shown in Figure 4.4.

Table 4.1: Comparison of Total City Costs (low number of samples) by Threshold factors for No Control and with Control

Sl. Threshold Factor (α)	1	2	3	4	5	6	7
Value of Thr Factor (α)	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Total City cost- No Control	618,369	614,423	597,055	548,609	459,557	360,688	249,683
Total City cost- with Control	617,332	614,423	592,166	538,175	451,634	358,313	245,320
Improvement in cost with model	1,038	0	4,889	10,434	7,923	2,375	4,363

Table 4.2: Comparison of Total City Costs (large number of samples) by Threshold factors for No Control and with Control

Sl. Threshold Factor (α)	1	2	3	4	5	6	7
Value/ of Thres Factor (α)	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Total City cost- No Control	618,369	618,369	618,369	618,207	609,251	584,308	522,593
Total City cost- with Control	618,369	618,369	618,369	618,207	605,607	578,668	504,448
Improvement in cost with model	0	0	0	0	3,644	5,640	18,145

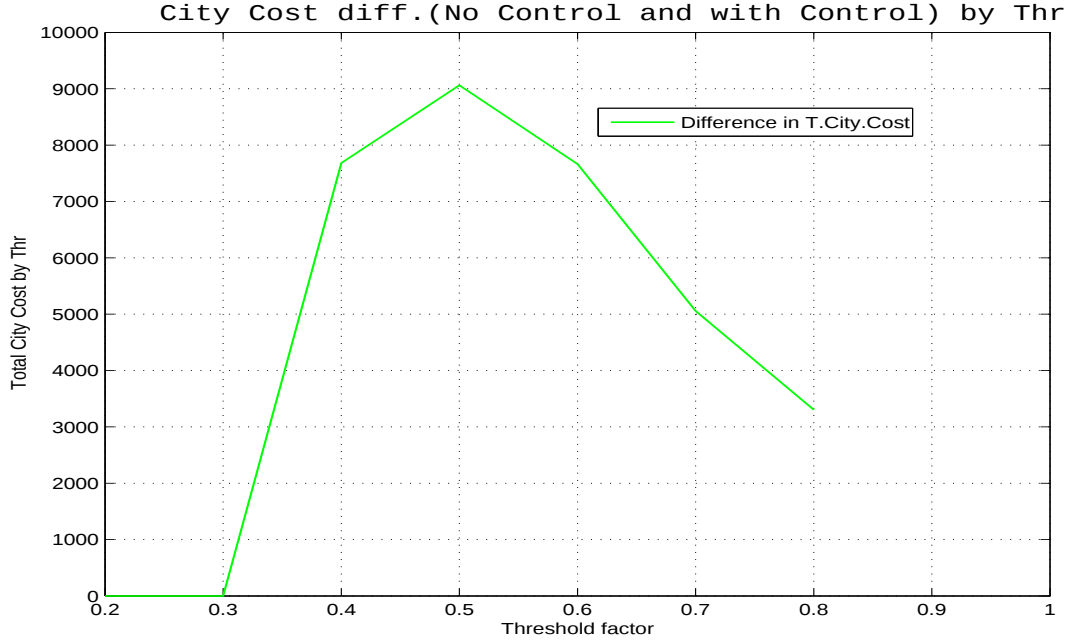


Figure 4.2: Difference of Total City Cost by Threshold Factor for No Control vs with Control

Similar trend of better performance of the proposed model is noticed (Figure 4.5) through the ideal city cost curves where cost of all selected intersections is estimated for the highest value (80%) of threshold factor.

The 2 curves in Figure 4.6 show the average traffic over the 24 hours of simulation period. The amount of traffic in the road-network is lower for our proposed model. These values of the traffic under the proposed model are generated by averaging the quantities related to all 7 threshold factor-values.

4.3.1 Sensitivity Analysis

For the sensitivity purpose, we estimated the performance indicator (costs) by simulating the proposed model over a period of 24 hours by using the following equation 4.1. In this connection, we checked the impact of varying different parameters of the system, like weight (w), hourly mean arrival rate λ_h , and the Non-compliance factor θ . We checked the impacts of the variations of the above factors on the system performances through

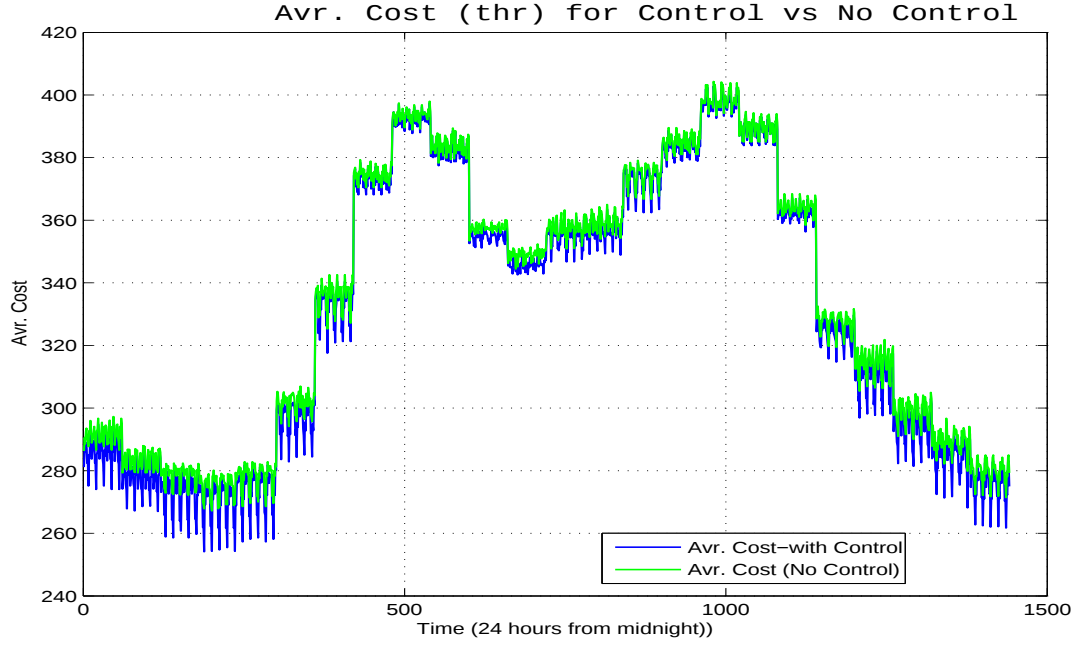


Figure 4.3: Comparison of Av. Cost (all thresholds) for No Control vs with Control (normal weight, arrival rate and theta)

the impacts on the cost functions and the quantities of traffic.

$$J(t_k) = E\left(\sum_{i=1}^N \sum_{d=1}^{n_i} [w_{id} I_1(x_{id}(t_k) \geq l_{id}) + \kappa_{id}(t_{k-\gamma}, t_k) * (\phi_{id})(t_k) * w_{id} I_2(x_{id}(t_{k-\gamma}) \& x_{id}(t_k)) \geq l_{id}, L_{id}(t_{k-\gamma}, t_k) = 1]\right) \quad (4.1)$$

In this connection of sensitivity analysis, 2 different sets of mean arrival rates (λ) have been used in this simulation. Figure 4.7 shows the comparison between the Average Costs with the proposed scheme for High and Low Lambda λ (without varying the other parameters like weight, non-compliance factor θ). With the higher arrival rate the performance is reduced i.e. cost is increased but during the morning rush hour of the day the performance is almost same because that time both the rates are almost identical. Figure 4.8 shows the average cost for the highest threshold factor value and Figure 4.9 shows the quantities of traffic generated in these two different scenario. The distance between these two different sets of mean arrival rate λ_1 and λ_2 (Low and High rates) has been calculated to be 175.21.

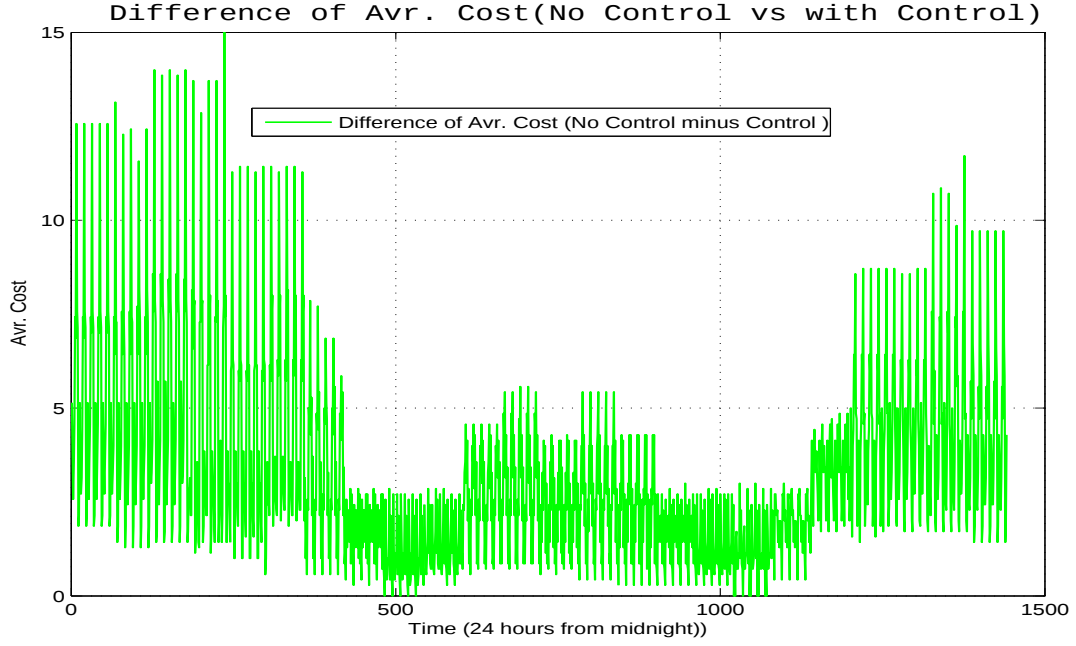


Figure 4.4: Difference of Average Cost (No Control minus With Control)

To evaluate the performance indicator i.e. the cost functions, we have used the **weight factors** (proportionate to the importance of each road-segments included in this scheme) which are to be ultimately determined by a city authority at the time of implementation of this scheme. In order to see the impact of the changes in the importance (weight factors) we simulated the scheme with two different set of weights and estimated the average city cost (mean of costs related to each threshold factors) over time (Figure 4.10); the significant increment in weights push the performance down i.e. average cost faces a big increase and similar scenario in ideal cost as well (Figure 4.11). Figure 4.12 reveals the total city cost by different threshold factors for both the weight sets.

In the current model, Non-Compliance Factor θ is an important parameter which will be determined by the scheme by analyzing the captured data (when physically being implemented); to see the impact of the variation in this parameter on the performance of traffic we simulated the scheme with two different sets of θ . Figure 4.13 represents Average Cost of all threshold factors over the 24 hours simulation period and Figure 4.14 displays impact on Ideal City Cost for the best Threshold factor. Figure 4.15 specifically shows the impact on the amount of traffic (all-threshold factor average) for the different sets of θ .

