TECHNICAL UNIVERSITY OF CRETE
SCHOOL OF PRODUCTION ENGINEERING AND MANAGEMENT

Comparison of decentralized and centralized signal control methods on a large-scale urban network

MSc Thesis for the postgraduate program
"Operational Research"

Pappa Theodora

Chania 2016

This master thesis is accepted from the committee:

Papamichail Ioannis, Assistant Professor ……………………………..

Papageorgiou Markos, Professor ……………………………..

Nikolos Ioannis, Associate Professor ……………………………..

Thanks

Finalizing this master thesis, I would like to thank Dr. Diamantis Manolis for the great assistance that he provided to me, as well as Dr. Christina Diakaki for her assistance whenever she was asked throughout my thesis. Also, I would like to thank Prof. Ioannis Papapichail and Prof. Markos Papageorgiou who gave me the opportunity to work with them since 2013. Finally, I would like to thank my family and Kiriakos for always supporting me.

Contents

Table of figures

Tables

Abstract

Nowadays, the rapid increase of the number of vehicles has turned the traffic congestion to a frequent occurrence in urban areas and, as the construction of new infrastructure is usually not possible, there is a great need to exploit the existing infrastructure through a more efficient management of the traffic flow. Signal control includes a variety of methods and has been considered as one of the major means to respond to this challenge.

Traditionally, centralized control strategies, developed based upon more or less complex traffic flow models, have been considered as the most appropriate approach towards traffic flow management and control in urban areas. Recently, however, a shift is observed towards the development of approaches, which, based on a decentralized and model-free logic, are expected to improve the traffic flow efficiency at network level, with a minimum design effort and infrastructure investment.

It is the aim of this thesis to present, study, and compare two innovative decentralized approaches proposed in the relevant literature. The first, which is the basis of the SURTRAC traffic control system, considers the signal control as a job scheduling problem, while the second which is known as the max or back pressure algorithm, considers the signal control problem as a resource allocation problem. The thesis aims also at comparing the effectiveness and performance of these decentralized approaches against a well-established centralized strategy, the TUC (Traffic-responsive Urban Control) strategy, which has been developed so as to provide coordinated traffic responsive control in large-scale urban networks.

For the purpose of the investigations, the simulation model of a part of the urban network of Chania, Greece, is used under several scenarios of demand. Summarized conclusions are finally given, on the strengths and weaknesses of each approach, together with some directions for future research.

1 Introduction

As a result of population, motorization and urbanization growth, in some cases traditional urban strategies cannot meet the requirements of a modern city. Traffic congestion remains an important problem in many cities around the world. This phenomenon increases the need to manipulate the traffic demand, if the supplied infrastructures cannot manage it. The investment of new infrastructures is an expensive solution for the authorities. The most attractive denouement is to develop a strategy that can manipulate the traffic demand without infrastructure alteration. A traffic network is shown at Figure 1.1.

Figure 1.1 – A traffic network

Traffic congestion occurs when the number of vehicles that use the same infrastructure is larger than the capacity. The positive outcome of this problem is the formulation of large manageable queues. The worst outcome of congestion is infrastructures' degradation with delays, reduction of safety and increase of environmental pollution.

The effective, secure and less polluting transportation through the available infrastructure reinforces the need for its optimal utilization via appropriate traffic control measures. The traffic flow in a network depends on some external parameters that can be categorized into two groups:

- ***Control inputs*** are related with control devices, such as traffic lights, detectors, etc.
- ***Disturbances*** concern values that cannot be manipulated but can be measured, such as demand, or detectable, such as incidents.

The output of the traffic network can be measured via indices such as total time spent or total travelled distance by all vehicles in the network. The main core of the control loop is the control strategy, which specifies the control inputs, based on measurements or estimations, so as to achieve the main objective.

However, during the solution of an optimal control problem, several difficulties may be encountered:

- The switching of traffic lights needs the introduction of binary variables, which increases the complexity of the problem.
- The problem is getting larger when the congestion occurs to the whole network.
- Unexpected disturbances may influence the traffic flow.
- The necessary measurements are mostly local and noisy due to various physical effects.
- There are hidebound real-time constraints, such as decision making within a specified space time.

These difficulties appear in problems with more than one intersection. To solve this kind of problems, control strategies have been developed which can be classified as follow:

- ***Fixed-time strategies*****:** they are based on historical constant demands.
- ***Traffic-responsive strategies***: they use real-time measurements to calculate the appropriate signal settings in real time.
- ***Isolated strategies*****:** they are applied in single junctions.
- Strategies which are not applicable to undersaturated or oversaturated traffic conditions.

Isolated fixed-time strategies can only be implemented to undersaturated traffic conditions. Stage-based strategies such as *SIGSET* and *SIGCAP* define the optimal splits and cycle time in order to minimize the total delay or maximize the capacity of the junction. A common type of strategies is phase-based strategies which also determine the optimal stage changing.

Isolated traffic-responsive strategies use real-time measurements provided by loop detectors in order to determine splits and cycle time for given stage sequence. The *vehicle-interval method* is one of the simplest strategies of this category which can be implemented to two-stage junctions. The stages of the junction have minimum green durations. If no vehicle has been detected during the minimum green duration, the strategy continues to the next stage. If a vehicle passes during a critical interval, a green extension is provided so as the vehicle can cross the junction. If no vehicle is detected during this interval, the strategy moves on to the next stage.

Fixed-time coordinated control strategies are only implementable to networks with undersaturated traffic conditions. The most overused strategies of this class are MAXBAND and TRANSYT.

The MAXBAND strategy (Little et al. 1981) considers a two-way arterial with junctions and aims to define the offsets in order to maximize the number of vehicles that can travel without stopping (green wave) with given splits. To reduce the computational effort the usage of a branch-and-bound solution could be beneficial. The basic method was extended, so as to be implementable to networks arterials, making use of cycle constraints.

TRANSYT (Robertson 1969) is a determining optimum fixed-time traffic signal method, in which known flows are allowed to pass through the roads of the network with the minimum resistance. This assists the flow interaction between road sections, the spreading of platoons and the flow control by signals. The calculations correspond to a short solution time. The method converges quite well on the optimum signal settings and minimizes the total delay and the number of stops. Also, the signal offsets and the green times can be optimized. Finally, the method has been tested in networks over 50 intersections.

The most representative of the ***coordinated traffic-responsive strategies*** is the SCOOT strategy (Hunt et. al 1982). SCOOT (Split Cycle Offset Optimization Technique) is the traffic-responsive version of TRANSYT. SCOOT uses traffic volume and occupancy measurements from the upstream of the network links. This strategy requires real measurements and it is applied in real time to investigate the results of changes of splits, offsets and cycle time. If these changes are efficient they are applied to the network.

Traditionally, control strategies of a centralized logic have been considered as the most appropriate approach. Classical signal control strategies assume a cyclic operation of traffic lights, where each of which acts through the coherence of phases. In this study a well-established centralized control strategy and two innovative decentralized approaches are presented.

2 *The investigated signal control methods*

Nowadays, the improvement of traffic flow in urban areas is getting more and more important. Eliminating traffic problems in cities, ameliorates the quality of life and significant problems such as fuel consumption and wasted times could be solved. In this chapter presents some basic notions for an urban network, as well as the main characteristics of decentralized and centralized approaches that have been studied in this thesis.

2.1 Basic notions

An urban network consists of *streets* that cross at *junctions*. The urban junctions consist of approaches and a common *crossing area* (Figure 2.1), which can be signal-controlled. That makes it a part of the signal control. An *approach* can have one or more lanes but these lanes constitute only one independent *queue*. A *traffic stream* is composed by all vehicles that cross a junction from the same traffic stream. When two traffic streams can safely cross the junction simultaneously, they are called *compatible*; otherwise they are called *incompatible* or *conflicting*.

To ensure the safe crossing of conflicting traffic streams and pedestrians movements, *traffic lights* are used at junctions. Their control is based on the *signal cycle* and its duration is called *cycle time*. The signal cycle consists of a set of stages which must not operate simultaneously. During a *stage*, a set of compatible streams has right of way (r.o.w.). Between stages, a few seconds are interfered, which are specified for every signal cycle and they are called *lost times*. They are used to avoid intervention between conflicting streams of subsequent stages.

During a signal cycle of a centralized approach at an urban network, all cycle times of all junctions coordinate. This is the minimum requirement for its implementation. However, the decentralized approaches, which are investigated in this study, require for their implementation only the *sequence* of the stages and the minimum and maximum green durations, which determine the *minimum* and *maximum cycle times* for each junction of the network.

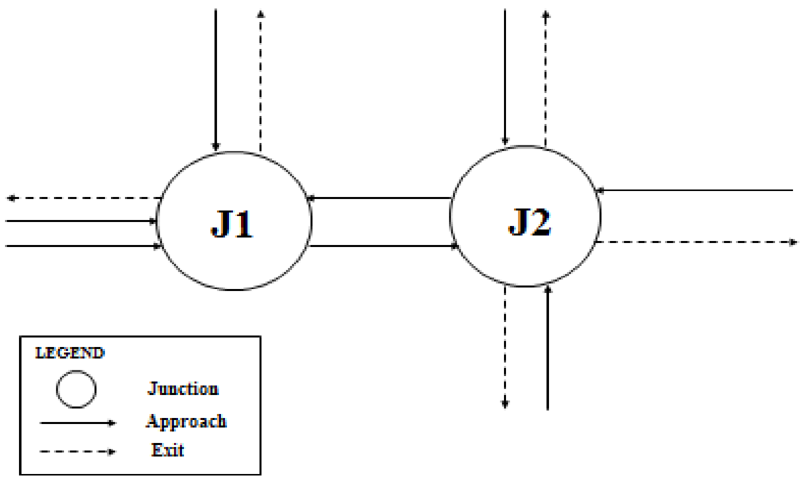


Figure 2.1 - Network with 2 junctions

2.2 Intersection traffic control

A signalized intersection is considered with a set of entry and exit approaches. Each approach has specified characteristics as fixed length and a set of lanes. A *phase design* defines the traffic movements and the traffic signals. This *phase* design contains a set of *phase*s I, in which each *phase* index $i\in[1,|I|]$ corresponds to the right-of-way for a route i. Each route involves a set of incompatible movements that allow the safe crossing of vehicles into the junction, in which movement determines the traffic flow from the entrance to the exit of an approach. If one movement has right-of-way, all the other movements must have a red traffic light, to ensure the safe crossing of them (Xie et al., 2012). To ensure safety, there are some operating constraints on the *phase* switching:

- The *phases* must switch in a specific order; to switch a *phase* the following equation is used: $(i) = (i+1)\text{modulo}(|I|)$, where i corresponds to the current *phase*.
- The duration that a *phase* can be active is between $[G_{min}^{(i)}, G_{max}^{(i)}]$, where $G_{min}^{(i)}$ and $G_{max}^{(i)}$ are the minimum and maximum green times of *phase* i.
- Between the *phases*, a fixed intergreen time $Y^{(i)}$ must be interposed, during which no vehicles can pass from the intersection.

The definition of a *phase* contains two indices (i,g): i which corresponds to the *phase* and g which corresponds to the duration of the *phase* i. The phase switching sequence corresponds to the sequence of phases, given an initial phase condition (i_c, g_c), where i_c the current green *phase* index and g_c is the duration the current *phas*e has been green. The operation period can be calculated by adding the duration of the phases and the associated intergreen times. This can be extended by increasing the duration g_c whenever it is necessary.

For intersection optimization, some input information is used such as operating constraints, route flow information and related setting parameters, which are constant in every intersection. The operating constraints include the definition of signal time and the condition of the current *phase*. The route flow information includes the size of the formulated queue $q^{(i)}$ and temporary arrival description of incoming vehicles between $[0, H_p^{(j)}]$ on each route j, where $H_p^{(j)}$ correspond to the prediction horizon. The origin time point is set at the stop line of the intersection. The maximum prediction horizon is H_p=$max_{i=1}^{|I|} H_p^{(j)}$.

2.3 Job scheduling algorithm

Strategies based on intersection optimization have been widely proposed and investigated for distributed traffic signal control in road networks. In this master thesis, a schedule driven intersection control strategy is presented, which is known as *Job Scheduling algorithm* and is used by the system SURTRAC (Scalable Urban Traffic Control) (Smith et al., 2013).

This decentralized approach considers the traffic signal control problem as a *single machine* scheduling problem. The vehicles that enter in a junction approach within a specified time period are grouped into clusters. These clusters correspond to the different jobs that a single machine (the signal controlled junction) must integrate with the minimum delay. An important notation is that the *phases* of a junction cannot operate simultaneously.