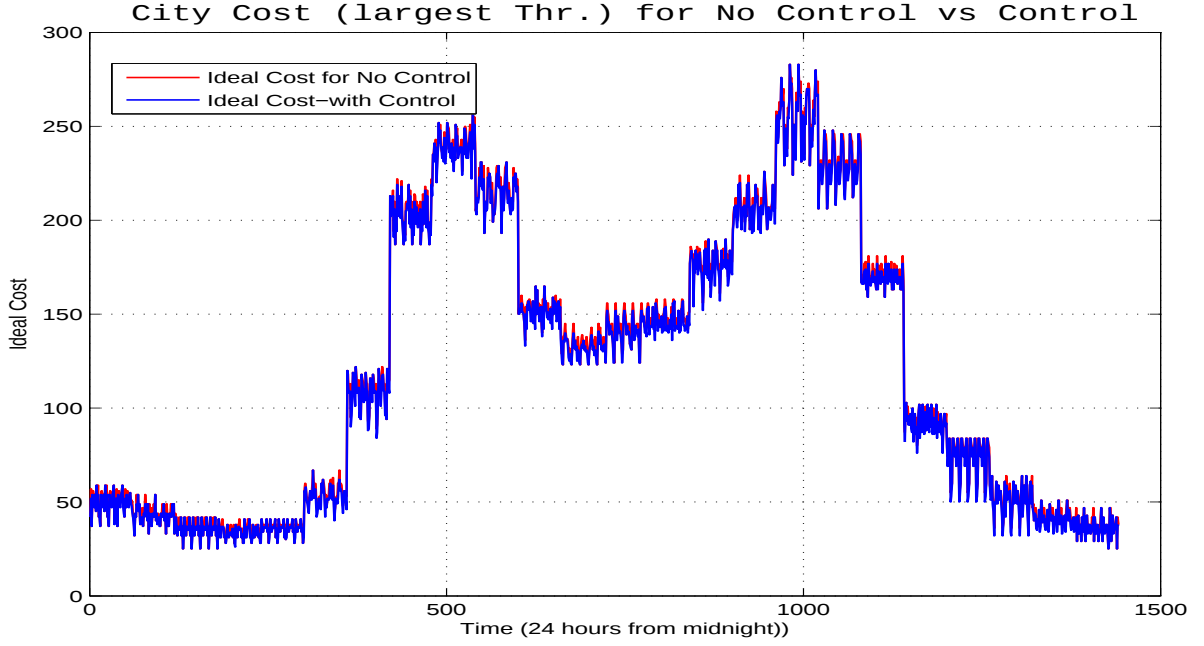


Figure 4.5: Ideal City Cost for best Threshold for No Control vs with Control(normal w , λ , and θ)

4.4 Distributed or Brute Force Approach

For determining the optimum setup, we used the exhaustive search technique; exhaustively searching over all possibilities for a specific configuration. Since in this approach we consider different values for different road-segments, we call it distributed approach computationally infeasible for larger configurations. To determine the optimum setup for larger configurations, very high computing capacity and long-time are required, to evaluate all possibilities. So, we have undertook the search process over a reasonable size of data. We have selected three (3) intersections and their four (4) major directions and a sub-set of the α , i.e. three different values for the simulation process $\alpha = \{30\%, 50\%, \dots, 80\%\}$. Thus we have got $3 \times 4 = 12$ road-segments and if we allow each of the 12 segments to choose one (1) threshold factor from the 3, then we have $3^{12} = 531,441$ different choices¹. Since we have a reachable number of choices here, we adopted the

¹In the case where repetition is allowed and order matters, if n is the number of things to choose from, and r of them are chosen, then the total number of choices will be: $n * n * \dots$ (r times) $= n^r$.

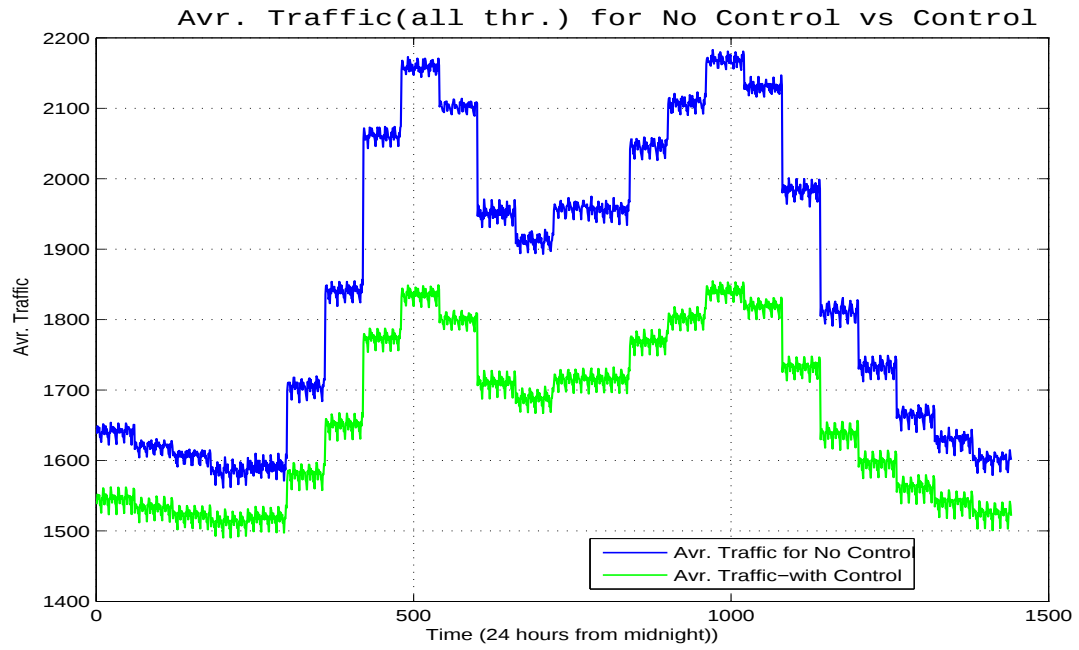


Figure 4.6: Average Traffic (all thresholds) for No Control vs with Control(normal w , λ , and θ)

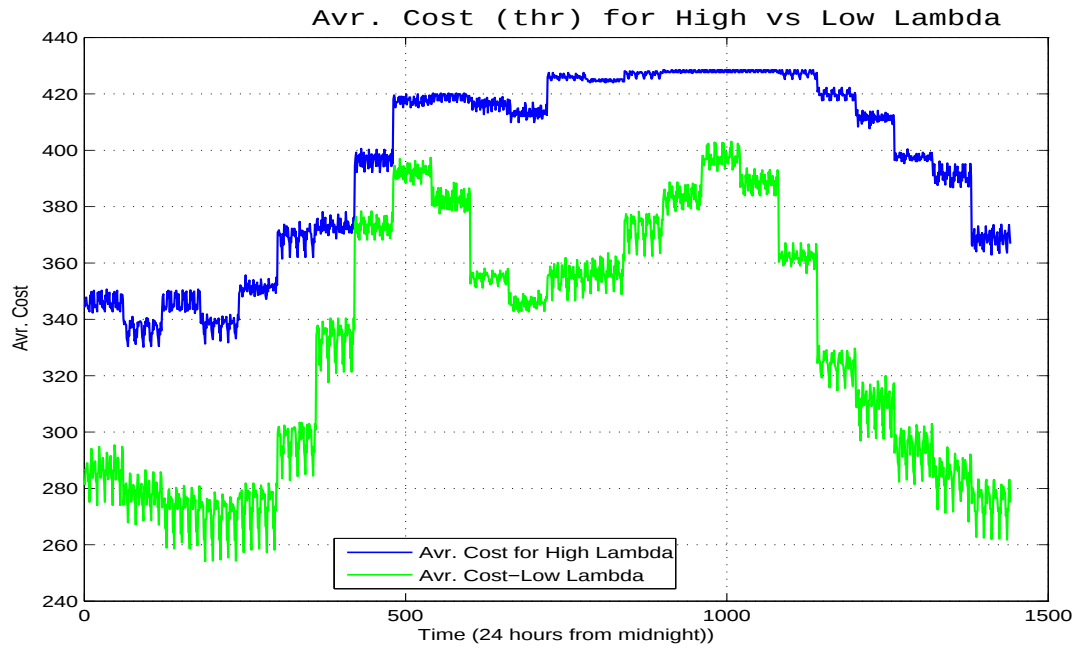


Figure 4.7: Varying λ : Impact on Average Cost (all thresholds)

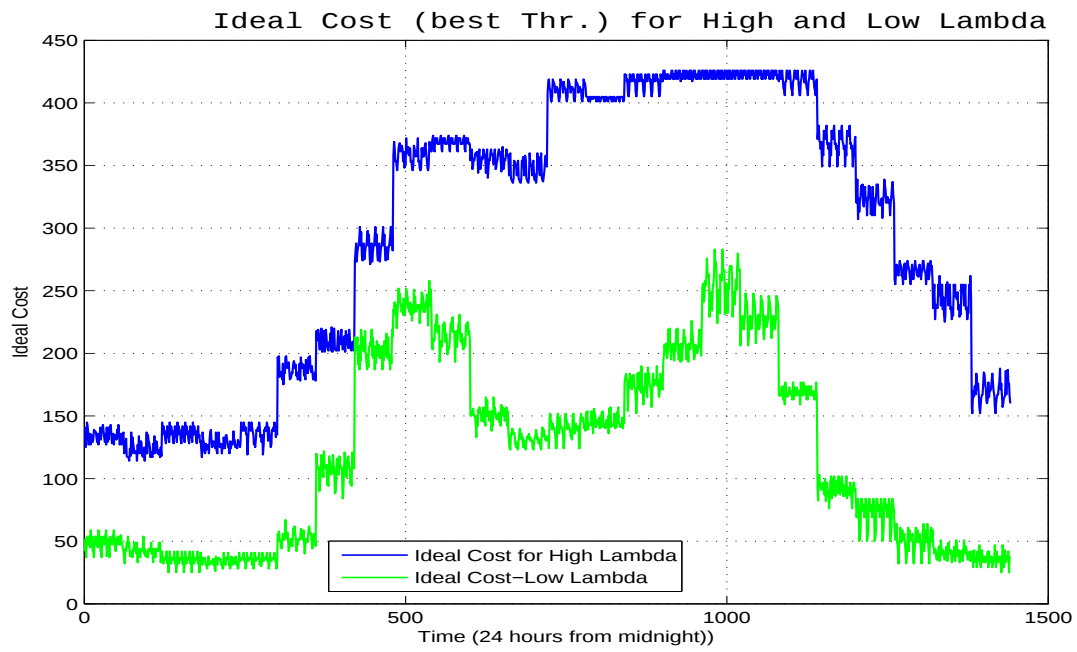


Figure 4.8: Varying λ : Impact on Ideal City Cost for best Threshold

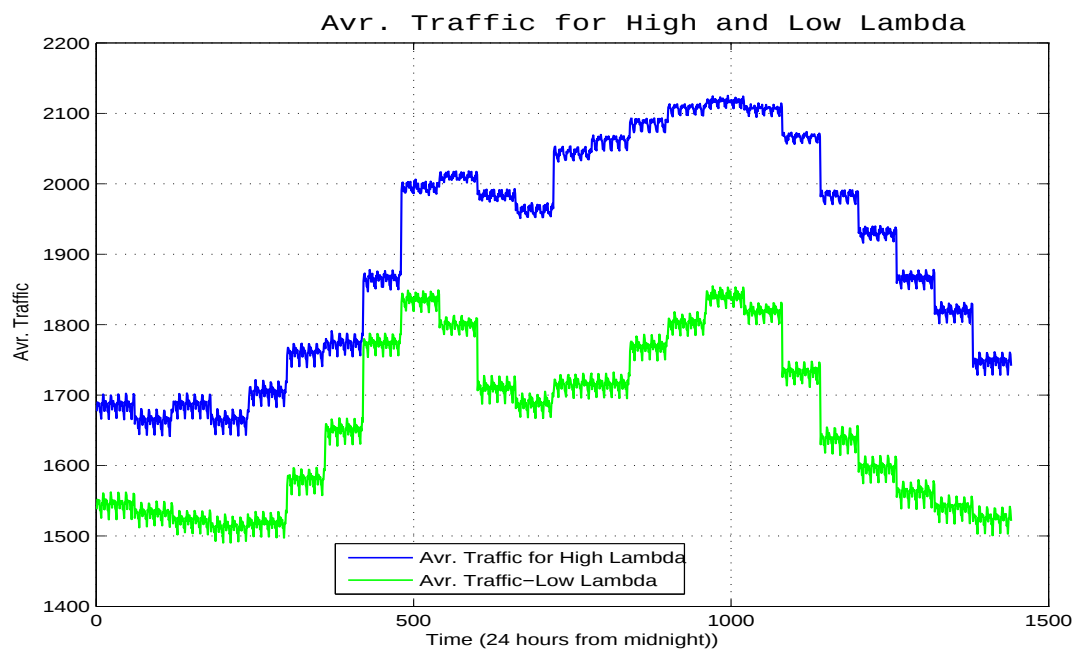
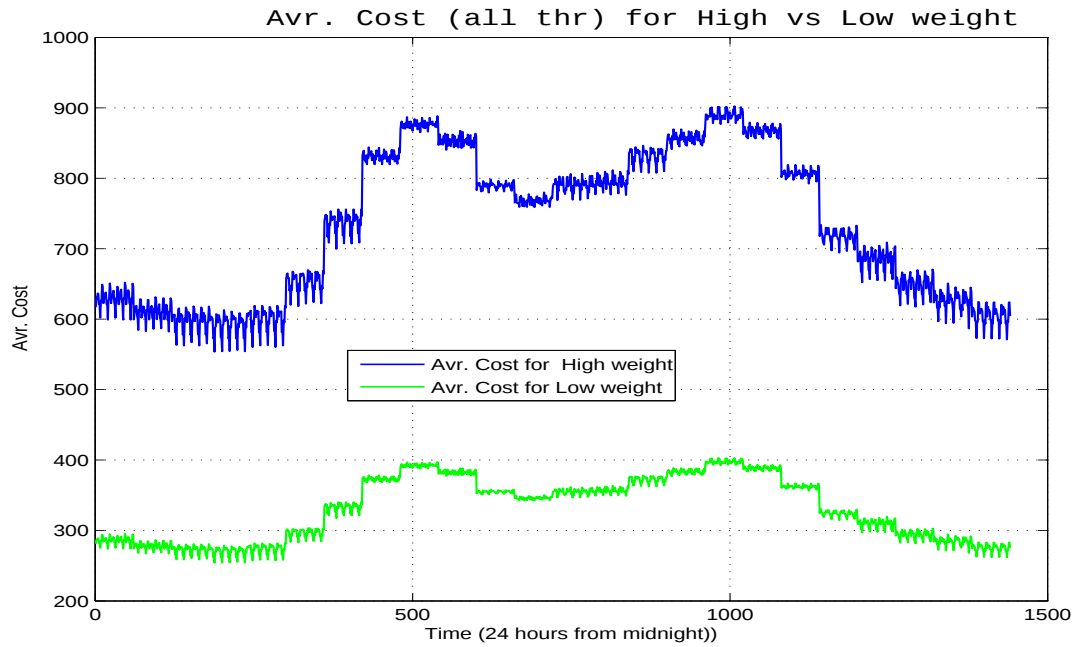


Figure 4.9: Average Traffic (all thresholds) for High vs Low Mean Arrival Rate(λ) (with normal w, θ)

Table 4.3: Distances among different directions of 2 set of Mean arrival rates

Road Type	Distance between rows	λ_1	λ_2
1	1, 2	15.14	20.43
1	2, 3	14.48	13.03
1	3, 4	15.41	17.23
1	4, 1	15.44	25.80
2	1, 2	14.63	17.87
2	2, 3	20.14	13.41
2	3, 4	11.71	23.17
2	4, 1	14.10	26.06
3	1, 2	8.93	20.90
3	2, 3	10.74	17.91
3	3, 4	9.33	26.81
3	4, 1	8.53	27.10

Figure 4.10: Average Cost (all thresholds) for High and Low weight (normal λ and θ)

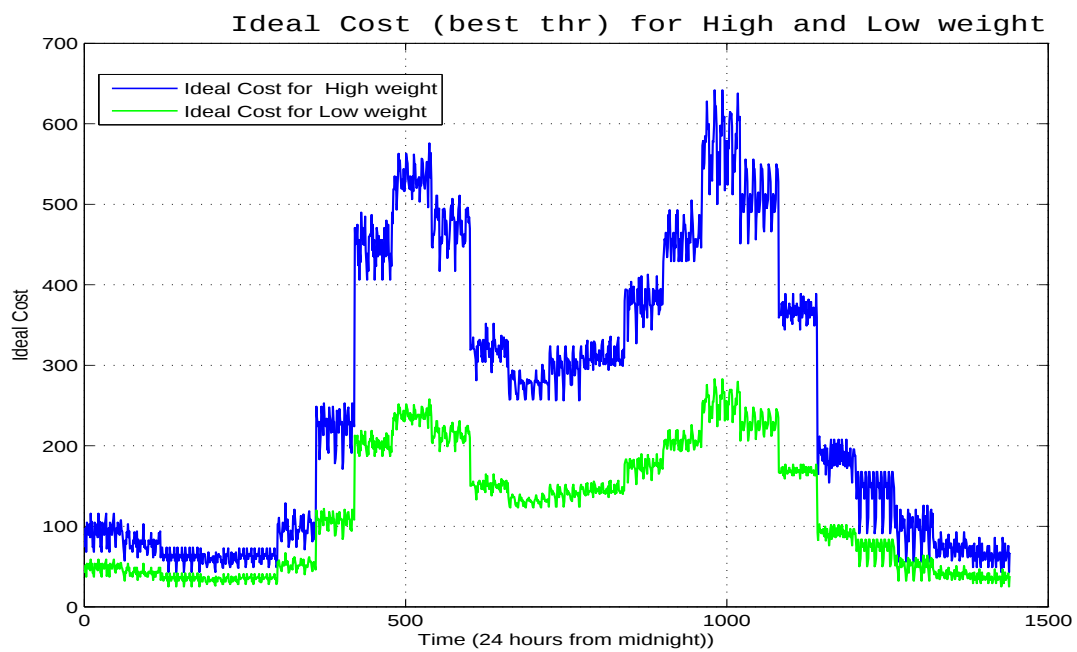


Figure 4.11: Ideal City Cost for best Threshold for High and Low weight (normal λ and θ)

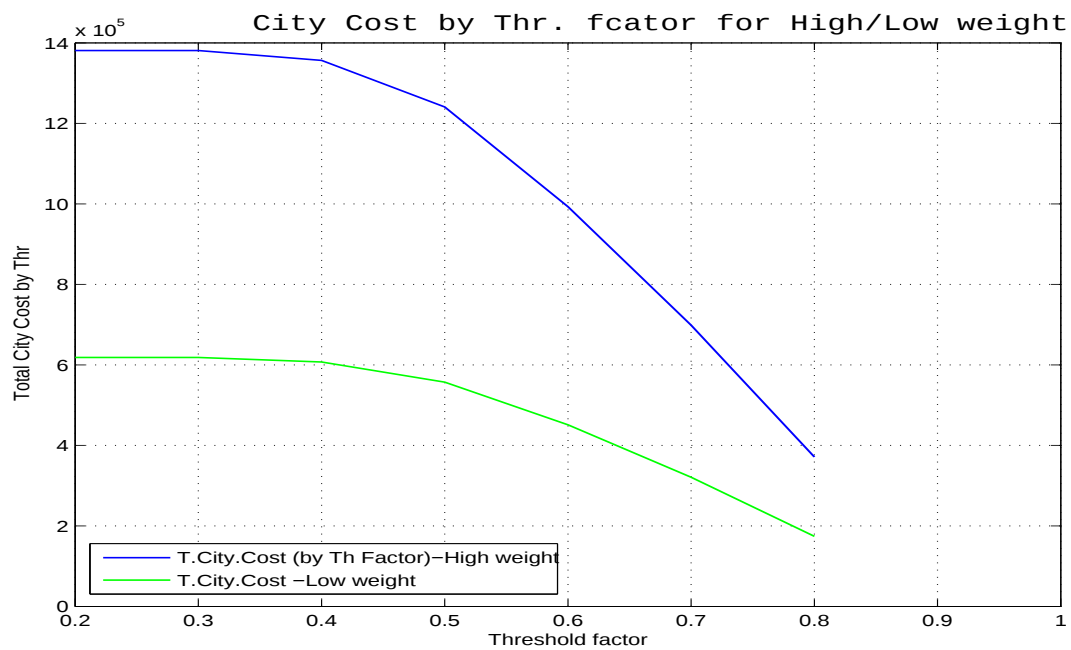


Figure 4.12: Comparison of Total City Cost by Threshold Factor for High and Low weight (normal λ and θ)

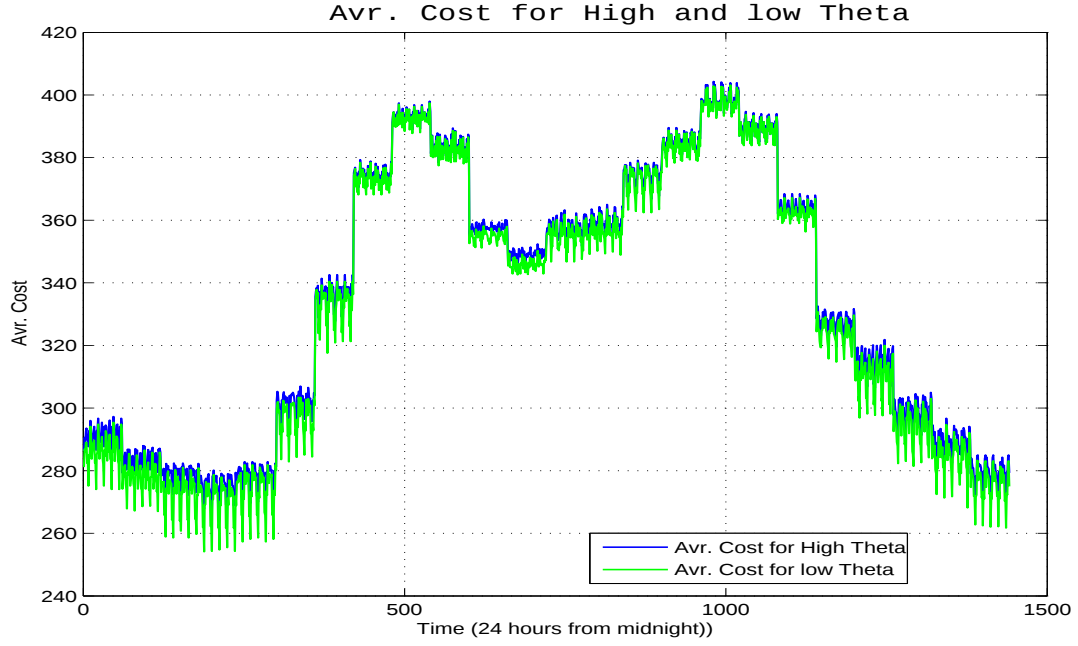


Figure 4.13: Comparison of Average Cost for High and low Non-Compliance Factor (θ)

brute force approach of search technique to determine the optimum choice. The formal approach would have been more promising but would have needed more time; so, to save time, we decided to use the Brute Force approach.