The basic frame of this method is described with the following *steps*:

- Clustering
- Queueing
- Scheduling
- Control decision

2.3.1 Clustering

As it is mentioned above, the incoming vehicles of a junction are grouped into clusters so as to be served. Each cluster belongs to a sequence $C^{(i)}$. The traffic flow is not uniformly distributed within the prediction horizon H_p. Each set C includes clusters $(c^{(1)}, c^{(2)}, \ldots, c^{(|n|)})$, where $|C|$ is the number of clusters in C, and these clusters are characterized from five attributes which are $|c|$, arr, dep, dur, fr, where:

- $|c|$ is the number of vehicles in c
- arr is the expected arrival time in reference to the stop line of the junction for the first vehicle in c
- dep is the expected departure time in reference to the stop line of the junction for the last vehicle in c
- dur is the duration between dep and arr
- fr is the average flow rate when cluster c is serviced

The most important attributes are the $|c|$, arr, dep because the abstraction of arrival time from departure time gives the duration of the cluster ($dur = dep - arr$). Also, dividing the number of vehicles in a cluster with the duration gives the flow rate ($fr = |c| / dur$) (Fig 2.2).

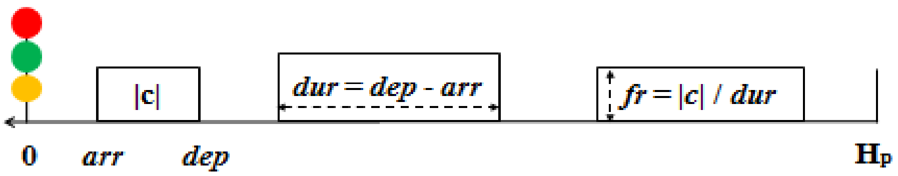


Figure 2.2 - Example of clusters on a route

The distance between the entrance detector and the exit detector of every link is known and the speed of the vehicles is considered to be constant. Dividing the distance by the speed, the prediction horizon can be estimated and divided into time segments with a fixed interval for detection, symbolized as $\boldsymbol{samp}$. The scale of the segments starts from 1 to $\boldsymbol{H_p/samp}$ and the number of the vehicles that arrive in the $\boldsymbol{h^{th}}$ segment is denoted as $\boldsymbol{a^{(h)}}$. The vehicles that belong to a segment move to the next one in order to exit from the junction. The size of $\boldsymbol{a^{(h)}}$ always changes according to the arriving vehicles that are added. If $\boldsymbol{a^{(h)}}$ is a positive value, is restructured to an arriving cluster which is stored into $\boldsymbol{C}$, with number of vehicles equal to $\boldsymbol{a^{(h)}}$, departure time equal to $\boldsymbol{h \times samp}$ and service duration equal to the time step $\boldsymbol{samp}$. This process continues until all the arriving vehicles have be classified into clusters.

If the arriving vehicles are within a critical interval, they will be continuously served. The new cluster consists of any two merged arriving clusters, when the time gap between them is within a critical threshold, which must be always positive ($\boldsymbol{thc} \geq 0$). In other words, the clusters $c_{(1)}$ and $c_{(2)}$ are merged into one cluster $c_{(0)}$ for which the arriving time (arr), the departure time (dep), and the number of vehicles ($|c_{(0)}|$), are calculated as follow:

$arr(c_{(0)}) = min(arr(c_{(1)}) , arr(c_{(2)}))$,

$dep(c_{(0)}) = max(dep(c_{(1)}) , dep(c_{(2)}))$ and

$|c_{(0)}| = |c_{(1)}| + |c_{(2)}|$.

2.3.2 Queuing

For each cluster the departure time can be predicted. If there is a red traffic signal and the detector at the stop line has not count any exiting vehicle, the cluster that was supposed to exit is called queue (q) and it will be the first cluster that will be served from this approach. The arrival time of this cluster is $arr(c_{(q)})$=0, the flow rate is $fr(c_{(q)})$=sfr (saturation flow rate) and the number of vehicles of this cluster is $|c_q|=q$. The length of the queue is changing depending on the arriving clusters. If the last vehicle of the queue has not been served and vehicles from the next cluster arrived, then it will be merged with the queue and the necessary time to be served is extended. The technique that is used to succeed it extends the initial queue cluster c_q as follows:

Anticipated queue clustering: By the term ***anticipated queue*** is meant the number of vehicles that are currently or will, in the future, participate in the queue, before the existing vehicles of the currently served queue exit the junction. The anticipated queue is an extension of the initial queue cluster c_q. The arriving time (arr) and the *flow rate* (fr) of the new queue cluster do not change and the number of vehicles ($|c_q|$) increases only if any vehicle participates in the queue. The *departure time* (dep) and the service *duration* of the queue cluster (dur) increase depending on the increase of $|c_q|$. All the clusters in C are examined separately. Supposing that the j^{th} cluster of C ($c^{(j)}$) arrives before all the vehicles of queue cluster c_q depart from the junction ($arr(c^{(j)}) \leq dep(c_q)$), the anticipated queue is extended as follows:

a. If the j^{th} cluster will leave the junction earlier than the queue cluster ($dep(c^{(j)}) \leq dep(c_q)$), or the flow rate of the first is higher than the queue's cluster flow rate, then the $c^{(j)}$ totally joins into c_q. The number of vehicles of queue cluster becomes $|c_q| = |c_q| + |c^{(j)}|$ and $c^{(j)}$ is removed from set C.

b. Else, a part of the cluster $c^{(j)}$ or all cluster's vehicles join into the queue cluster c_q. The necessary duration to be served the queue cluster is extended by $\delta dur = \frac{\mathrm{dep}(c_q) - \mathrm{arr}(c^{(j)})}{1 - \frac{\mathrm{fr}(c^{(j)})}{\mathrm{sfr}}}$, depending on whether the flow rate of the later part of cluster $c^{(j)}$ has not changed:

   i. If the extended duration (δdur) is equal or higher than the duration of cluster $c^{(j)}$, it joins into the queue cluster c_q and it is removed from C, with queue length equal to $|c_q| = |c_q| + |c^{(j)}|$.

   ii. Else, the *earlier part* of the cluster $c^{(j)}$ participates in the queue cluster and the number of vehicles becomes $|c_q| = |c_q| + |c^{(j)}| * \frac{\delta \mathrm{dur}}{dur(c^{(j)})}$.

   The *later part* of the cluster $c^{(j)}$ remains in C, as a new cluster (c^{new}). The arriving time of the new cluster is calculated as $arr(c^{new}) = arr(c^{(j)}) + \delta dur$, its departure time is $dep(c^{new}) = dep(c^{(j)})$and the flow rate is $fr(c^{new}) = fr(c^{(j)})$.

The whole process is terminated depending on the following conditions:

- If the cluster $c^{(j)}$ arrives after the departure of all vehicles of queue cluster c_q ($arr(c^{(j)}) > dep(c_q)$), **or**
- If the choice (b- ii) has been completed.

2.3.3 Scheduling

After formulating the clusters and exporting the queues of each approach, the algorithm develops a time schedule which determines the coherence and the duration of the cycle stages so as to serve all the vehicle clusters. The algorithm develops all the possible schedules to decide which of them can best serve all the clusters. Then, the algorithm chooses the schedule with the minimum delay, using a forward recursive algorithm. The state space can be introduced as a decision tree. Each schedule starts from the route node and every new job is added to the end of sequence at each stage. States which define the same jobs and the same last job are grouped at the same depth of the decision tree. Only the state with the minimum delay will be kept, using a greedy state elimination strategy. For these calculations, the algorithm takes into account not only queue delays but also lost times.

Figure 2.3 shows two example schedules with their phase switching sequence. For the *Schedule 1* the phase sequence is (1, 3, 1, 2, 3, 3, 1 and 1). Firstly, the first cluster of the phase 1 will be served, then the first cluster of phase 3 will be served, then the second cluster of the phase 1 will be served, etc. Commonly, for the *Schedule 2* the phase sequence is (3, 1, 1, 2, 3, 3, 1 and 1).

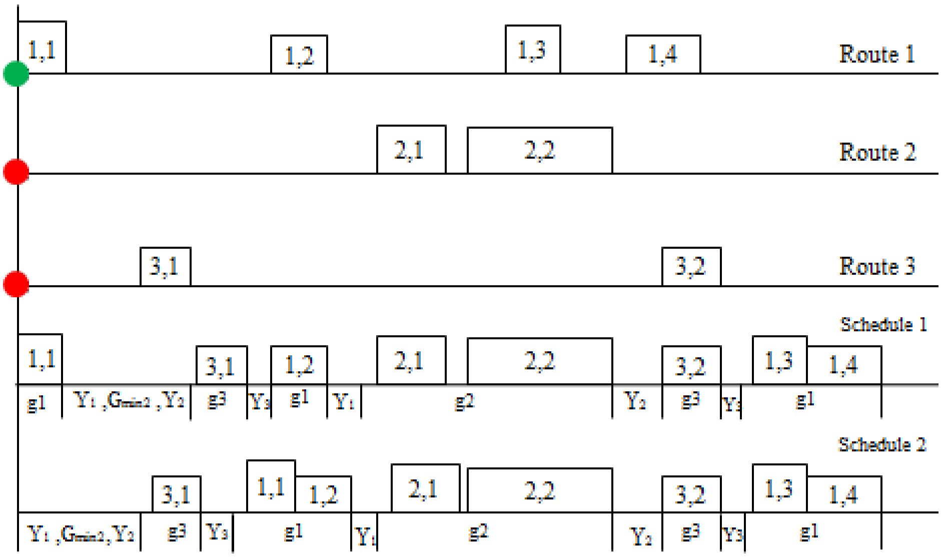


Figure 2.3 - Schedules of clusters with phase switching

2.3.4 Control decision

The last part of the algorithm is the decision making. For as much as the scheduling has been completed, the first stage of the schedule is applied. If the first cluster of the selected schedule belongs to the current stage, the duration of the current stage will be extended depending on the duration of the cluster to be served. Else, the algorithm will continue to the next stage. At this point it should be noted that only the first part of the best schedule is applied. The algorithm makes decision when the previous decision has completed or the minimum green duration has ended.

The Job Scheduling algorithm presents some several weaknesses. As mentioned above, the number of the incoming vehicles must be accurate, for the right implementation of the method. In real traffic conditions, this could be difficult because of some possible malfunction of a detector (wrong measurements at the entrance or exit detector). The correct count of the existing vehicles can be achieved with the usage of latest technology detectors or cameras. Another important drawback of job scheduling method is that the computational time grows exponentially with the number of formulated clusters. To reduce the computational cost, the clusters merge into one if the time gap between them is lower than a threshold. The last significant drawback of this approach is that two different stages of the signal control of a junction cannot serve the same traffic stream. This fact intensifies the need to study the network carefully.

2.3.5 The SURTRAC System

The job scheduling algorithm operates under the SURTRAC system, which is formulated as a schedule-driven process. As mentioned above, each junction is operated independently by a local scheduler. The scheduler contends a phase schedule which aims to minimize the total delay time of the vehicles in the network. Also, it continuously makes decisions to update the schedule that will export the optimal solution (Smith et al., 2013). Central to this method is the formulation of intersection control optimization as a scheduling problem. The main characteristics of SURTRAC are:

- Operates totally decentralized; each junction acts independently and asynchronously. The green time differs in each junction and its calculation is based on the incoming flows.
- Aims at managing road networks with multiple traffic flows.
- Operates in real time; after making a decision the allocation plan is recomputed to response to sudden changes in traffic conditions.

2.4 Max pressure or back pressure algorithm

The max pressure algorithm is a decentralized approach that considers the incoming vehicles of a junction as customers that must be served by a number of servers. The available servers correspond to the different stages of the urban junction. The stages of a junction cannot operate simultaneously. The overall objective of this approach is to maximize the number of the served vehicles of a network, i.e. to maximize the throughput of the system. The vehicles arrive at the junction independent and identically distributed (Varaiya 2013).

For the max pressure algorithm, many alternative variants have been proposed. The variant that is used in this study respects fully the stage sequence such as some minimum and maximum green duration for each stage. These admissions assist the safe pedestrians' crossing and also avoid drivers' confusion.

2.4.1 Calculation of pressure

The basic idea of the max pressure algorithm is based on the calculation and the utilization of a pressure for every signalized link of the network. Many variations of this approach have been proposed (Varaiya, 2013; Kouvelas et al., 2014; Gregoire et al., 2014). This pressure is related to the length of the queues and their capacity. The pressure of a link can be calculated with the following Equation 2.1 (Kouvelas et al. 2014):

$$p_z = \left[\frac{x_z}{x_{z,max}} - \sum_{w \in O_n} \frac{\beta_{z,w} x_z}{x_{w,max}}\right] * S_z \qquad (2.1)$$

where

$\boldsymbol{z}$ is the current link,

$\boldsymbol{w}$ is one of the downstream links of link z,

$\boldsymbol{p_z}$ is the pressure of link z,

$\boldsymbol{x_z}$ is the number of vehicles waiting to be served in link z,

$\boldsymbol{x_{z,max}}$ is the storage capacity of link z,

$\boldsymbol{\beta_{z,w}}$ is the turning rate of link z to the link w,

$\boldsymbol{x_{w,max}}$ is the storage capacity of link w, and

$\boldsymbol{S_z}$ is the saturation flow of link z.