According to our traffic and cost model (equations 3.1 and 3.2) we simulated the traffic and the related cost of congestion for each of the choices (permutation sets) for the duration of the whole day (24 hours time). At each iteration period, we generated traffic for all road-segments, sequentially one by one, following Poisson distribution. For this, we have used the Matlab's Poisson Random Number Generator; and in order to involve Monte-Carlo method in this process we have generated random numbers (of 'num_sample' quantity) with the seed of hourly mean arrival rate for each road-segment (direction). We feed these random numbers to our system as the arrival rates (in equation 3.1) and generate traffics for all the samples; from the mean value of these traffic amounts - we deduce the traffic for that road-segment and the congestion status; similarly using (equation 3.2) we determine congestion cost. Thus, we compute traffic and cost for all the road-segment's under an intersection; then repeat same procedure to get traffic for all intersections for one iteration period. This process is repeated for all the 1440 iteration periods to get the traffic amounts for the whole simulation period of 24

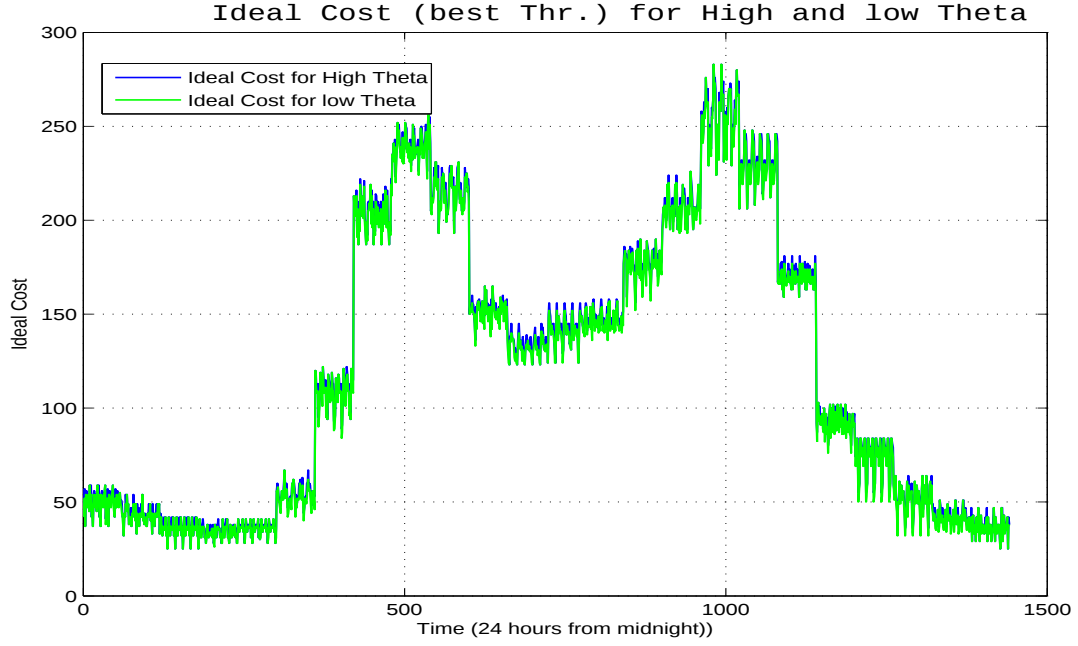


Figure 4.14: Ideal City Cost for best Threshold for High and low Non-Compliance Factor (θ)

hours. For the purpose of demonstrating the benefits of our model, we also simulate the traffic and the cost in the regular situation without the control of our system (controlling traffic arrivals with the threshold distance). In order to maintain consistency of traffic arrivals in simulating our system with different parameter-variations, and also the regular situation - without the proposed control of our model, we use the same data-set of the arrivals for the 24 hours generated through the Matlab's Poisson Random Number Generator.

If each permutation set's cost is estimated separately, then we can see that, in the initial stage of the simulation, while mostly lower values of threshold factor are used for different road-segments, the cost is higher. Furthermore, when lower values of threshold factor are selected in most of the road-segments and some of them adopt the higher values, the cost slowly is reduced (Figure 4.16). *One aspect is important to mention that because of the very large size (larger than 0.5 M) of the data (total number of permutations), the diagram for the whole data-set on any aspect becomes very unclear, therefore some sub-sets² of the data has been presented to discuss the simulation results; but to*

²rectangular marked sections of the diagram in Figure 4.16

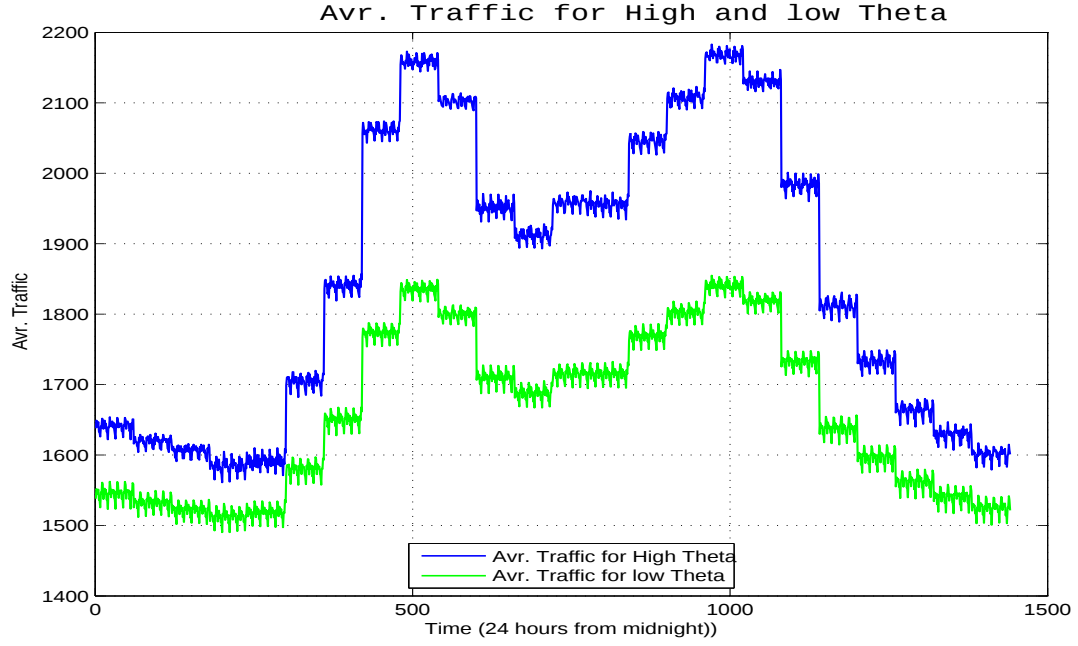


Figure 4.15: Average Traffic (all thresholds) for High vs Low θ (Non-Compliance Factor)

have some overall idea or pattern, the total-diagrams like Figure 4.16 are provided in the thesis although they are very un-readable. At the last stage of simulation while in most of the road-segments, higher values of threshold factor are selected, the cost is the least. If the cost is estimated for the regular situation without any control of our model in traffic arrival, the cost is higher than that of all the controlled sets. Since there are numerous data-points in this diagram, it's not very easy to understand, Figures 4.17 and 4.18 show costs, related to some important sub-sets of the same data to enable one to easily visualize the cost curves for four different sub-sets of 50 permutation sets each; the horizontal axis represents the permutation-serial numbers of different choices.

Figure 4.19 displays the traffic-performance or costs for each the permutation set by the permutation serial number in the horizontal axis; as there are more than half a million sets together, the diagram is not that easily visible. Figure 4.20 shows cost for the regular situation without the proposed control. It is easy to see that this cost is higher than the cost with proposed control and Figure 4.23 explicitly show the difference and some sub-sets of the cost-difference are shown in Figures 4.24 and 4.25.

Traffic amount in the city during the whole day-period of simulation by the proposed

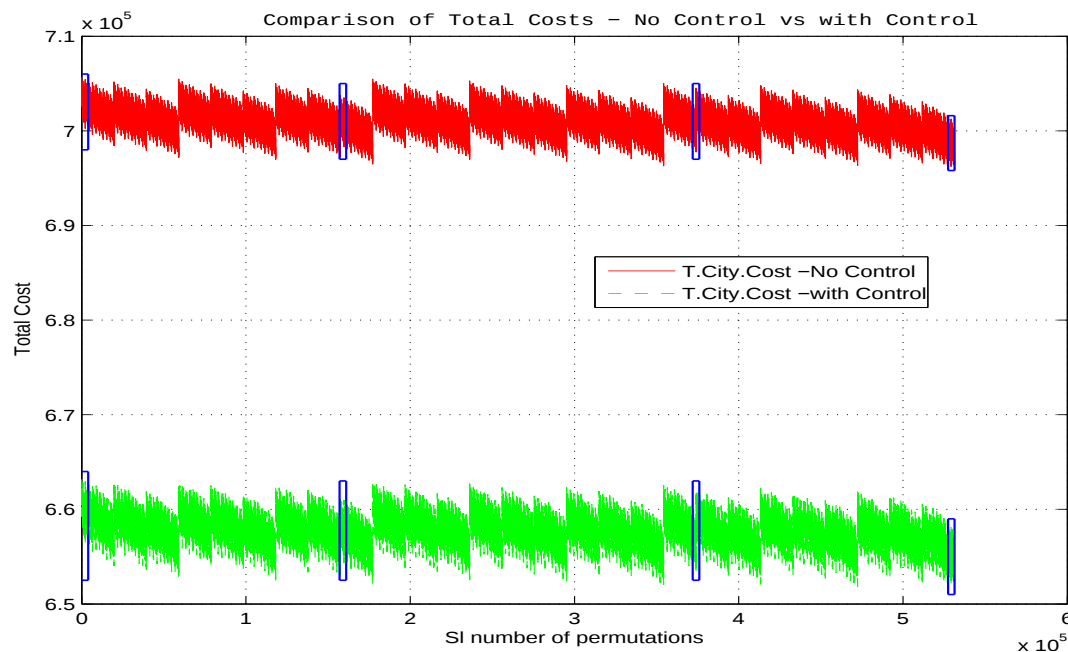


Figure 4.16: Total Costs - No Control vs with Control for each permutation set

scheme is presented in the Figure 4.26 but this figure is not readable on paper-printouts though; therefore, to have clear view, Figure 4.27 and 4.28 are provided to visualize the traffic quantity by each of the permutation set, while Figure 4.29 shows the difference between the traffic of the proposed scheme and the regular situation without control. Again, items are provided in separate diagrams for clear views.