In this study, the pressure of the link is calculated from the Equation 2.2:

$$p_z = \left[\frac{x_z}{x_{z,max}} - a * \sum_{w \in O_n} \frac{\beta_{z,w} x_z}{x_{w,max}}\right] * S_z \qquad (2.2)$$

where $\boldsymbol{a}$ is a parameter that shows which is the percentage of participation of the downstream information within Equation 2.2. If downstream information is unavailable, this parameter is equal to zero.

The usage of downstream information for a junction leads to eliminate the forwarding of vehicles at links that are almost fully occupied. This procedure assists to avoid wasted green times, reducing the pressure of the current studied link when this problem occurs to its downstream links.

Finally, the above downstream percentage will be taken into account for the Equation 2.2, if and only if it is higher than a specified percentage (see Chapter 4). These two percentages are set depending on the tested network. It is necessary to investigate exhaustively all the possible combinations of these values that lead to the optimal solution.

Afterwards, the algorithm calculates the pressure of each stage of the controlled junction. The stage's pressure is the sum of all links' pressure that receive right of way at this stage, and it is computed from Equation 2.3:

$$P_j = \sum_{z \in v_j} p_z \qquad (2.3)$$

where $\boldsymbol{v_j}$ is the set of links that receives right of way at stage j and

$\boldsymbol{p_z}$ is the pressure of link z.

For links that receive right of way at more than one stage, a parameter has been utilized that shows in which percentage, each link participates in each stage.

2.4.2 Control decision

For every controlled junction the pressures of all stages are calculated. All stages will be activated respectively to their sequence. The algorithm finds out the stage with the maximum pressure. If the stage with the maximum pressure is currently active, it is granted a green extension on its green duration. Else, if the maximum pressure belongs to another stage, the algorithm will continue to the next stage. To avoid the continuous stage changing for stages that have the same pressure, a constraint is set. If the queue of the currently active stage is higher than a percentage of the queue of the stage with the maximum pressure, the algorithm will not change stage. The algorithm makes decision whenever the minimum green has been reached or the previous decision has ended.

2.5 Traffic-responsive Urban Control strategy (TUC)

The studied decentralized approach, Traffic-responsive Urban Control strategy (TUC), has been developed to provide coordinated, traffic-responsive control in large-scale urban networks, even in saturated traffic conditions. The control objective of the TUC strategy is the minimization and balancing of incoming vehicles within the streets of the network. This can be achieved with the appropriate manipulation of the green splits, assuming given cycle times and offsets (Dinopoulou et al. 2002). This objective is attained with the usage of appropriate methodological tools that attain the following characteristics:

- *High efficiency* as proved by the results of investigations under both simulated and real-life traffic conditions.
- *Robustness* with respect to measurement inaccuracies.
- *Reliability* with respect to hardware failure.
- *Generality* that conducts to easy application in networks with different characteristics.
- *Extreme simplicity*.
- *Limited measurement requirements* as far as it concern the equipment.
- *Low computational effort*.

Three alternative control laws have been developed, for TUC, as an optimal control problem based on a store-and-forward type of mathematical modeling. The first control law uses the Linear-Quadratic (LQ) methodology to the formulated optimal control problem. This control law requires availability of nominal values of green splits. If such data is unavailable, a variation of this control law may be used. Otherwise, a control law developed by Linear-Quadratic-integral (LQI) methodology to the formulated optimal control problem may be used.

The implementation of TUC requires the numbers of vehicles within streets. Otherwise, occupancy measurements may be used to estimate the required numbers of vehicles, with the usage of non-linear transformation functions. The TUC strategy consists of four main parts (Diakaki et al. 2003):

- *Split control*: The aim of this part of TUC strategy is to minimize the risk of oversaturation and the spillback queues. It is based on the Linear-Quadratic regulator theory of automatic control.
- *Cycle control*: The scope of this part is the cycle regulation to the maximum saturation level. It uses a feedback-based algorithm (P-regulator) that modifies the network cycle time.
- *Offset control*: The aim of this part is the coordination of main stages of successive junctions along arterials. It is applied by a decentralized feedback control law.
- *Public transport priority*: The aim of this part is to provide priority to public transportation vehicles. It is effectuated through a rule-based algorithm.

A remarkable ability for user of TUC strategy is that a combination of four parts can be applied. In other words the user can apply only split control, or split and cycle control, and so forth. These parts are applied for specified control intervals. The user also has the ability to use different control intervals for each part.

In this study only the three control laws have been tested, but in the following sections an overview is given for all of them.

2.5.1 Split control

This part of TUC is formulated as a LQ optimal control problem. The control object is the minimization of risk of oversaturation and spillback of link queues. The green-phase durations of all stages of all junctions take values around nominal values without influencing the offsets or the cycle times. The LQ approach consists of the following equation:

$$\boldsymbol{g}\,(\boldsymbol{k}) = \boldsymbol{g}^{\boldsymbol{N}} - \boldsymbol{L} \times (\boldsymbol{x}(\boldsymbol{k}) - \boldsymbol{x}^{\boldsymbol{N}}(\boldsymbol{k})) \quad (2.4)$$

where:

- $\boldsymbol{k}$: discrete-time index for each cycle
- $\boldsymbol{g}$: vector of green times for all stages of all junctions
- $\boldsymbol{g}^{\boldsymbol{N}}$: vector of the nominal values
- $\boldsymbol{L}$: control matrix
- $\boldsymbol{x}$: vector of numbers of vehicles x_z within the links z that approach the controlled junctions
- $\boldsymbol{x}^{\boldsymbol{N}}(\boldsymbol{k})$: vector of the nominal values

The matrix $\boldsymbol{L}$ is different for each network considering its characteristics and it is calculated offline once. These calculations are not considered in real time and it has been proven that they have low sensitivity. The $\boldsymbol{L}$ control matrix is the direct result of the LQ problem formulation, which can be very laborious for large networks.

2.5.2 Cycle control

The alteration of cycle time via traffic lights impacts the traffic conditions. For this approach, the cycle time is the same for the whole network, which is synchronized for all the junctions of the network with the assistance of suitable offsets. An increase in the cycle time of an oversaturated junction grows its capacity; but in an undersaturated junction increases vehicle delays because of the extension of the waiting times.

The objective of cycle control should be to increase the capacities of the controlled junctions as much as necessary in order to restrict the maximum observed saturation level in the network. Throughout TUC application, this objective is succeeded by applying a feedback algorithm, which uses as a criterion for the cycle increases or decreases the maximum saturation level of the prespecified percentage of the network links. The feedback algorithm has three main steps. The first two steps endeavor to regulate the network cycle time to the maximum saturation level. The third step aims to eliminate the delays that could arise at undersaturated junctions. The steps of this algorithm are following:

- The percentage p of the network links with the maximum load $\sigma_Z(k)=x_Z(k)/x_{Z,max}$. The averaged loads formulate the maximum load $\sigma(k)$.
- The cycle of the network is calculated from the feedback control law (P-regulator):

$$\boldsymbol{C}(\boldsymbol{k}) = \boldsymbol{C}^{\boldsymbol{N}} + \boldsymbol{K}^{\boldsymbol{c}}[\boldsymbol{\sigma}(\boldsymbol{k}) - \boldsymbol{\sigma}^{\boldsymbol{N}}] \quad (2.5)$$

  where:

  $\boldsymbol{C}^{\boldsymbol{N}}$: a nominal network cycle time

  $\boldsymbol{\sigma}^{\boldsymbol{N}}$: a nominal average load

  $\boldsymbol{K}^{\boldsymbol{c}}$: a control parameter, the value of which influences the intensity of the control reactions.

  The cycle time that has resulted from the Equation 2.5 is set within the range $[C_{min}, C_{max}]$, if necessary so as to be feasible. These values correspond to the minimum and maximum allowable cycle times, respectively.

The determined cycle time is forwarded to the next split control interval as shown in Figure 2.4.

2.5.3 Offset control

The traffic conditions also can change by determining the offset between successive junctions. This technique can create a “green wave” along successive junctions. The offset control of TUC takes into account the following assumptions:

- Offset is primarily determined by one direction arterials that do not cross each other.
- For arterials with two directions, the offset is defined for each direction. The offset that is applied at last, is a weighted mean of the offsets of the two directions.
- For arterials that cross each other, TUC considers a priority sequence of the arterials considering the relative importance regarding offset specification.

Finally, the offset control is applied to each arterial, initiating from the arterial with the highest priority.

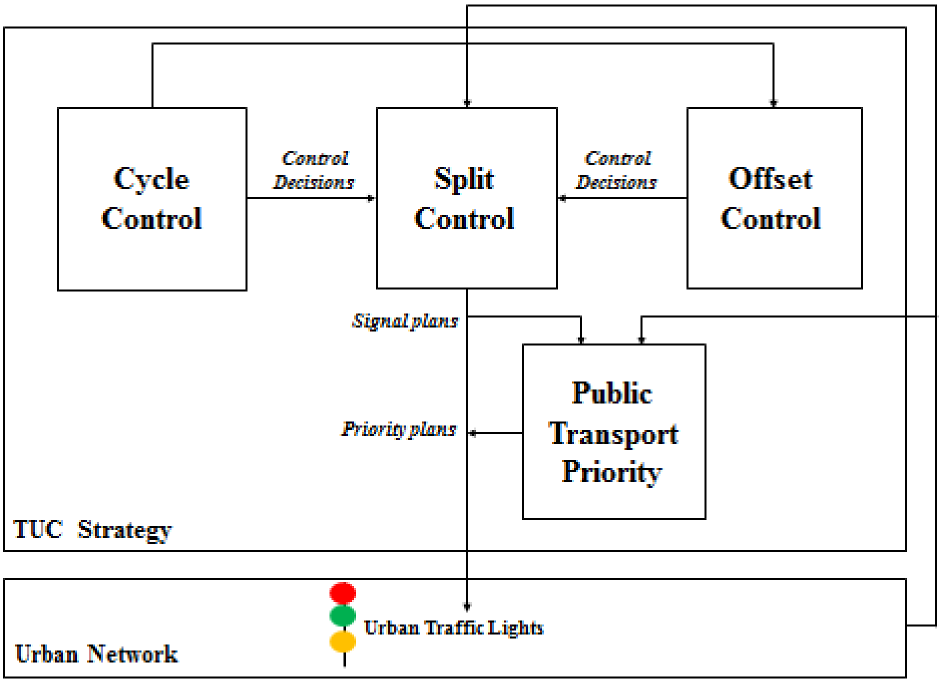


Figure 2.4 – The architecture of TUC strategy

The specification of the ideal offset would take into account the queue of the links. In particular, if the two following traffic flow waves meet exactly at the tail of the existing queue, there is an ideal offset.

Flow wave: The upstream junction (J1) (Figure 2.5) switches the green light and as a consequence the *flow wave* is shaped. This wave moves downstream with v_z and it is anticipated to reach the tail of the existing queue at time $[\,1 - \sigma_z(k)] \times l_z / v_z$ after the green switch.

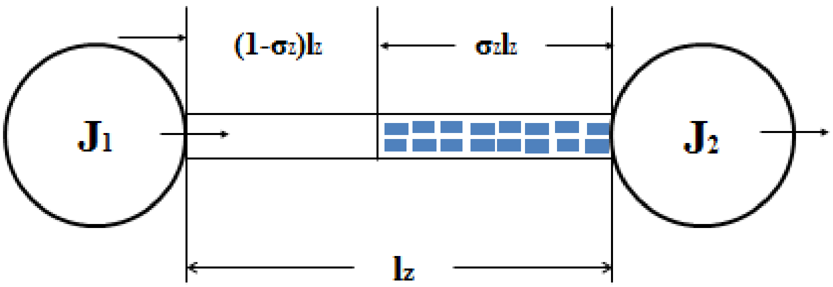


Figure 2.5 - A link z between two junctions

Kinematic wave: The downstream junction (J2) switches the green light and as a result is created the *kinematic wave*, which moves upstream with speed v^c. The speed v^c is estimated approximately at 15 km/h. The kinematic wave is expected to reach the queue tail at time $\sigma_z(k) \times l_z/v^c$. The ideal offset between junctions J1 and J2, in the direction that is shown at Figure 2.5, should satisfy the Equation (2.6):

$$\frac{[1-\sigma_z(k)]*l_z}{v_z} = t_{j_1,j_2}(k) + \frac{\sigma_z(k)*l_z}{v_z} \qquad (2.6)$$

Solving the Equation (3) the offset feedback control law is shown in Equation (2.7):

$$t_{j_1,j_2}(k) = \frac{l_z}{v_z} - l_z * K_z^o \frac{x_{z(k)}}{x_{z,max}} \qquad (2.7)$$

where $\boldsymbol{K_z^o}$ is a control parameter which rises from the equation $\frac{v^c - v_z}{v^c * v_z}$.

2.5.4 Public transport priority

The priority of the public transport vehicles in TUC strategy can be achieved with the following two ways:

- The measurements, which are used in the split control law, can be weighted to provide the presence of public transport vehicles.
- Application of a supplementary module that operates locally the outcoming decisions of TUC, so as to provide priority of public transport vehicles.