Finally if all the aggregate traffic is sorted out by the road-segments (Figure 4.30) for both with the proposed control and without control, it is evident that in all cases the total traffic is smaller in quantity for each road-segment and create less pressure on the resources.

4.5 Conclusion

We have simulated the traffic model with 2 different approaches - the single threshold approach and the distributed approach with a comparatively small configuration in order to keep the computations manageable. In order to avoid the discrepancy Monte-Carlo Method has been adopted in the first approach and Sensitivity Analysis is performed to see the impact of the control factors on the system outputs, Distributed approach with

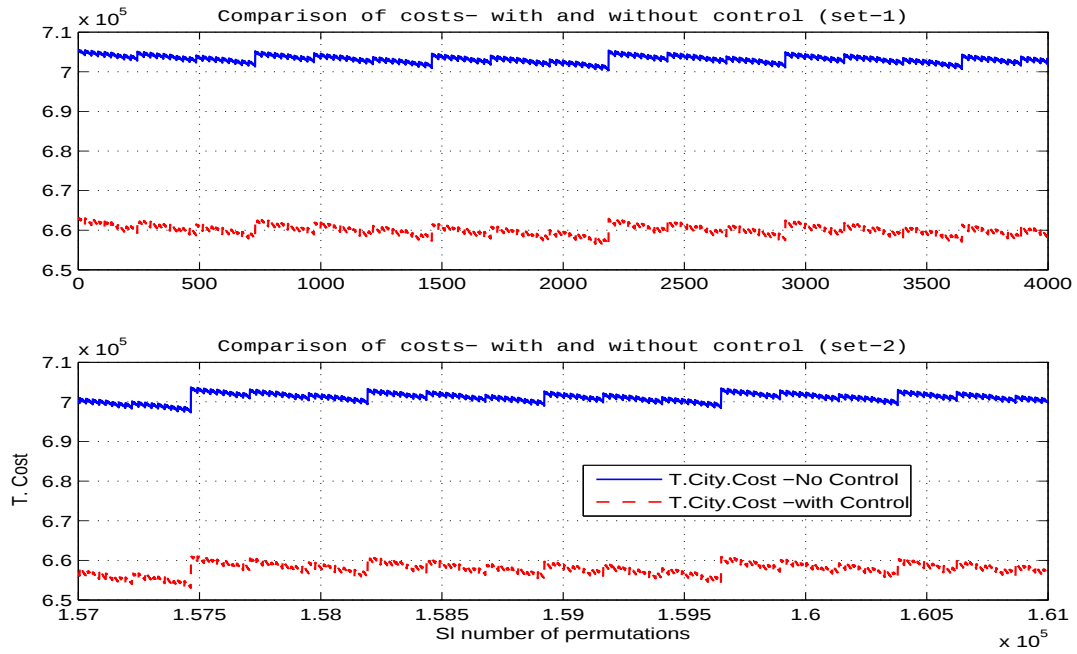


Figure 4.17: Comparison of costs- with and without control (set-1 and 2)

a smaller configuration of 3 intersections with 4 directions. Comparison of the proposed model and the regular situation without the controls of this model has been performed to show the model's superiority. Overall conclusions and future works will be added in the next chapter.

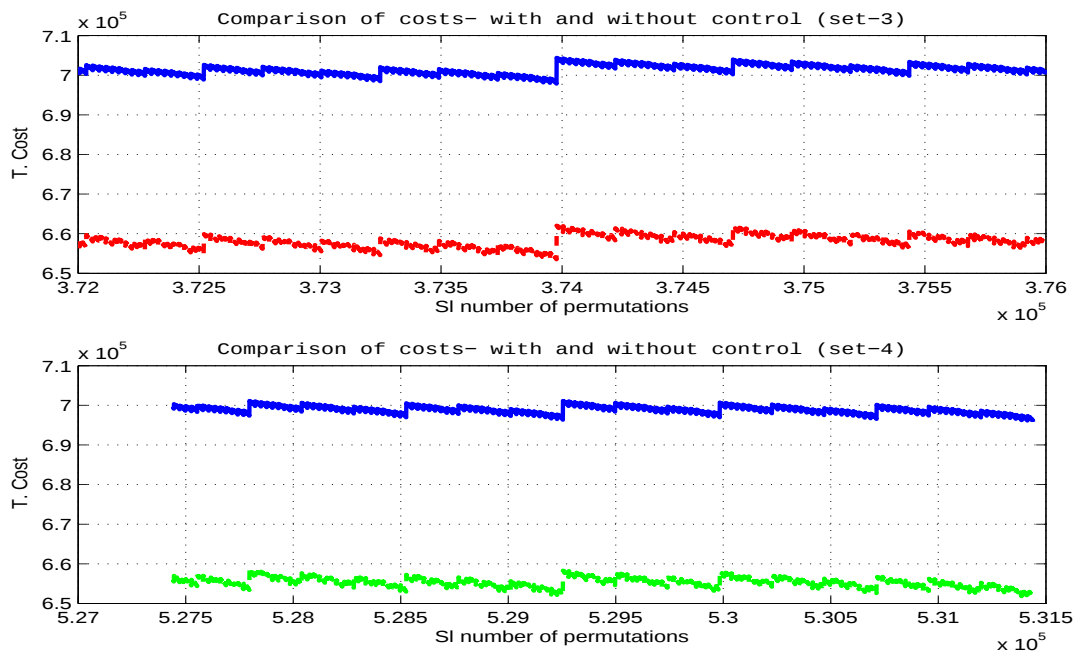


Figure 4.18: Comparison of costs- with and without control (sets-3 and 4)

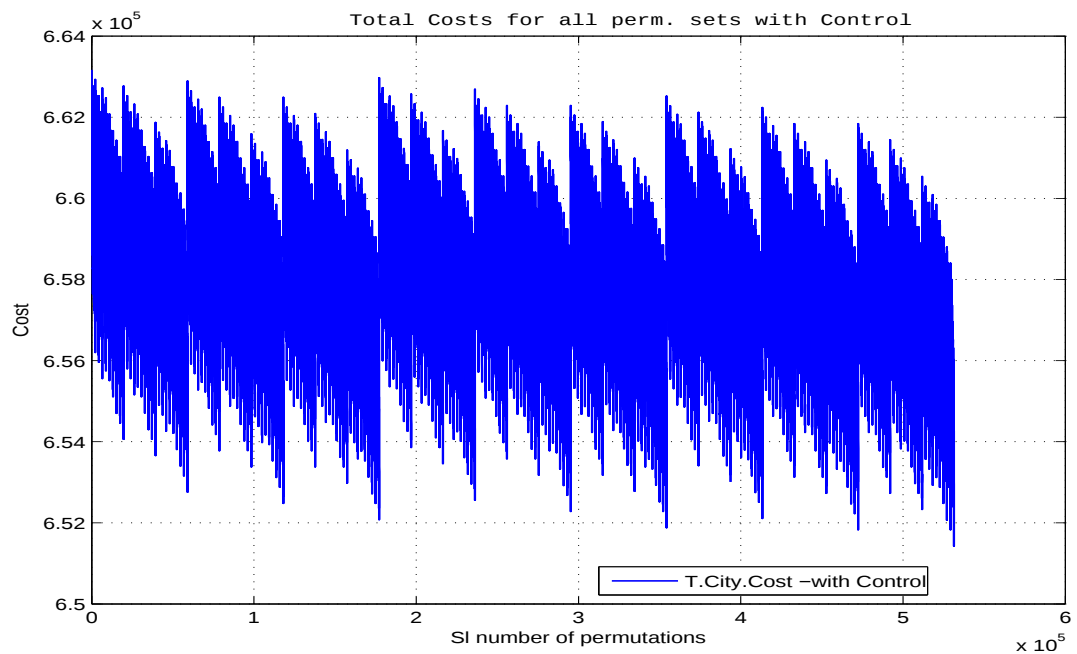


Figure 4.19: Total Cost for each permutation set with Control

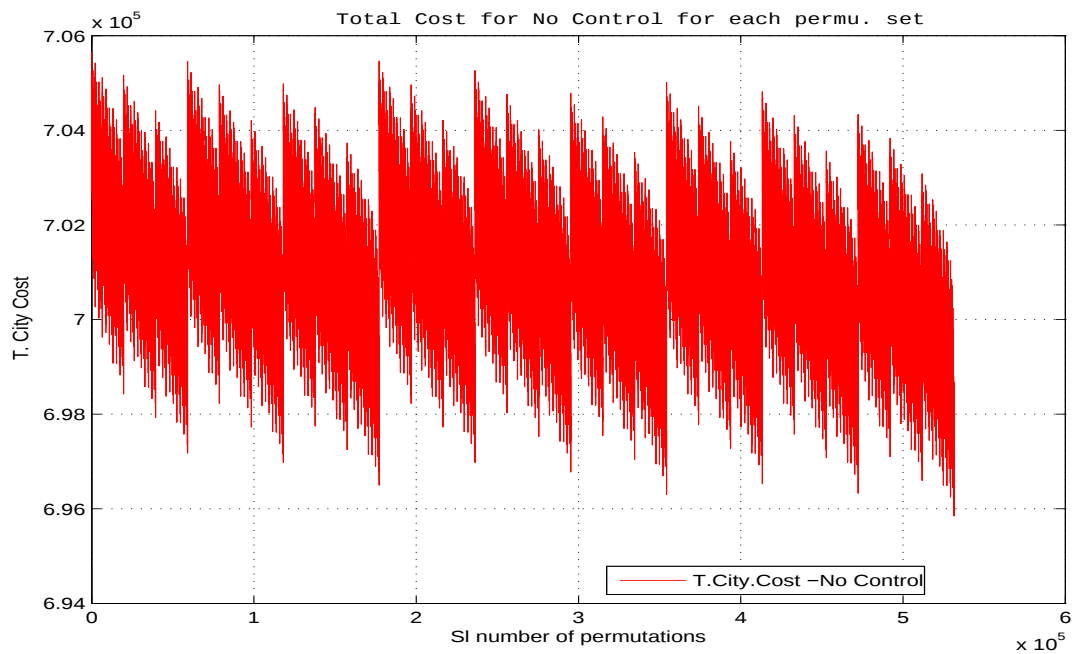


Figure 4.20: Total Cost for No Control situation for each permutation set

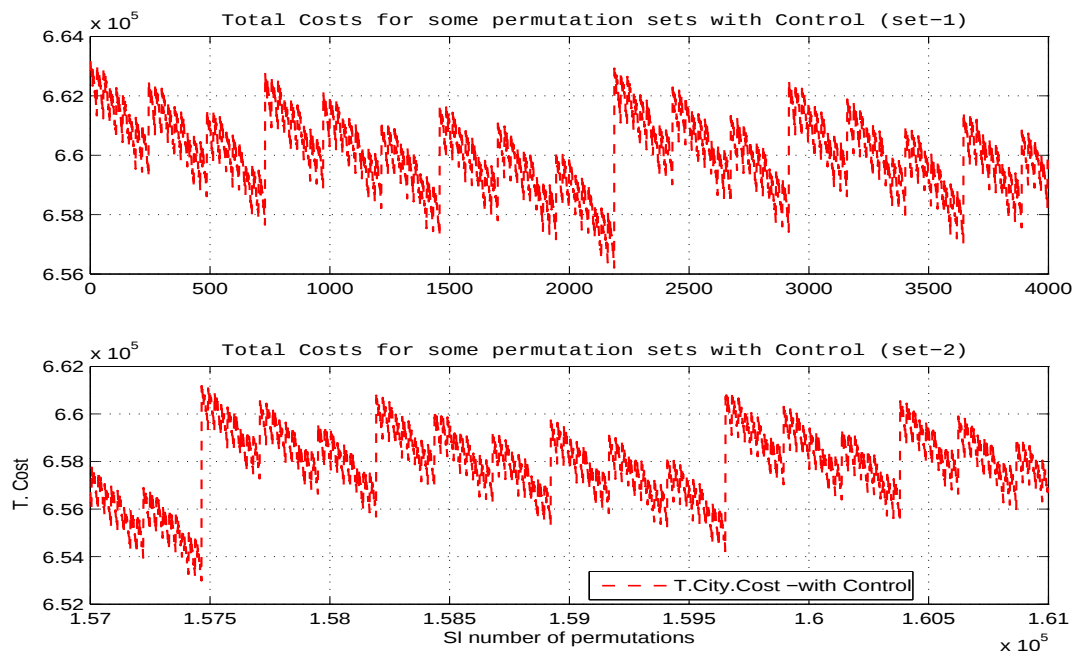


Figure 4.21: Total Costs for some selected permutation sets (1 and 2) with Control

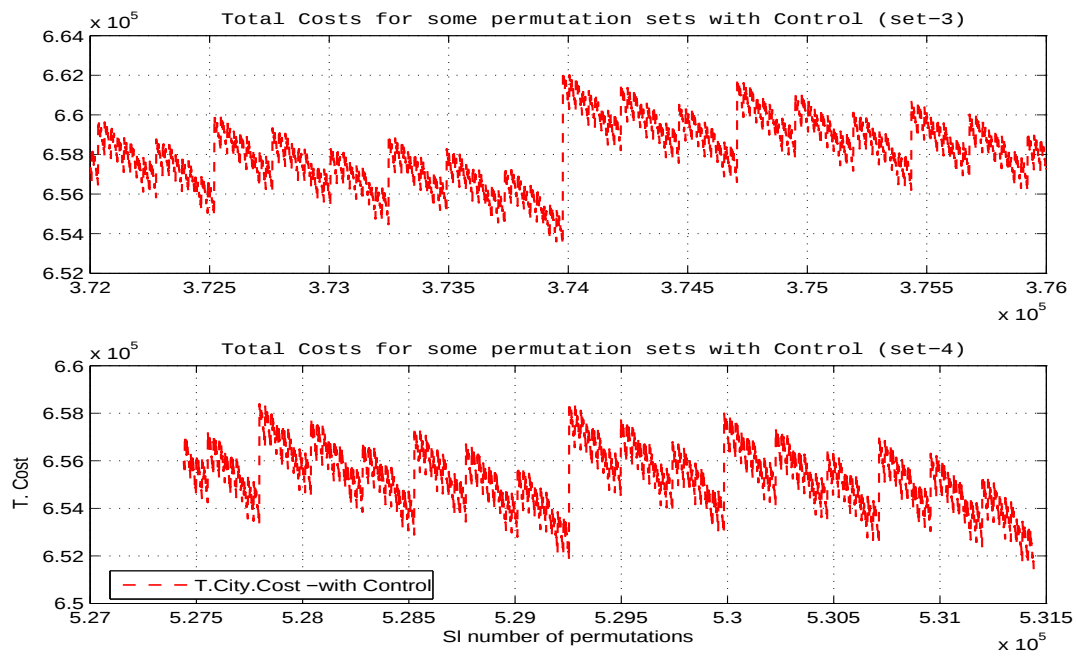


Figure 4.22: Total Costs for some selected permutation sets (3 and 4) with Control

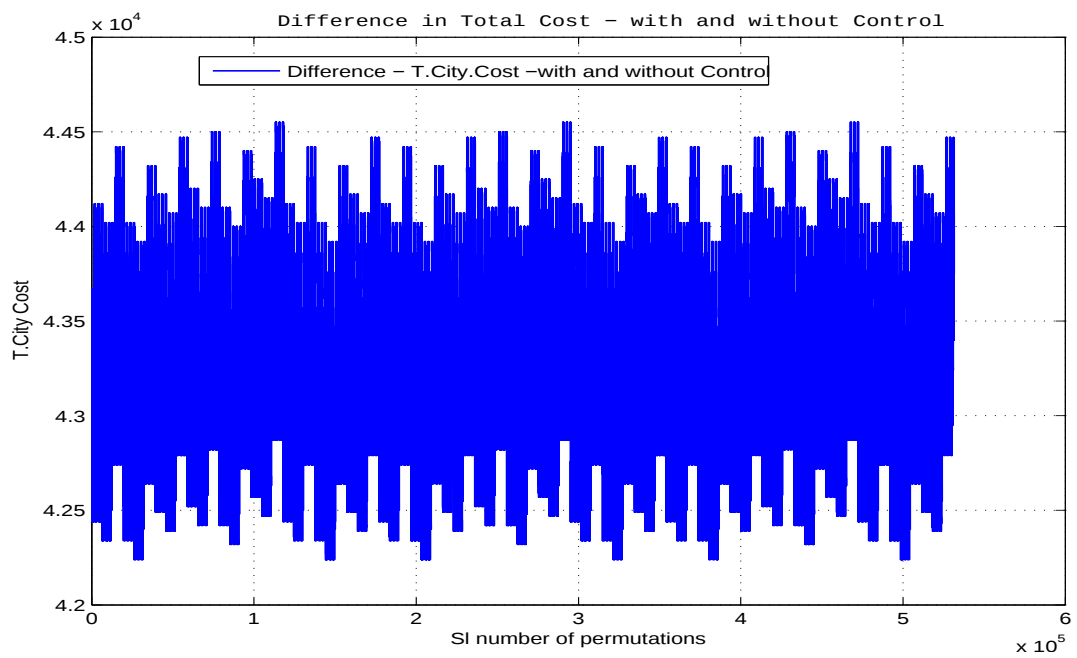


Figure 4.23: Difference in whole-day Total Cost for each permutation set (No Control vs with Control)

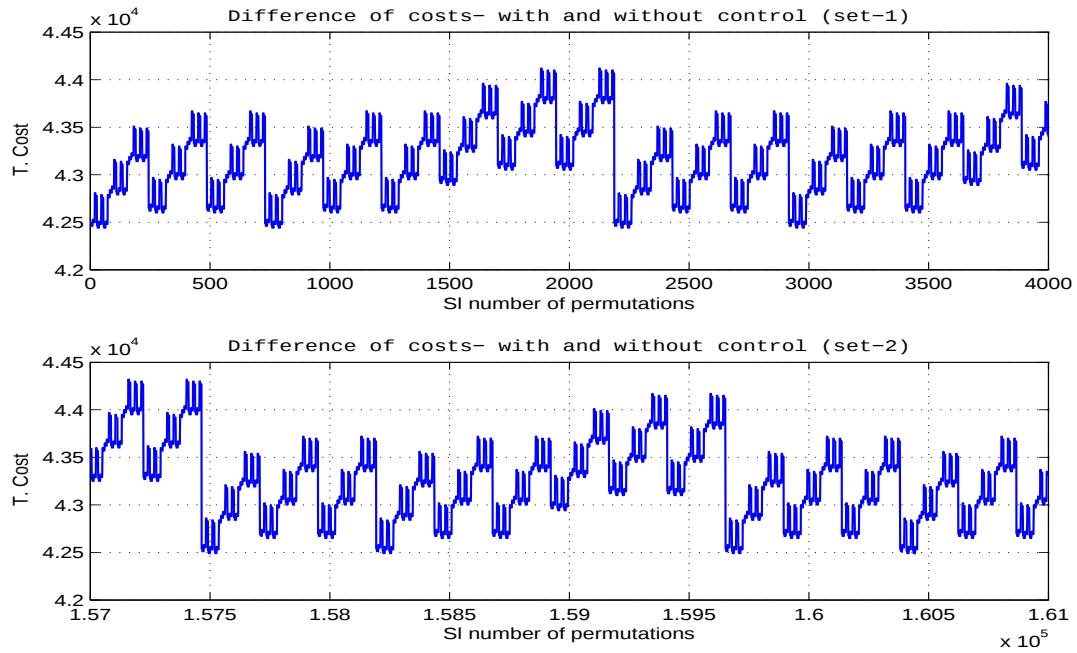


Figure 4.24: Difference of costs- with and without control (set-1 and 2)

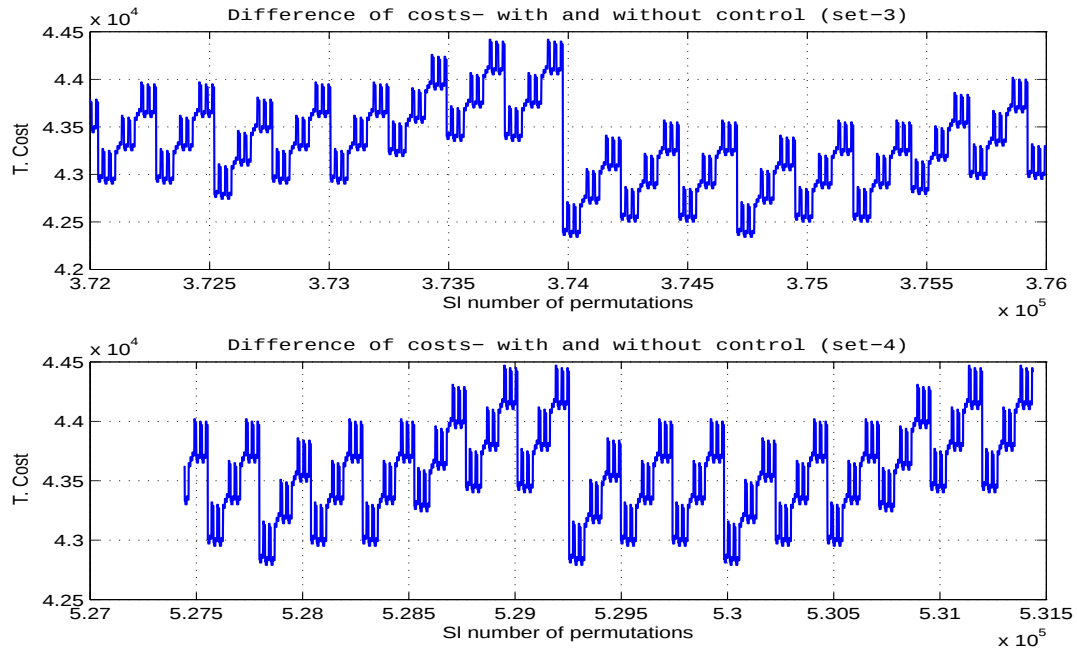


Figure 4.25: Difference of costs- with and without control (set-3 and 4)