The first approach is more appropriate for networks with many partially intersecting public transport lines and high number of movements of public transport vehicles, and requires only the number of public transport vehicles within the network links. The second approach is not suitable for networks such those of the previous approach, because the modification of the signal state can become difficult, if the movement of public transport vehicles are frequent.

2.5.5 Hybrid TUC

A hybrid variant of TUC has been tested in this study (Kouvelas et al., 2011), as the TUC strategy is intended for congested networks. The hybrid variant of TUC has been proven efficient, during both off-peak and congested peak-period traffic conditions. The original TUC strategy uses a multivariable regulator which modifies given fixed-time plans that are based on the current needs of the network. The basic weakness of the regulator is that demonstrates low sensitivity in oversaturated conditions. On the other hand, in undersaturated conditions split decisions are close to utilized fixed plans. The strategy's performance relies on the quality of these plans. In order to develop suitable plans, the hybrid variant of TUC has been developed. In fact, hybrid TUC, in circumstances of low demand needs, uses the flow data that concern to that specific moment instead of the central control plans.

2.6 Presentation of the problem

This master thesis aims to compare and demonstrate the characteristics of two innovative decentralized approaches with a well-known and tested centralized strategy. The Job Scheduling algorithm is not strictly implementable in urban networks of arbitrary signal control characteristics, because it cannot serve an approach that has r.o.w. in more than two stages. The max pressure algorithm on its basic formulation, does not always obey the stage sequence that is however a significant element for real life implementation, in order to avoid drivers' confusion. The scope of this master thesis was to eliminate these problems and to give the ability to the approaches to be implementable in a network.

The approaches are applied in a simulation model, which depicts a part of the urban network of Chania in Greece. The traffic conditions are reacted under several demand scenarios. During the implementation of the investigations some peculiarities were observed for each method that are presented in Chapter 4. Conclusions and remarks are also obtained in this research, for each method separately, but also comparatively, in Chapter 5.

3 *Microscopic simulation*

3.1 Introduction

The microscopic traffic simulator AIMSUN (User's manual, 2004) (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) was used in this study, which can manage different traffic networks. It is imbedded in the simulation environment GETRAM (Genetic Environment for TRaffic Analysis and Modeling).

AIMSUN executes a microscopic traffic simulation. That means that the behavior of each vehicle in the network is continuously modelled during the simulation time period. AIMSUN is a combination of discrete and continuous simulator, which means that there are elements (vehicles, detectors) that their state changes continuously over simulated time into short time intervals. There are also elements (traffic signals, entrance points) that their state changes discretely over simulated time. In general, AIMSUN can depict in detail a traffic network and has the ability to model most of the elements that exist in real traffic networks such as detectors, traffic lights, Variable Message Signs, ramp metering devices, etc.

The necessary input data for the implementation of the simulator is a simulation scenario and a set of parameters that determine the experiment. The scenario is synthesized by the network description, the traffic control plans the traffic demand data and the public transport plans. The first one includes information such as the geometry of the network, turning movements, location that the detectors are placed in the network and layout of links and junctions. The traffic control plans include the description of phases and the duration for signal controlled junctions, the definition of priority for unsigned junctions and information for the ramp-metering. The traffic demand data can be defined as traffic volumes at the input section, the turning proportions and the initial state of the network. The vehicles are distributed stochastically in the network. The traffic demand data can also be determined as an O/D matrix, which is the number of trips of the vehicles from every origin centroid to any destination. A public transport plan includes definitions of bus lines and timetables for each line.

The simulation parameters are fixed values (simulation horizon, statistic intervals, etc.) which define the experiment, and some variable parameters are used to regulate the models (lane changing zone, reaction times, etc.).

The output data are a continuously graphical representation of the performance of the simulated network, statistical data of the network (traffic flow, speed, delays) and data from detectors in the network (occupancy, speed).

3.2 Input parameters

The microscopic simulation must be consisted of a high quality of detail. The quality of the model depends on the accuracy of the input data, which are the network layout, the traffic demand data, the traffic control and the public transport.

3.2.1 Network layout

A traffic network comprises several sections (one-way links) which are connected to each other through intersections, with different traffic features. To design the network model are required details for every section such as number of lanes, reserved lanes and side lanes. Also details for the turning movements for every junction are required. The speed limits for every section are necessary for the advisable flow of the vehicles in the network, as well as the turning speed at every junction. The position of the detectors and their measuring capabilities are very important for the right description on the network. The network model can include more elements that exist in a real network. The user has the ability to interfere at the most of the capabilities that compose the network model.

3.2.2 Traffic demand data

As mentioned above, the traffic demand data can be determined by two different ways the traffic flows at the section and an O/D matrix.

For the first case, the traffic flows, are required the vehicle types and their attributes. Also the vehicle classes are necessary for the implementation of the reserved lanes. The flows at the input sections (the entrances to the network) for each vehicle type as well as the turning proportions at all sections are also necessary.

For the application of the O/D matrix centroid definitions must be available. As in the previous case vehicle types and classes are necessary too. Finally, the number of trips going from every origin centroid to any destination one are required.

3.2.3 Traffic control

AIMSUN includes different types of traffic control. These types are the traffic lights, the give-way signs and the ramp metering. The two first types are used by junctions and the third is used for sections that end up in join nodes.

The traffic control is defined by some input data for each case.

- *Signalized junctions*: location of signals, the signal groups into which turning movements are grouped. The coherence of the phases and its durations are specified.
- *Unsignalized junctions*: the definition of priority rules and stop signs.
- *Ramp metering*: location and type of metering as well as control parameters.

3.2.4 Public transport

The network model can include public transport if it is necessary. Some input data are required for its implementation. First of all, for the Public Transport Lines it is necessary to define a set of sections which comprise the route of a particular bus. Also, the reserved lanes and the bus stops are important to describe the behavior of a bus. Finally, an allocation of the bus stops and a timetable complete the description of public transport in the network.

3.3 AIMSUN API

AIMSUN API (Application Programming Interface) gives the ability to the user to communicate with the simulator. The user can evaluate whichever external application, as a signal control strategy, that needs access to the data of AIMSUN and requires dynamic changes of their situation.

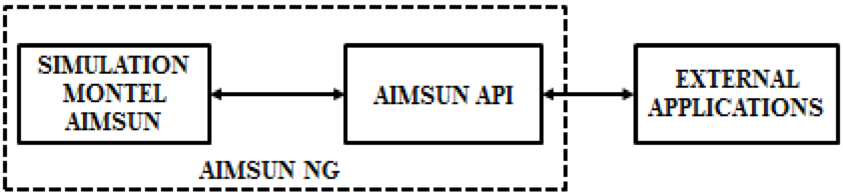


Figure 3.1 – Conceptual diagram of AIMSUN API

There are two directions of communication for AIMSUN API. The first one is between the simulation model of AIMSUN and the AIMSUN API, and the other is between AIMSUN API and the external applications (a signal control strategy) (Figure 3.1). In both cases, the two sides of communication are interactive.

3.4 Simulation parameters

For the implementation of a simulation are imported the following notions: the demand scenario, the experiment and the replication.

3.4.1 Demand scenario

An AIMSUN demand scenario includes up to five types of data. These are the network description, the traffic demand data, the traffic control plan, the public transport plan and the GETRAM Extensions. The first type includes the topology of the simulated network. The traffic demand data, as mentioned before, are determined with two ways and only one of those ways can be used. The traffic control plan includes information about the signal-controlled junctions, the unsignalized junctions and about the ramp-metering. A public transport plan involves the description of bus lines and timetables for them. The GETRAM Extensions is a set of user-defined Dynamic Link Libraries.

3.4.2 Experiment

The experiment involves information for the movement of the vehicles. The basic movement models are the Car-Following model and the Lane-Changing model. In the experiment is set the time simulation step, the reaction time of the vehicles, the distribution that is used to dispense the vehicles into the network etc.

3.4.3 Replication

The execution of the simulation is completed with the replication. Every replication uses a different seed for the random number generator and as a result every replication gives different outcomes. In order to have correct conclusions, a several number of replications, with different seeds, must be conducted in order to eliminate the effects of demand stochasticity.

3.5 Simulation outputs

The simulation outputs that are exported from AIMSUN are averages referring to the whole network and some of them follow:

- *Delay time*: average delay time per vehicle per kilometer (in s/km).
- *Densit*y: mean density of vehicles on the entire network (in veh/km).

- *Harmonic Mean Speed*: harmonic mean speed for the vehicles that have abandoned the network (in km/h).
- *Total Distance Travelled*: total number of kilometers travelled by all vehicles that have passed through the network (in km).
- *Total Travel Time*: total travelled time by all vehicles that have passed through the network (in h).
- *Number of stops*: average number of stops per vehicle per kilometer (stops/veh/km).
- *Mean flow*: average number of vehicles that have crossed the network during the simulation period (veh).

4 Simulation investigations

In this chapter the network that was used for this research and the results from the simulation investigations, such as conclusions strengths and weaknesses for each method are presented. The simulation model of the network that was used, i.e. the urban network of Chania, is presented in the next section.

4.1 Simulation model

4.1.1 Control cases

The simulation investigations for the studied methods include comparisons among the following control cases:

- ***Control case 1*****:** Application of fixed-time signal control at the whole network. This case has been developed to provide a comparison basis and it involves the application of fixed 90 seconds cycle time plans, with green times allocated to the junction stages. A time delay among the start time of the cycle times of the junctions of the network is also introduced in order to create green wave in arterials.
- ***Control case 2*****:** Application of the TUC strategy.
- ***Control case 3*****:** Application of the job scheduling algorithm.
- ***Control case 4*****:** Application of the max pressure algorithm.

The control cases are applied and tested in one and half hour simulations for the following demand scenarios:

- ***Demand scenario 1*****:** Dense traffic conditions; it involves a total demand of 4850 veh/h in the peak period.
- ***Demand scenario 2*****:** Congested traffic conditions; it involves a total demand of 5650 veh/h in the peak period.

The performance indices for which the four control cases are compared are the delay and the density. These performance indices are calculated as averages of the corresponding results of 10 simulation replications to eliminate the effects of demand stochasticity.

- ***Delay*****:** Average delay time per vehicle (s/km)

- ***Density***: Mean density of vehicles on the whole network (veh/km). A decrease of this index designates an improvement of the traffic conditions, as it shows an increase of the mean speed in the network.

4.1.2 Network of Chania

To test and compare the capabilities of the studied approaches, they were applied on the urban network of Chania. This urban network consists of 13 controlled junctions. It also includes 47 controlled links in which 15 of them are entrances of the network (Figure 4.1). None of the controlled junctions of the signal control operate in more than four stages.

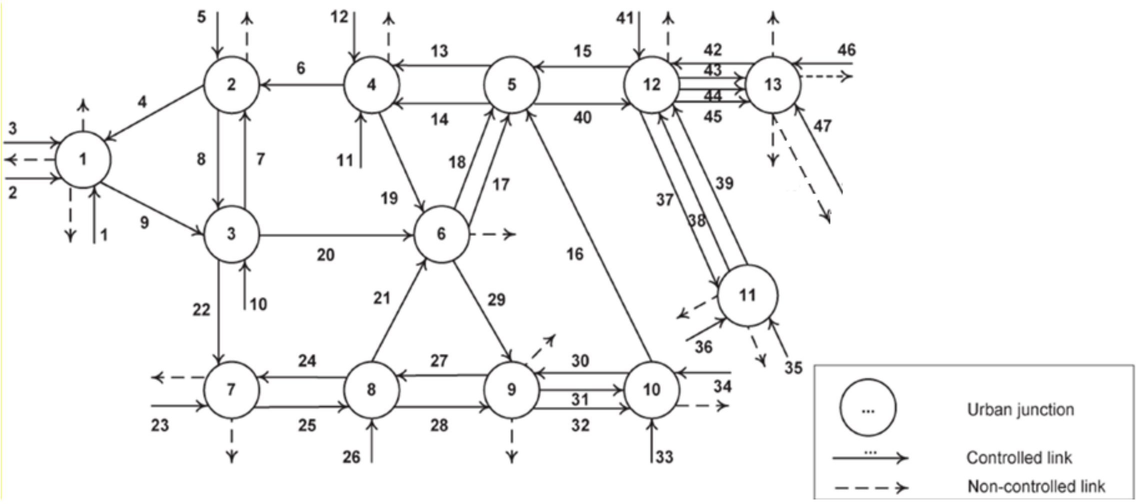


Figure 4.1 – The urban network of the city center of Chania, Greece

4.1.3 Job scheduling algorithm: Implementation issues

As it was mentioned in Chapter 2, some of the methods have some difficulties on their application. Primarily, for the implementation of this decentralized approach, it is necessary to define some parameters for the queue estimation (see section 2.3.1). The first parameter is the fixed interval that is called $samp$ and is set equal to 1. The saturation flow rate sfr is set to 0.8 and the value of the *threshold* that concerns to the clustering is set to 3.

Another important implementation issue is that a junction cannot serve two different stages in the same traffic stream. In such cases, each junction of the network must be studied carefully and some heuristic rules should be used in order to make the method applicable to the simulated network.

It is also very important for the algorithm to calculate the accurate number of the vehicles in every approach at every time instant. This can be realized with two detectors at each controlled link. The first set of detectors must be located at the entrance of the link and the second at the exit. The detectors must be the same number with the number of lanes of each link.

In real implementation, the accurate calculation of the vehicles is not always possible. A potential overestimation or underestimation may be caused by detectors that count more or less vehicles than those actually crossing over them. When this problem occurs at entrance detectors, while the corresponding stop-line detectors count accurately, the estimated queue for the case of overestimation does not clear, or its value is less than 0 for the case of underestimation.

In a case of underestimation, i.e. the estimation of vehicles is less than 0, the SURTRAC system has the ability to turn this value into 0 so as to avoid perpetuation of this error. On the other hand, in case of overestimation of a queue causes waste of green time, because the provided green extension is higher than necessary. To deal with such cases, a counter has been defined, which takes the value 1, if a vehicle crosses the stop-line detector and 0, otherwise. If during a given time gap (6 s) the counter remains at the 0 value, the queue is set to 0. To avoid potential correction errors due to a downstream blocking that prevents queue clearance, the aforementioned correction takes place only if the queues of downstream links have occupancy lower than 60%. These values have been set based on AIMSUN observations and correspond to the specified simulated network.

4.1.4 Max pressure or back pressure algorithm: Implementation issues

Max pressure presents also some implementation difficulties that must be determined at each network. First of all it is necessary to declare the way that the collection of the measurements is done. As done in the job scheduling algorithm, also in the max pressure algorithm the collection of measurements is done with two detectors, one at the entrance and one at the stop line. The calculation of the queues is done with the same algorithm in order to have a fair comparison between them. Possible wrong queue estimations are corrected with the same method as for the Job Scheduling algorithm (see section 4.1.3).

To apply the max pressure algorithm, some parameters must also be defined. First of all, it must be mentioned that the parameters that were used for the queue estimation are the same with those of the Job Scheduling algorithm. Then, the rate that each link joins every stage of a controlled junction should be defined. If a link has right of way in more than one stage, then a matrix with the rates of participation must be created. If a link has right of way only in one stage, its rate will be equal to 1. However, the rates that each link participates at the downstream links must also be defined.

Another important value that must be defined is the space time of the extension time that a stage can receive. For this study, the time extension is set to 2 seconds to let the stage autonomous to avoid waste of green time.

For this variation of the max pressure algorithm the frequent stage changes are avoided if more than one stage has the same pressure but the currently active stage has larger queue than a predefined threshold, which is calculated with tuning for every network.

Another research that has been done, and improved the results of the algorithm, concerns to the usage of downstream information. In order to suppress lost green times due to a possible downstream blockage, the pressure of an approach is reduced appropriately based on downstream information on the corresponding queue lengths, when these queue lengths surpass a predefined threshold. The upstream information was also used in order to increase the pressure of the link; such as the downstream information is used to reduce the pressure of a link, as the number of the incoming vehicles from upstream junctions, is known. This process did not improve the results, with or without the usage of downstream information.

To define the suitable thresholds that concern not only to downstream information but also to stage changing, an exhausted tuning for each one of them must be done. The rates that are related with downstream information differ depending on the pressure threshold that was mentioned above. The best combinations are shown in Table 4-1.

Table 4-1 Correspondence of thresholds for downstream information

Pressure threshold	Downstream threshold	Percentage participation
35%	80%	10%
65%	85%	10%

With the completion of the above investigations, the algorithm can eventually operate. For the study of max pressure algorithm, two pressure thresholds were chosen to investigate their performance in the simulated network. The results of this implementation are presented in Table 4-2 and Table 4-3. The control cases based on ***control case 4*** follow:

- ***Control case 4a*:** Application of max pressure algorithm with pressure threshold 35% for avoidance of stage changing.
- ***Control case 4b*:** Application of max pressure algorithm with pressure threshold 65% for avoidance of stage changing.
- ***Control case 4c*:** Application of max pressure algorithm with pressure threshold 35% for avoidance of stage changing, threshold for downstream information 80% and participation percentage 10%.
- ***Control case 4d*:** Application of max pressure algorithm with pressure threshold 65% for avoidance of stage changing, threshold for downstream information 85% and participation percentage 10%.

The comparison basis is the average values of C*ontrol case 1*. The max pressure algorithm performs better for pressure threshold equal to 65% for both demand scenarios. With the application of the downstream threshold the results improved by 1%. The *control case 4d* is the best version of the max pressure algorithm for both dense and congested traffic conditions.

Table 4-2 Performance of max pressure for demand scenario 1 (dense traffic conditions)

Control case	Delay T. (s/km)			Density (veh/km)		
	Average value	Standard deviation	% change of average values compared to control case 1	Average value	Standard deviation	% change of average values compared to control case 1
Control case 4a	87.70	5.44	-22.01	5.87	0.20	-12.13
Control case 4b	82.65	3.39	-26.78	5.72	0.11	-14.37
Control case 4c	87.86	5.36	-22.17	5.91	0.25	-11.53
Control case 4d	82.40	3.46	-27.00	5.71	0.09	-14.52

Table 4-3 Performance of max pressure for demand scenario 2 (congested traffic conditions)

Control case	Delay T. (sec/km)			Density (veh/km)		
	Average value	Standard deviation	% change of average values compared to control case 1	Average value	Standard deviation	% change of average values compared to control case 1
Control case 4a	158.49	14.39	-12.62	9.35	0.68	-8.87
Control case 4b	137.55	8.56	-24.16	8.62	0.35	-15.98
Control case 4c	152.77	9.21	-15.77	9.22	0.45	-10.14
Control case 4d	137.51	11.00	-24.18	8.62	0.52	-15.98

It is observed that for the max pressure algorithm it is more important to achieve a well-tuned pressure threshold, to approach the optimal solution, than using downstream information in a not so well-tuned pressure threshold. This can be explained with a closer observation on a depiction of cycle times. The pressure threshold gives the ability to the algorithm to extend the green durations of a stage if it has a large number of vehicles to serve, and the time extension that was given was not enough to serve them. This procedure is more obvious at the peak period in congested traffic conditions (Figure 4.3).

In Figure 4.2 it can be unequivocally shown that junction 5 has, for the dense traffic conditions, identical cycle times for *Control case 4a* and *Control case 4c*. This is true also for the cycle times of *Control case 4b* and *Control case 4d*. In other words, the downstream information is useless for the control of this junction. This is a phenomenon that is observed at the start of the simulation for the congested traffic conditions (Figure 4.3), until the peak period. During the congestion the *Control case 4d* reaches higher cycles with larger green durations than the others. The *Control case 4b* also achieves high cycles but the green durations are smaller due to the absence of downstream information.

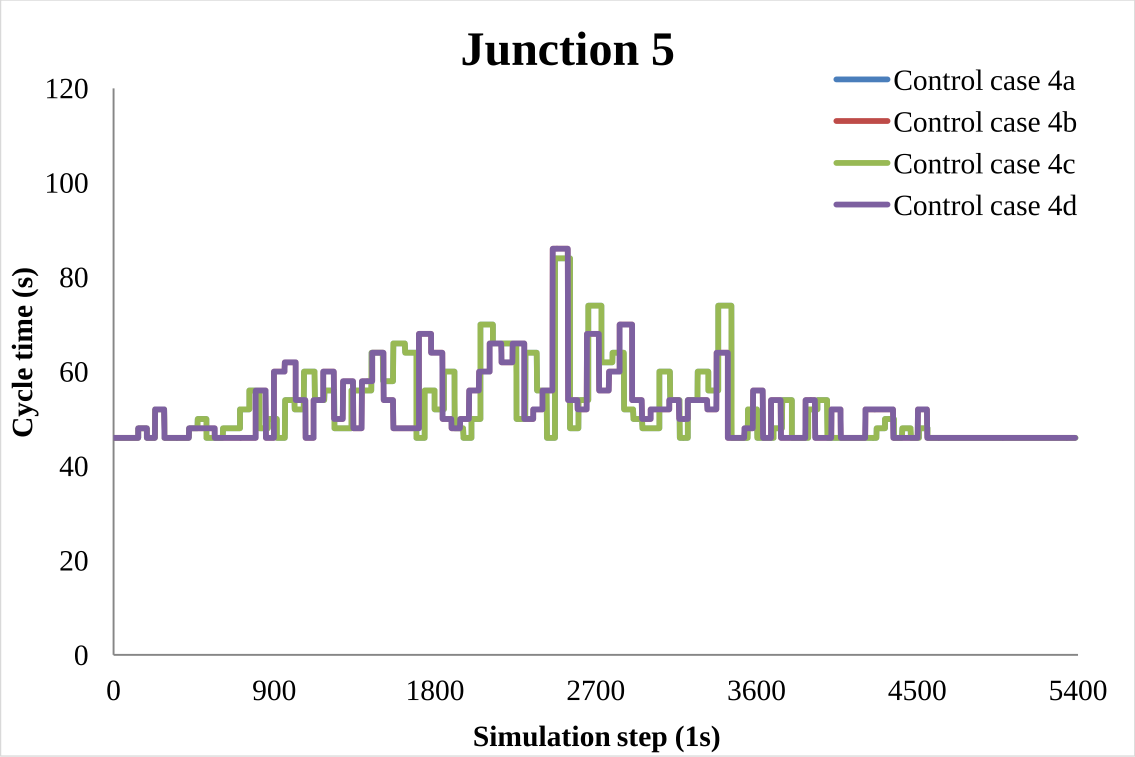


Figure 4.2 - Cycle time comparison for demand scenario 1 (dense traffic conditions) of control case 4a, control case 4b, control case 4c and control case 4d for junction 5.

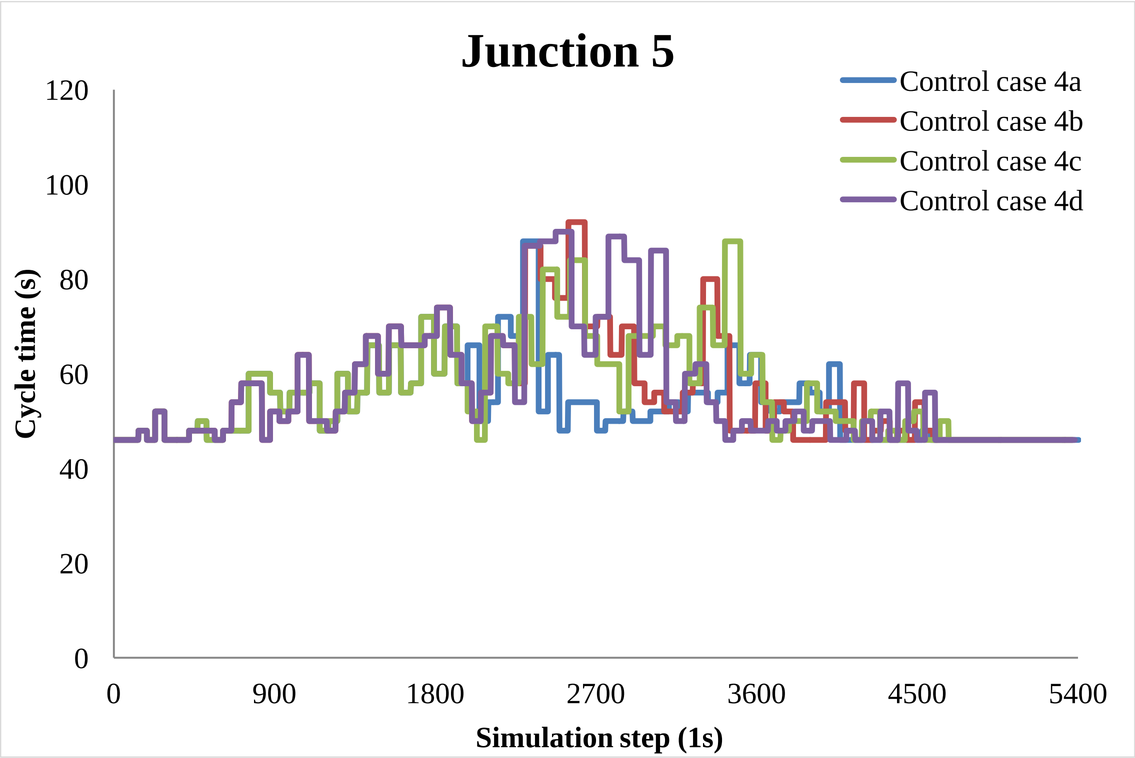


Figure 4.3 - Cycle time comparison for demand scenario 2 (congested traffic conditions) of control case 4a, control case 4b, control case 4c and control case 4d for junction 5.