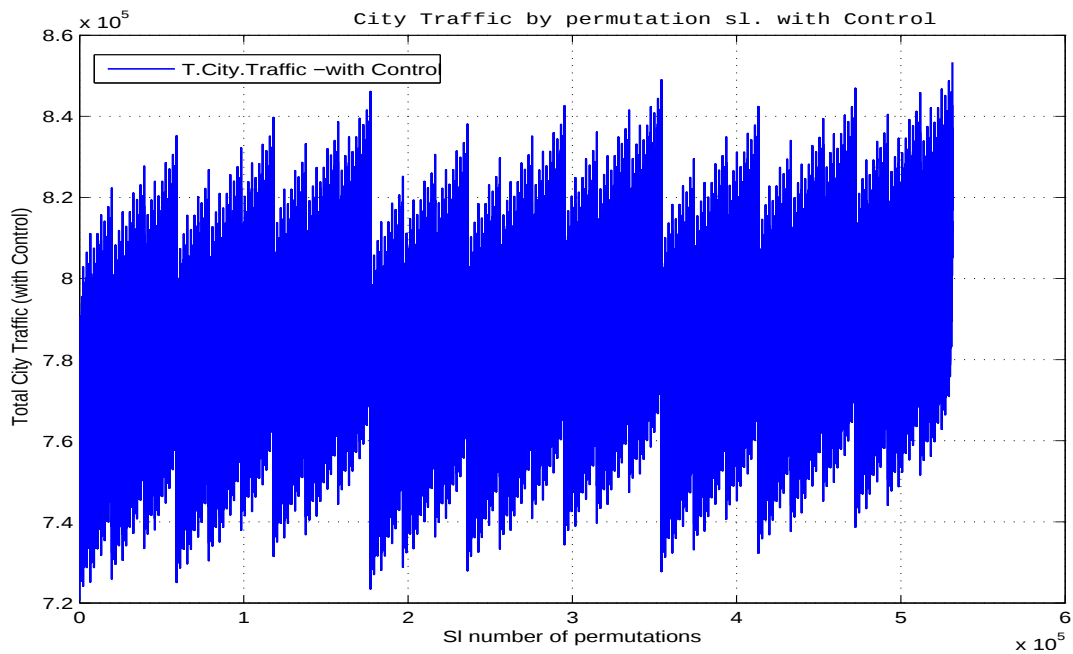


Figure 4.26: Total City Traffic (with Control) for each permutation set

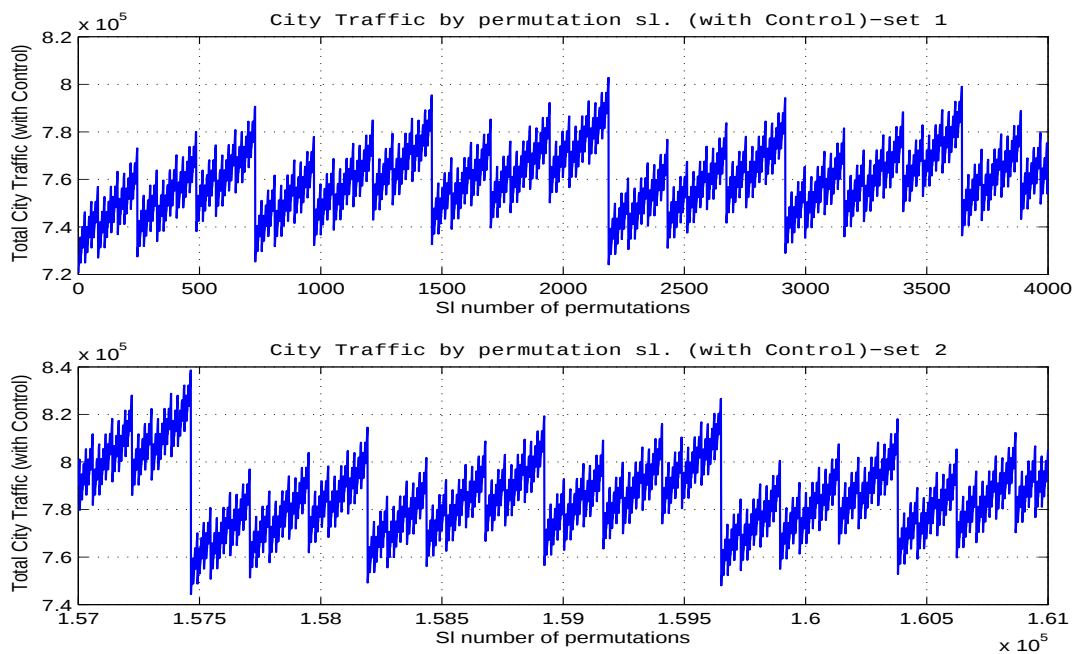


Figure 4.27: City Traffic by permutation sl. (with Control)-set 1 and 2

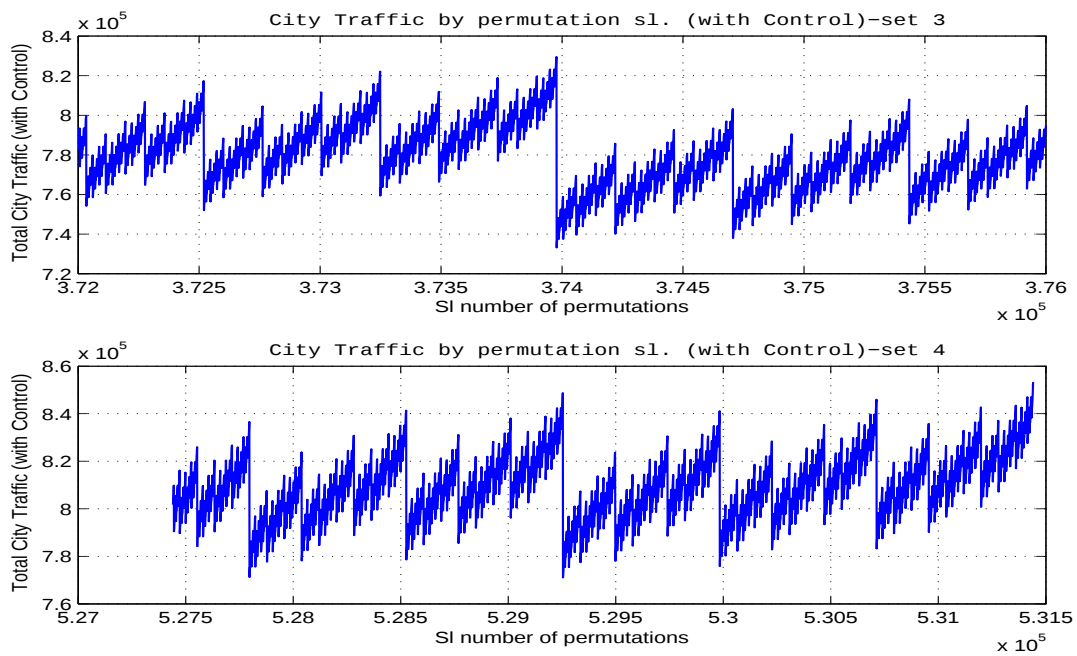


Figure 4.28: City Traffic by permutation sl. (with Control)-set 3 and 4

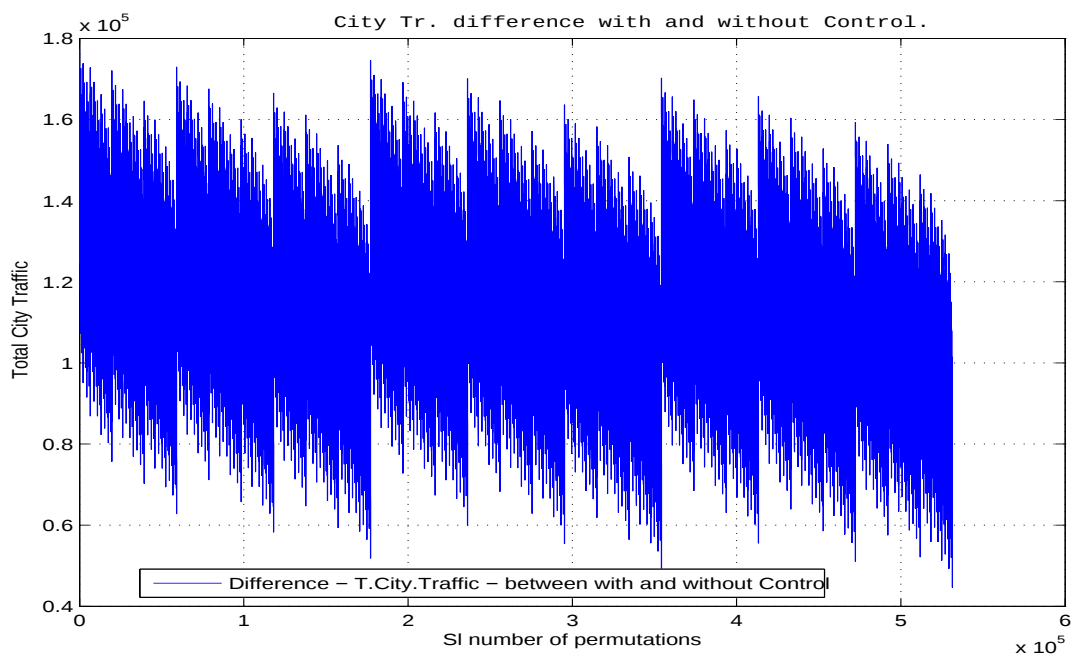


Figure 4.29: Difference of City Traffic between No Control vs with Control for each permutation set