4.1.5 Traffic-responsive Urban Control (TUC): Implementation issues

In order to apply TUC strategy, the control plans that should be used must be defined. For this study, the control laws were applied with two combinations.

- ***Control case 2a*****:** Application of hybrid TUC strategy with the cycle control, the offset control and the split control.
- ***Control case 2b*****:** Application of hybrid TUC strategy with the cycle control and the split control.

Finally, an extra limitation was applied that concerned to the time gap between two cycle changes. This limitation gives the ability to the algorithm to change cycle and offset every 5 minutes. The time gap has been set after tuning.

A close review of the results designates that hybrid-TUC strategy presents better results for both dense and congested traffic conditions with the implementation of the offset control compared with the version that does not use the offset control. It is obvious that the results of control case 2b are worse than those of control case 2a.

Table 4-4 Performance of hybrid-TUC for demand scenario 1 (dense traffic conditions)

Control case	Delay T. (sec/km)			Density (veh/km)		
	Average value	Standard deviation	% change of average values compared to control case 1	Average value	Standard deviation	% change of average values compared to control case 1
Control case 2a	89.29	3.65	-20.90	5.87	0.13	-12.13
Control case 2b	95.66	3.48	-15.26	6.19	0.15	-7.34

Table 4-5 Performance of hybrid-TUC for demand scenario 2 (congested traffic conditions)

Control case	Delay T. (sec/km)			Density (veh/km)		
	Average value	standard deviation	% change of average values compared to control case 1	Average value	standard deviation	% change of average values compared to control case 1
Control case 2a	130.86	6.84	-27.85	8.37	0.31	-18.42
Control case 2b	161.14	16.27	-11.15	9.83	0.79	-4.19

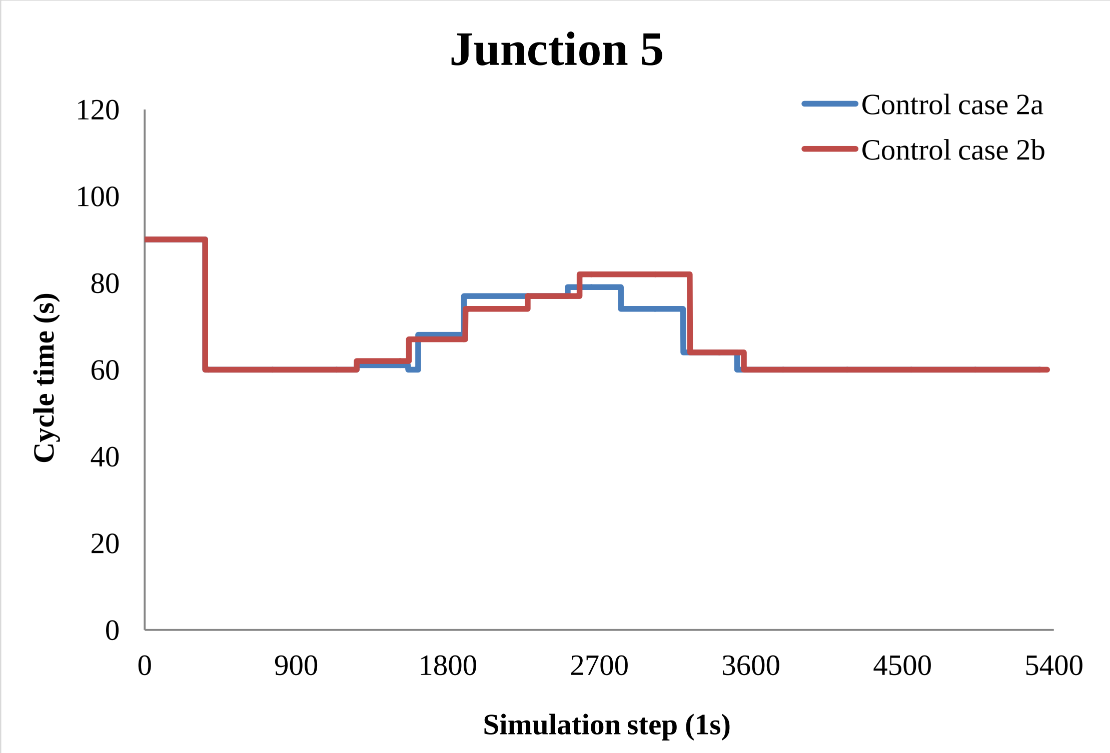


Figure 4.4 - Cycle time comparison for demand scenario 1 (dense traffic conditions) of control case 2a (hybrid-TUC with offset control) and control case 2b (hybrid-TUC without offset control) for junction 5.

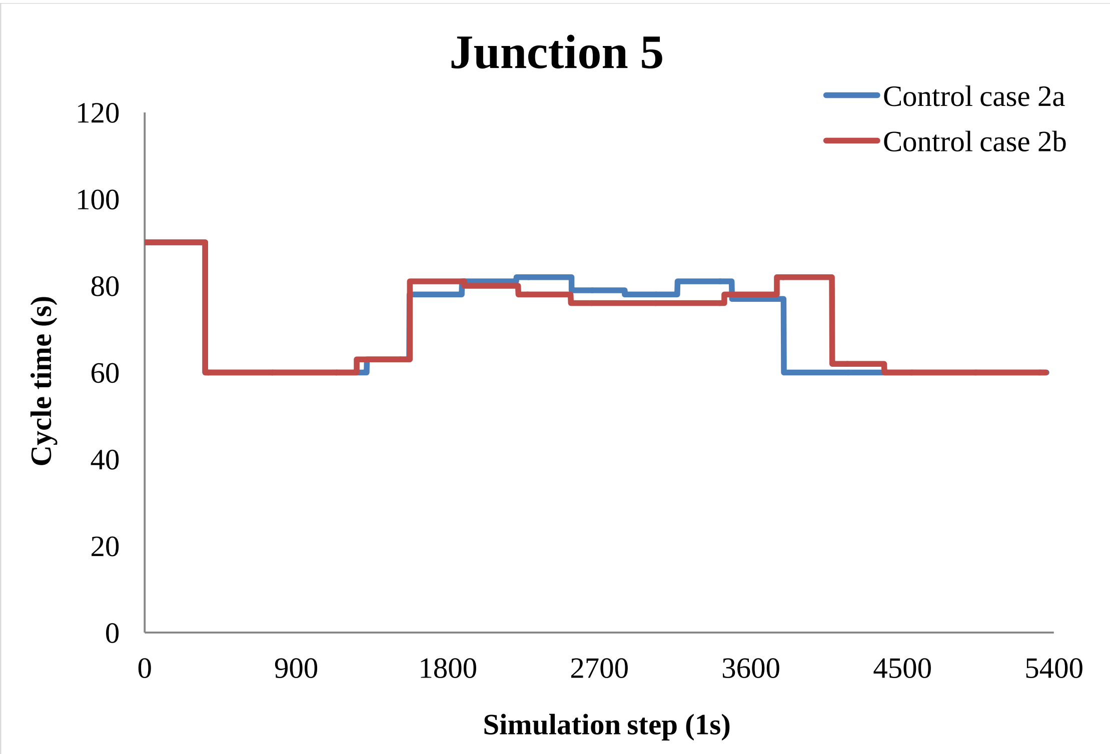


Figure 4.5 - Cycle time comparison for demand scenario 1 (dense traffic conditions) of control case 2a (hybrid-TUC with offset control) and control case 2b (hybrid-TUC without offset control) for junction 5.

The differences between the control cases can be shown at cycles' figures. For dense traffic conditions (Figure 4.4) the cycles between the two cases are exactly the same for the first and the last half hour of the simulation. At the peak period, for a half hour, as far as the traffic conditions are dense, the offset control provides higher cycles gives significant advantage to the network compared with the control case without offset control. When the traffic conditions become less dense, takes place the opposite procedure. The same process is being operated also for the congested traffic conditions (Figure 4.5). From cycles' figures it can be extracted that offset control is useful for the network in order to avoid wasted green times.

4.2 Simulation results

Considering the above observations, all approaches were tested and compared with the fixed time plans. The performance indices are the average delay time per vehicle (in s/km) and the mean density of the whole network (in veh/km). The results of 10 replication simulations with different seeds to eliminate the effects of demand stochasticity are presented as averages. Also, in results' tables are presented the standard deviation and the (%) change of average values compared to control case 1 (fixed time plans) (Tables 4-6 and 4-7).

The results of the four different control cases correspond to the best formulation of each approach. More specifically:

- ***Control case 1*****:** Application of fixed-time signal control at the whole network. This case has been developed to provide a comparison basis, involves the application of fixed 90 seconds cycle time plans, with green times allocated to the junction stages. A time delay among the start time of the cycle times of the junctions of the network is also introduced in order to create green wave in arterials.
- ***Control case 2*****:** Application of the best formulation of hybrid-TUC strategy, which includes split, cycle and offset control.
- ***Control case 3*****:** Application of job scheduling algorithm.
- ***Control case 4*****:** Application of the best formulation of max pressure algorithm with pressure threshold 65% for avoidance of stage changing, threshold for downstream information 85% and participation percentage 10%.

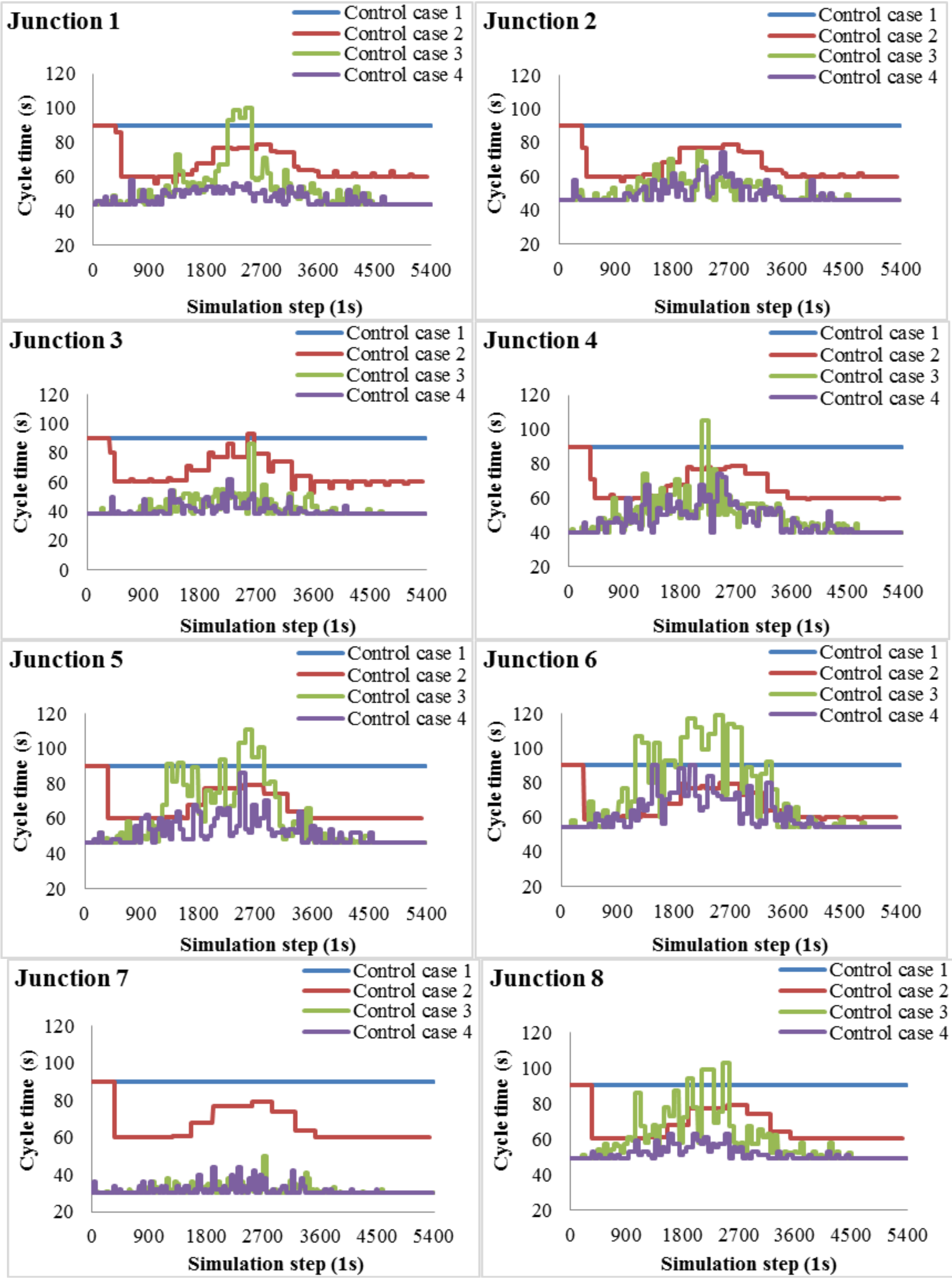
Table 4-6 Simulation results for scenario 1 (dense traffic conditions)

Control case	Delay T. (sec/km)			Density (veh/km)		
	Average value	Standard deviation	% change of average values compared to control case 1	Average value	Standard deviation	% change of average values compared to control case 1
Control case 1	112.88	5.27	-	6.68	0.22	-
Control case 2	89.29	3.65	-20.90	5.87	0.13	-12.13
Control case 3	88.04	3.37	-22.01	6.05	0.23	-9.43
Control case 4	82.40	3.46	-27.00	5.71	0.09	-14.52

Table 4-7 Simulation results for scenario 2 (congested traffic conditions)

Control case	Delay T. (sec/km)			Density (veh/km)		
	Average value	Standard deviation	% change of average values compared to control case 1	Average value	Standard deviation	% change of average values compared to control case 1
Control case 1	181.37	21.35	-	10.26	1.15	-
Control case 2	130.86	6.84	-27.85	8.37	0.31	-18.42
Control case 3	155.15	13.84	-14.46	9.54	0.71	-7.02
Control case 4	137.51	11.00	-24.18	8.62	0.52	-15.98

For both demand scenarios, with dense and congested traffic conditions, it is obvious that all methods perform better from the fixed time plans. In other words, the application of a control strategy in the network improves the traffic conditions. For dense traffic conditions (Table 4-6), the approach that shows the best performance is the max pressure algorithm, which is achieving delay time and density reduction about 27% and 15%, respectively. The other control cases, TUC and job scheduling algorithm, reach similar improvement of the traffic conditions. TUC achieves higher reduction at density and job scheduling at delay time and the differences between them are not significant. When the traffic conditions become congested (Table 4-7), TUC strategy (control case 2) outperforms all approaches and achieves delay and density reduction levels of about 28% and 18%, respectively. The job scheduling algorithm (control case 2) achieves the lowest reduction of delay time and density, which are 14% and 7% respectively, but still remains more efficient from fixed time control. The other decentralized approach, max pressure algorithm, manages quite well the traffic conditions at the period of congestion, and achieves delay and density reduction of 24% and 16%, respectively. These reductions are only 3% and 2%, respectively, lower than those of TUC, which is the best implemented approach.



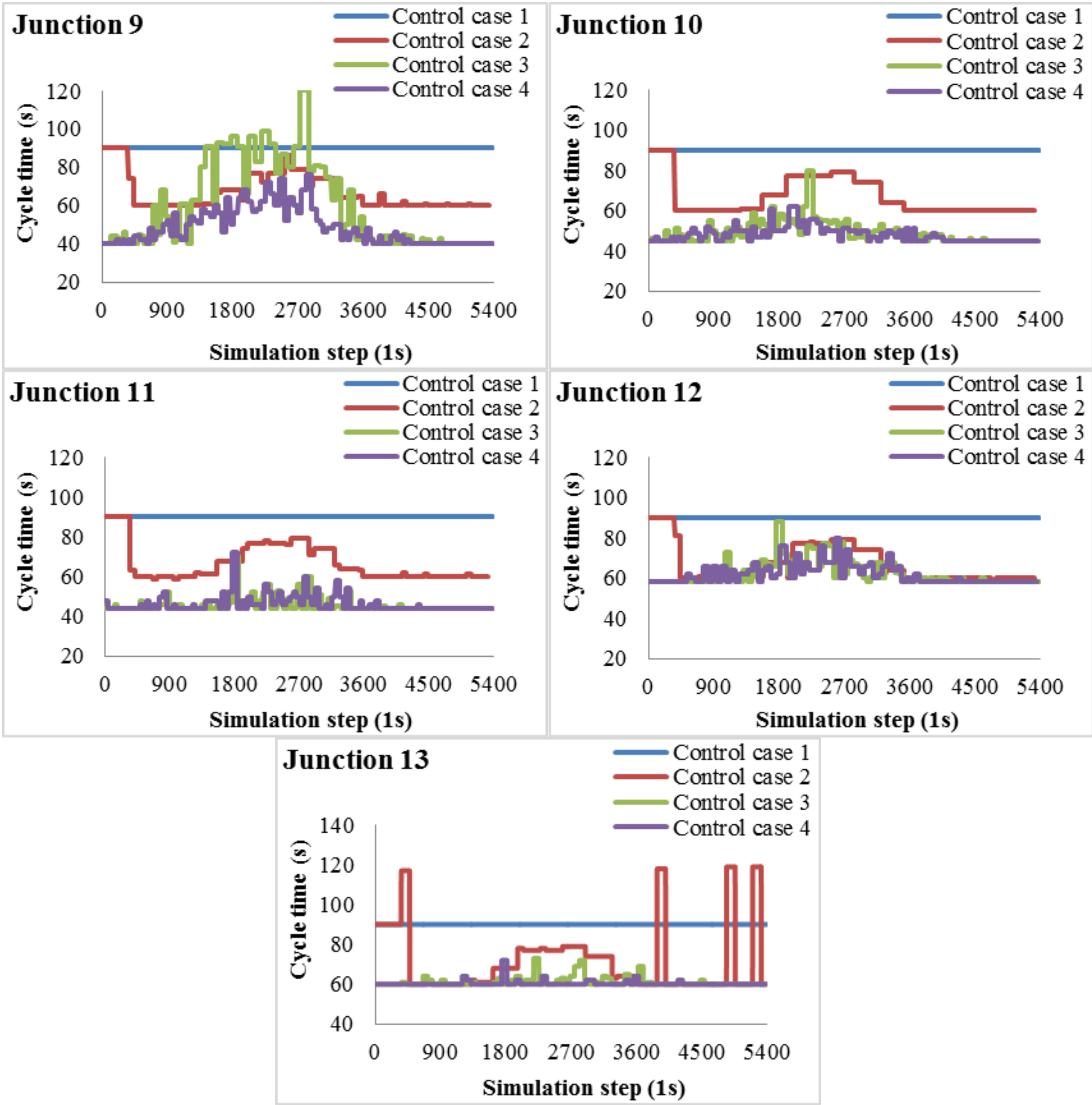
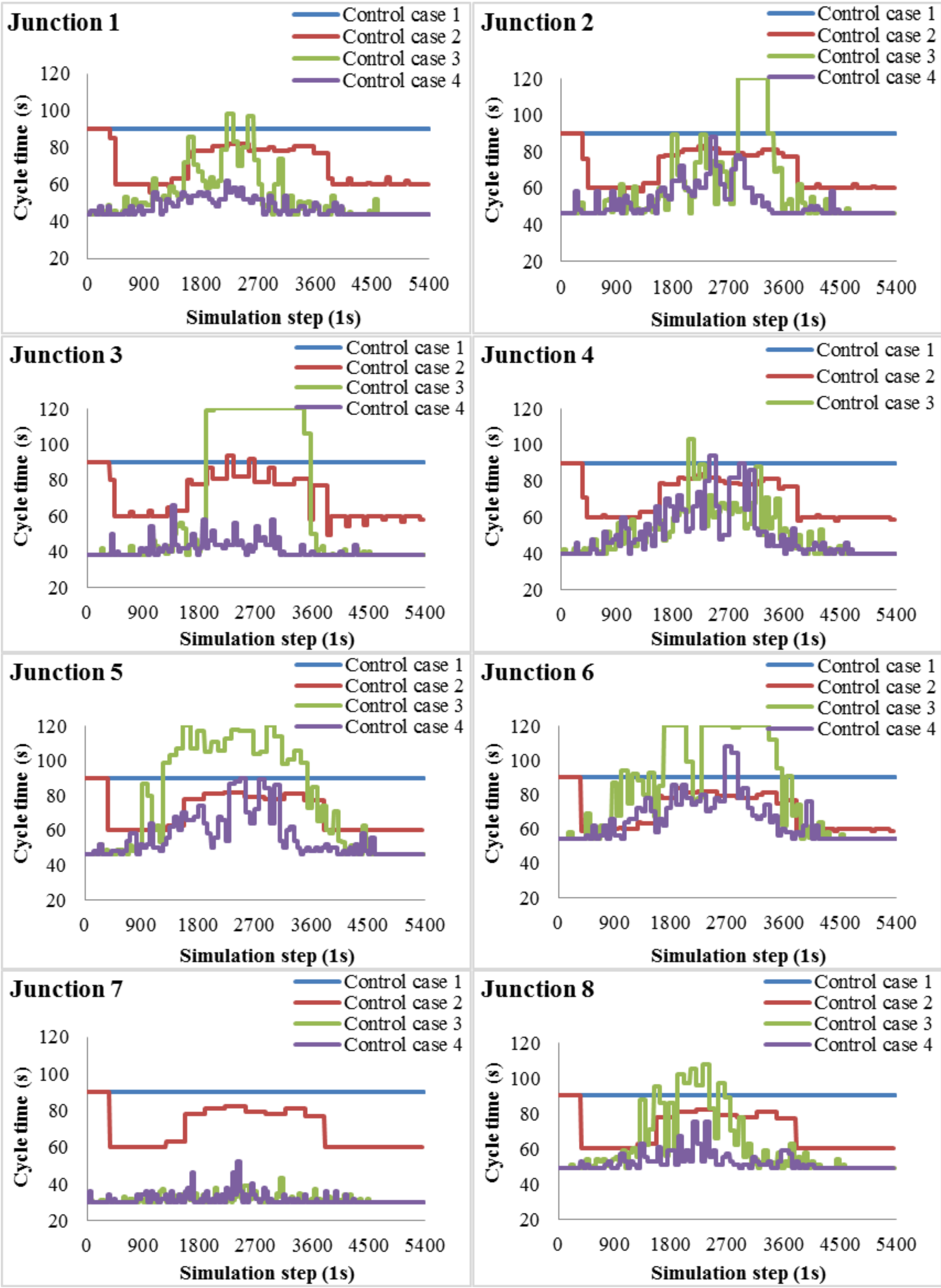


Figure 4.6- Cycle time comparison for demand scenario 1 (dense traffic conditions) of control case 1 (fixed control), control case 2 (hybrid-TUC), control case 3 (job scheduling algorithm) and control case 4 (max pressure algorithm).

For dense traffic conditions, both decentralized approaches (control cases 3 and 4) achieve delay reductions higher than TUC (control case 2). The main reason is the creation of lower cycle times (Figure 4.6) which reduces unnecessary vehicle delays. However, job scheduling algorithm increases the cycle times only when it is necessary (Figure 4.6 – Junctions 5, 6, 8 and 9). On the other hand, when traffic conditions become congested, job scheduling algorithm provides high cycle time of junctions (Figure 4.7 – Junctions 2, 3, 5, 6, 9 and 12) that leads to the degradation of network's performance, due to absence of offset regulation, which in TUC strategy is regulated during its implementation.

Job scheduling “looks” only upstream so as to achieve a good accommodation of the expecting traffic flow by managing of the future traffic light switching. It is not able to manage a downstream blocking using “negative” offsets. The lack of direct regulation of offsets influences also the formulated cycle times of max pressure algorithm which reduces the links’ pressures depending on length of the corresponded downstream queues. The relevant research is included at section 4.3.