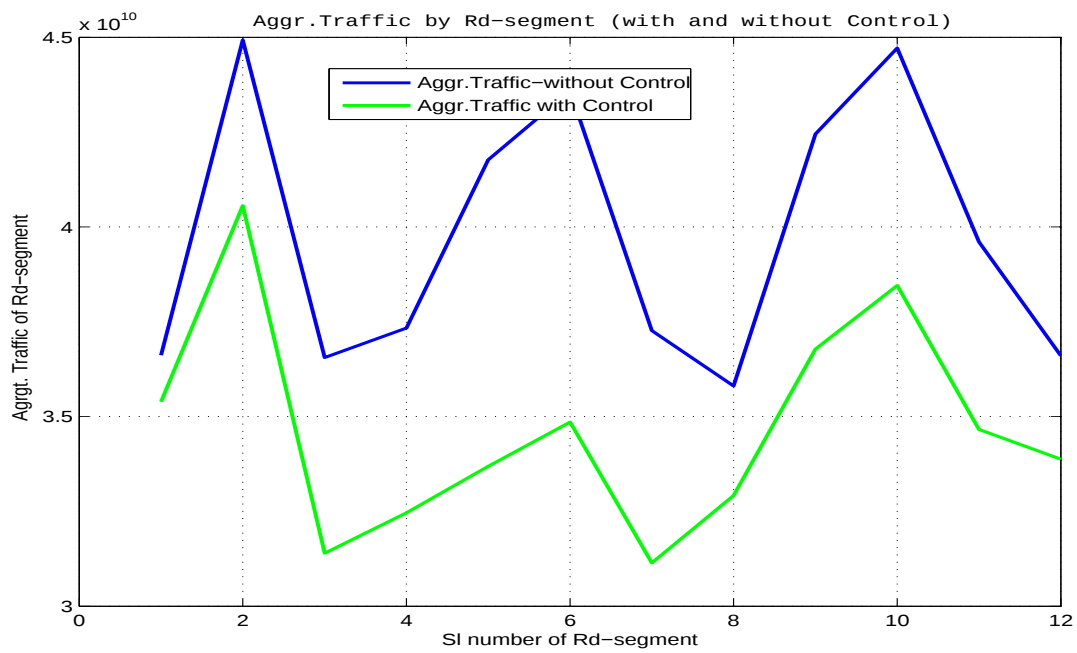


Figure 4.30: Aggregate Traffic by Road segment for No Control vs with Control

Chapter 5

Conclusion and Future Works

5.1 Conclusion

One of the main objectives of Intelligent Transportation Systems (ITS) is to make the road transportation system smooth and reduce the level of congestion. In order to reduce congestion on the road, numerous studies have been done in this field; some of the focusses of these studies include involving Wireless Sensor Networks (WSN) in road-infrastructure, improving the performance of the traffic light system, using mathematical models to optimize the traffic; using different sophisticated algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Fuzzy logic etc to optimize the traffic and reduce congestion. However, most of the studies focussed either on a block of adjacent intersections, or ignored the direction aspects of a congested node whereas congestion in an intersection does not necessarily block all the directions of an intersection. Few studies have included mathematical models, but most of which are not dynamic model. Also in a congested situation, managing the traffic in a bottom-up approach is important instead of adopting top-down approach by re-directing the traffic to an undesired route without providing the information to the drivers ahead of time.

So, in order to fill the research-gap in the road traffic management field, we have proposed a road-traffic monitoring scheme with dynamic mathematical traffic model that will not necessarily include all the neighboring intersections; rather the important major intersections of the city which may be dispersed in the city. This WSN based monitoring system has been presented with dynamic mathematical model for managing road traffic in important intersections of a city. The purpose of this model is to reduce the conges-

tion in the important intersections of a city by re-routing the vehicles before reaching the congested intersections through informing the down-stream driver's by broadcasting in a dedicated radio channel. This dynamic model can provide with the instantaneous status of the traffic of the road-network.

This proposed traffic monitoring scheme is a WSN based multi-hop relay network with hierarchical architecture and composed of ordinary nodes, cluster-head nodes, gateway nodes and Monitoring and Control Centers (MCC), etc. It will capture data from selected important road intersections of a city through ordinary nodes, Cluster-Head Nodes and then to the base stations; then the data transfer will take place in a wired mechanism sequentially from the gateway nodes to the MCC by using the internet. The MCC will periodically evaluate the congestion status of traffic; when congestion is detected, it will broadcast the information of the congested nodes through a radio channel so that the drivers of the down-stream vehicles (target audience) can take appropriate decision for Detour to a better performing road-segment.

This thesis considered a traffic network with twelve major (important) intersections across the city with four major directions: north, south, west, and east, and four minor turning directions: north-west, south-east, south-west, and north-east. All the intersections are assumed to have traffic arrivals following Poisson Distribution as they are dispersed intersections at different locations in a city (i.e. they are not necessarily neighbors). At maximum, an intersection may have lanes from 8 directions and some may have lanes of less number of directions but at least from 2 directions which makes it as an 'L' or 'T' junctions.

Our dynamic model includes two components, first one is for traffic generation and the second one is a cost function for performance measurement. Through collecting the traffic information, the MCC will evaluate the congestion status and in defining the congestion, threshold factors have been used in this model. For the congested situation of a road-segment, a cost function has been defined as a penalty and this cost is estimated using the weight factors proportionate to the importance of these selected intersections. Model was simulated in Matlab with traffic generated through Poisson Random Number Generator and cost function was estimated for the congestion status of the road-segments over the simulation period of 1440 minutes (24 hours) starting from midnight.

For determining the optimum setup, we used the exhaustive search technique but

for larger configurations, this is computationally infeasible over, all possibilities. Even in this brute force technique, we have got $3^4=12$ road-segments and we included three (3) threshold factors to choose from to define the threshold capacities of different road-segments and thus we had $3^{12} = 531,441$ different choices to evaluate. Since we have finite number of choices here, we adopted the brute force approach of search technique to determine the optimum choice. The formal approach would have been more promising but would have needed more time; so, to save time, we decided to the Brute Force approach.

Results showed that our proposed scheme can efficiently reduce cost by reducing road traffic congestion and improve the traffic performance. Contribution of this study to existing research is the true dynamic model itself and capability of handling all important intersections of a city by a model. Because of bottom-up approach of this system, vehicle drivers will not be forced to detour on an unwanted direction, rather they will have option to choose detour-path in case of congestion and thus will reduce frustration in drivers.

5.2 Future Works

Because of lack of time and resources we did not undertake the formal optimization procedure, thus for determining the optimum setup, we used the exhaustive search technique with a relatively smaller configuration of three (3) intersections and their four (4) major directions giving us $3^{12} = 531,441$ different choices to evaluate. In future with enough time and resources formal optimization of the model can be performed for larger configurations with more options of threshold factors.

Another interesting factor in this model is the non-compliance factor (θ), when it is measured in real time; it can be a good indicator of driving characteristics of drivers of a city and can be used in social studies for accident control. For our simulation we had to assume a θ , but in real time it may vary, which may affect the overall performance of this scheme. In future, some further research works can be carried out combining this scheme and the adaptive green-light control mechanism. One relatively newer topic also needs to be considered in the road-traffic optimization discussion which is ‘traffic-circles’. The inclusion of this aspect in the model will give excellent reliability to the analysis.

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Appendix A

Comparison of the research work of [1] and our proposed model

Laisheng et al. have proposed a traffic flow congestion control model based on grey forecasting process which will monitor the important roads of a city which easily get congested. The traffic flow forecasting model is developed with the use of Adaptive GM (1, 1) model¹. It generates time series data by using the raw data collected by the WSN and as time goes, it keeps updating the data by replacing the oldest data by the latest segment of data, which is the speciality of the Adaptive GM Model [1].

Data collected by the WSN is initially used as the raw data series:
 $X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\}$, n is the sample size of the data. Then time-series data is generated $X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\} \dots (1)$

where, $x^{(1)}(k) = \sum_{i=1}^k x^{(0)}(i), k = 1, 2, 3, \dots, n$; they have used the differential equation:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b \dots (2)$$

and least squares method to calculate the value of ‘a’ and ‘b’ using equation

$$(a, b)^T = [X^T X]^{-1} [X^T Y] \dots (3)$$

¹In grey systems theory, GM(n,m) denotes a grey model, where ‘n’ is the order of the difference equation and ‘m’ is the number of variables. GM(1,1) refers to the First Order, One Variable Grey Model.

$$\text{where } X = \begin{bmatrix} -\frac{1}{2}[x^{(1)}(1) + x^{(1)}(2)] & 1 \\ -\frac{1}{2}[x^{(1)}(2) + x^{(1)}(3)] & 1 \\ \vdots & \vdots \\ -\frac{1}{2}[x^{(1)}(n-1) + x^{(1)}(n)] & 1 \end{bmatrix}$$

and

$$Y = [x^{(0)}(2), x^{(0)}(3), \dots, x^{(0)}(n)]^T$$

Then the GM (1,1) forecast model is estimated by putting the value of a and b in the differential equation (2) as:

$$\hat{X}^{(1)}(k+1) = [x^{(0)}(1) - \frac{b}{a}]e^{-ak} + \frac{b}{a} \dots (4), \text{ where } k=1,2,3,\dots,n;$$

and $\hat{X}^{(1)}(k+1)$ is the predictive value of generated data series.

The modeling approach adopted here is to set original data series as:

$$\{x^{(0)}(i)|i=1,2,\dots,n\} \dots (5).$$

The new forecast value $x^{(0)}(n+1)$ is added to $x^{(0)}$, and the oldest data $x^{(0)}(1)$ is removed to get the new data series $\{x^{(0)}(i)|i=2,\dots,n,n+1\} \dots (6)$

The congestion control algorithm TRED (Traffic Random Early Detection) proposed in this paper has been adopted from the concept of computer networks AQM algorithm RED (Random Early Detection). It first calculates the average length of traffic queue and categorizes the situation of an intersection into one of the three stages of congestion, namely (i) Normal (No congestion), (ii) Non-compulsory (av. queue length is between minimum-threshold, and maximum-threshold) and (iii) Compulsory stage. Depending on the stage (probability of scheduling vehicles) it opts for the source side traffic to be redirected. In the 1st case, no action is taken and in the 2nd case scheduling the source side traffic to other lanes with the mark probability P_a has been recommend and in the last case of a serious congestion, redirection to other lanes is a must for eliminating congestion.

Indeed, this model is based on the algorithm of ad-hoc network traffic where approximation of large number is okay but in case of road traffic it is very different in nature; and also it is a very old algorithm which has been modified a lot even for the network traffic and now is of almost no use. The network traffic does not face any intersection or traffic signals while the road traffic has to pass through them in large numbers; also the

number of network packets pass through a Router is significantly large than the volume of traffic (number of vehicles) in an intersection. In addition to that, this model did not pay attention to the direction aspects of a road in case of congestion. An intersection may have lanes from all eight (8) directions and although some directions become congested, not necessarily all the direction's traffic are affected by that congestion and thus don't need to be re-directed to another lane. The lack of direction issue may make this model too much generalized and also inefficient for an intersection. Another aspect is the top-down approach, adopted in this model while the bottom-up approach could be brought forward where, after receiving the congestion information, drivers could make informed-decision considering all kind of information like the distance of the destination, congestion status and possible waiting time of alternative paths etc. Also the prioritization among the intersection in respect of congestion avoidance is not addressed by this model. Lack of any simulation result of the proposed system also is an issue for the further need of research.

Moreover, top-down approach has been adopted in this model while the bottom-up approach could be brought forward. The scheduler is proposed to redirect the traffic to another lane which may cause disappointment to some drivers because of increased length of detour path. In order to fill this gap we have proposed a true dynamic model which can address this issue properly. The only approximation used in our model is our assumption of the arrival is Poisson process but it is not the homogenous ordinary Poisson process, rather the time-varying Poisson process. In our model we have proposed the bottom-up approach, where the driver will choose the direction and the intersection where they will adopt the detour in order to avoid the congestion as the congestion status of the road-network will be broadcasted to all the drivers by radio system. Also, the issue of rescheduling the 'source side traffic' by the proposed system [1] will also face a big question; it will not be feasible if that lane (where traffic to be redirected) is also congested. On the other hand, the drivers will have the scope of choosing from more than one intersection and also the direction to turn in order to reach the desired destination if they are aware of the congestion status of the route towards their destination.