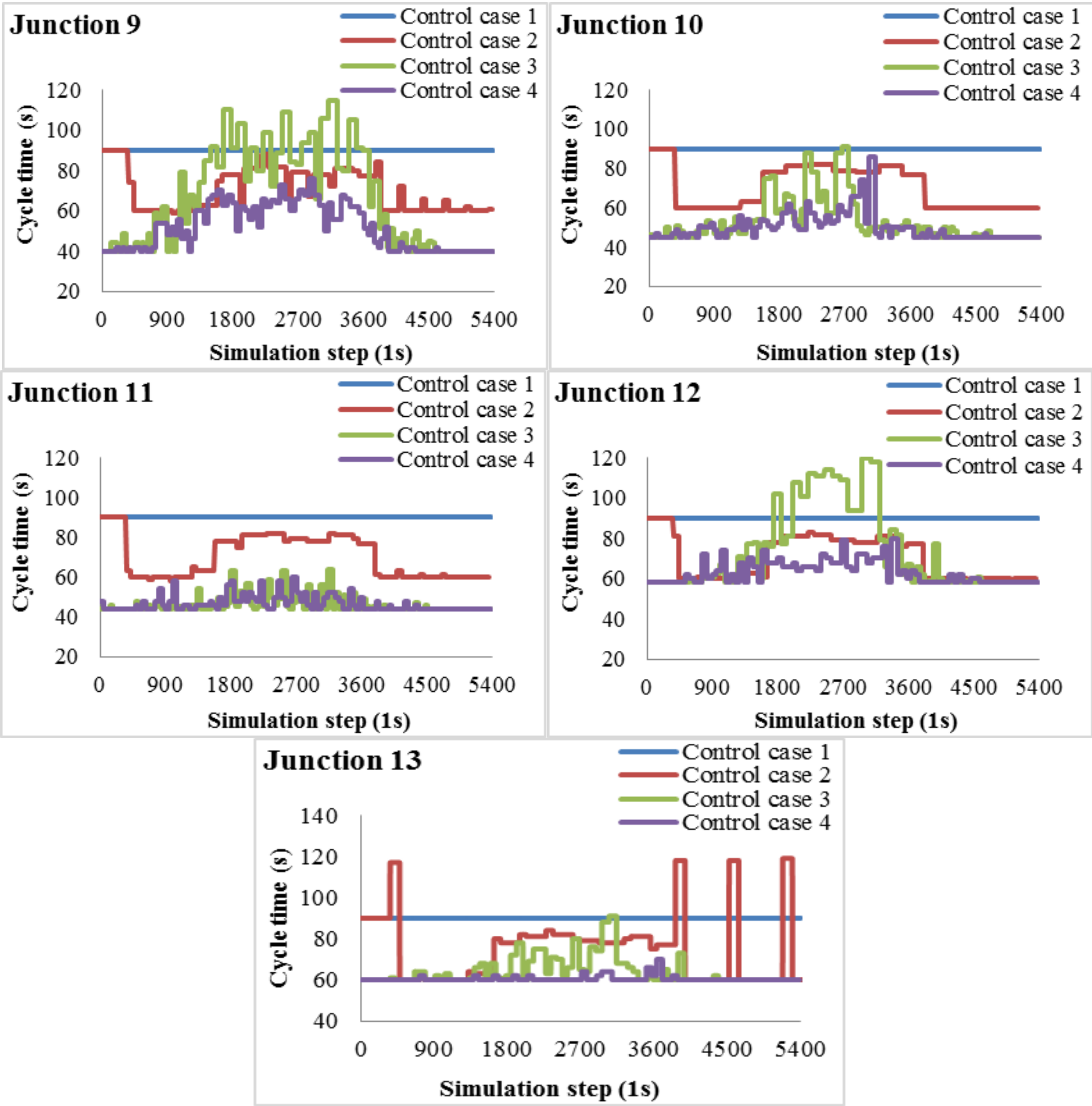


Figure 4.7 - Cycle time comparison for demand scenario 2 (congested traffic conditions) of control case 1 (fixed control), control case 2 (hybrid-TUC), control case 3 (job scheduling algorithm) and control case 4 (max pressure algorithm).

A closer observation, not only of the cycle time at the junctions but also of the green duration of the stages, can be helpful in explaining in detail the performance of each method. Figures 4.8 and 4.9 demonstrate the green durations of junction 5 for dense and congested traffic conditions, respectively. Junction 5 consists of three stages, the first of which receives the maximum duration of all, when necessary.

For dense traffic conditions (Figure 4.8) the fixed time control remains constant for all stages. All the stages of the TUC strategy start their green durations with their maximum value. At the peak period, alterations are frequent but with small differences between them. The job scheduling algorithm has the largest green durations for all stages. For the second stage, the method reaches the maximum green duration throughout the peak period. For the third stage the method provides as long green durations as necessary in order to serve most of the vehicles. These individual extensions are the cause of the large cycle durations. Finally, the max pressure algorithm provides large green extensions only for the first and the second stage. For the first stage, the maximum green duration is reached only once, at the peak period. On the other hand, for the second stage the maximum green duration is more often attained in order to serve the large number of vehicles. The max pressure algorithm does not provide to the third stage large enough green extensions, which can be observed by the absence of maximum green durations.

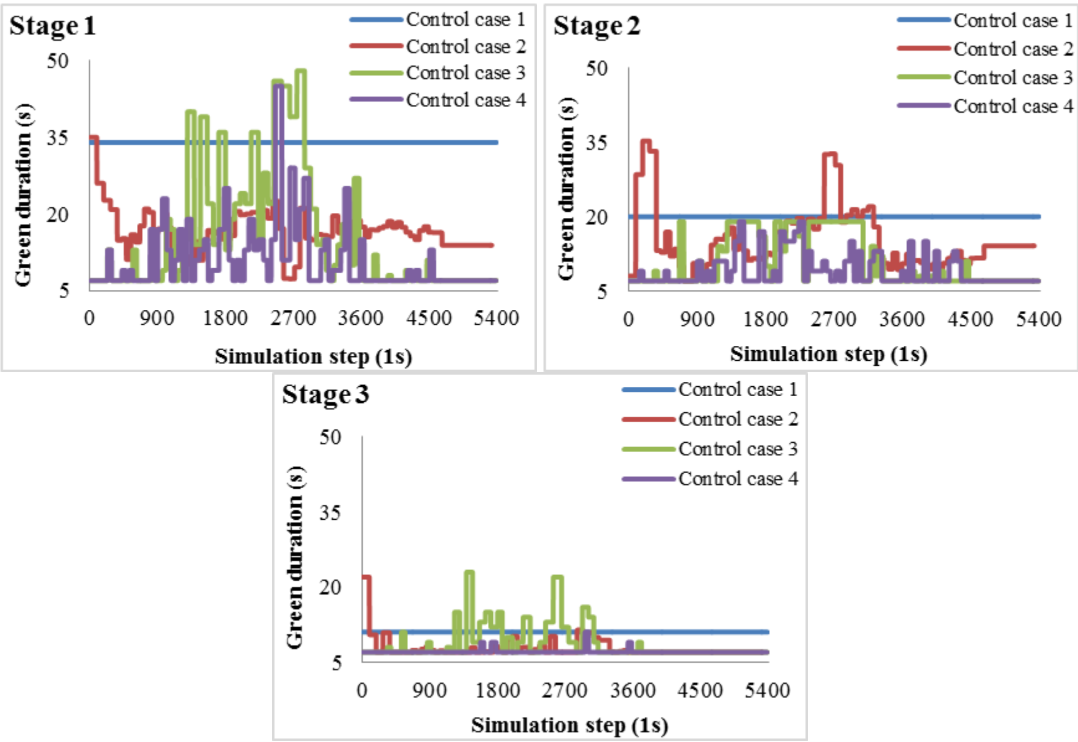


Figure 4.8 - Green duration comparison of junction 5 for demand scenario 1 (dense traffic conditions) of control case 1 (fixed control), control case 2 (hybrid-TUC), control case 3 (job scheduling algorithm) and control case 4 (max pressure algorithm).

For the congested traffic conditions (Figure 4.9), the behavior of each method does not change much. All methods present the same characteristics but with larger green durations. The TUC strategy reaches large green durations with few differences to each other. The job scheduling algorithm at the first and the second stage attains the maximum green duration throughout the peak period. The third stage reaches its maximum green but with many alterations. The max pressure algorithm at the first stage receives high values at the peak period, but not for long periods as with the other decentralized approach. The second and the third stages receive green extensions as for the first demand scenario but in a larger scale.

The TUC strategy splits the green durations of all stages in order to achieve the same cycle in whole network maintaining a good conduct between junctions with the assist of offsets. On the other hand, the job scheduling algorithm gives green extensions in order to serve all the vehicles of a stage. Finally, the max pressure algorithm provides as much green extension as it is necessary to serve the maximum possible number of vehicles of a stage until another stage has a larger queue.

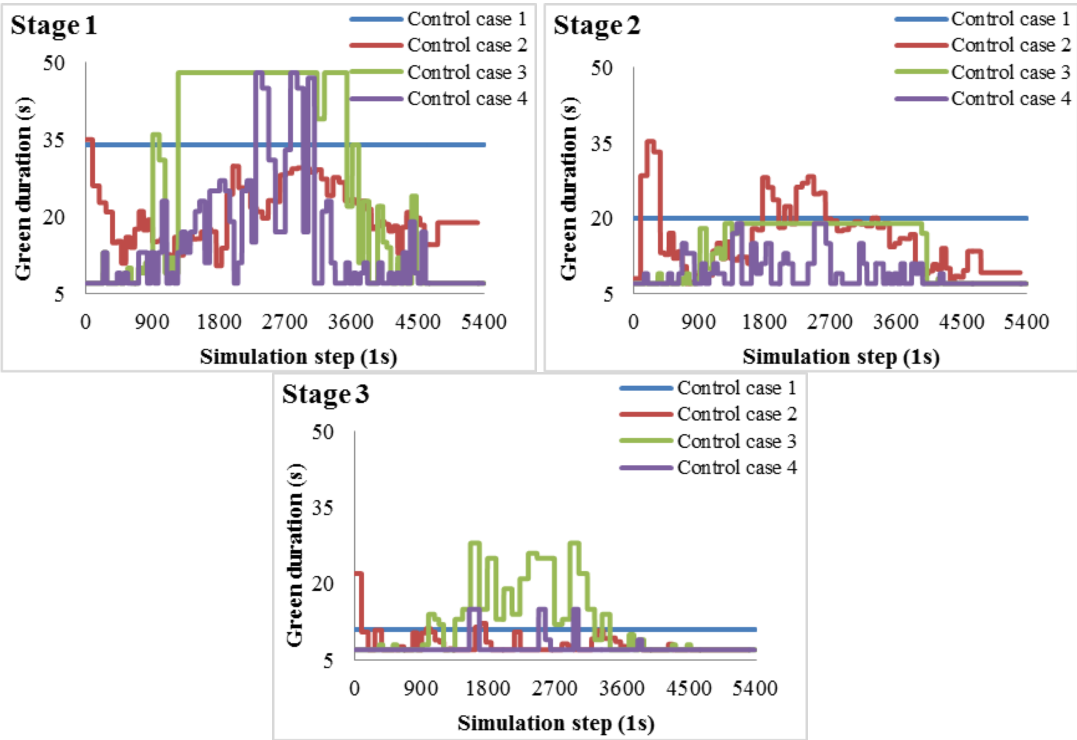


Figure 4.9 - Green duration comparison of junction 5 for demand scenario 2 (congested traffic conditions) of control case 1 (fixed control), control case 2 (hybrid-TUC), control case 3 (job scheduling algorithm) and control case 4 (max pressure algorithm).

4.3 Further investigations

The conclusions of this study have shown that all the examined methods achieved better results than the fixed time control. The main characteristic of the decentralized methods is that they operate independently and asynchronously with the other junctions. The TUC strategy, as a centralized approach, uses some information so as to achieve a green wave between some neighboring junctions. To this effect assists the offset control. The offset is calculated directly from the strategy.

The last part of this research about the decentralized approaches was to test if there is any type of communication between neighboring junctions. The job scheduling algorithm, which is used by the SURTRAC system, has been tested in such conditions and it has been proved that the communication between neighboring junctions is not achievable (Smith et al., 2013).

Based on this assumption, two junctions that are connected by an arterial street have been tested, in order to check whether or not an offset could be created. The junctions 4 (downstream) and 5 (upstream) were the most appropriate for this process. The distance between them is 30 m and none street is interposed between them, which means that no vehicle is lost or enters without being detected. Another important characteristic is that all stages of junction 5 head to junction 4 (Figure 4.10).

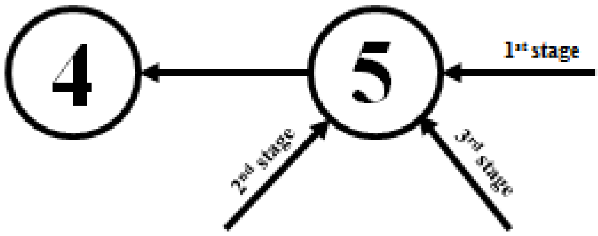


Figure 4.10 – Layout junctions

To ascertain whether or not an offset is created, the real difference between the green times of the connected stages of the junctions is compared with a theoretical value of offset. If these values approach each other, then it is considered that there is offset between these junctions. The equations for the comparison are:

$$\mathbf{T_{real}} = \mathbf{t_u} - \mathbf{t_d} \qquad (4.1)$$

where $\mathbf{t_u}$ and $\mathbf{t_d}$ are the time instances at which the upstream junction (i.e. junction 4) and the downstream junction (i.e. junction 5), respectively, receive a green light.

$$\mathbf{T_{theor}} = \frac{\boldsymbol{l}}{\boldsymbol{v}} - \boldsymbol{k} \times \boldsymbol{l} \times \frac{\boldsymbol{X}}{\boldsymbol{X_{max}}} \qquad (4.2)$$

where $\boldsymbol{k} = \frac{\boldsymbol{v}+\boldsymbol{w}}{\boldsymbol{v}\times\boldsymbol{w}}$

$\boldsymbol{l}$ is the distance between the junctions (in m)

$\boldsymbol{v}$ is the free speed of the network (in m/s)

$\boldsymbol{w}$ is the speed the queue is moving (in m/s)

$\boldsymbol{X}$ is the queue of the downstream junction at the moment that the green light of upstream junction starts (in veh)

$\boldsymbol{Xmax}$ is the capacity of the link that is interposed between the junctions (in veh)

As it mentioned above, all stages of junction 5 are connected with the examined stage of junction 4. Based on this statement, every stage of junction 5 has been tested so as to discover which one of them forms the best offset with junction 4 or it has a good offset with another one of them at the same time. Finally, it should be mentioned that to ascertain the existence of offset, only the demand scenario 2 has been tested (congested traffic conditions).

The implementation of Equation (4.2) to junctions 4 and 5 requires the definition of some parameters so as to extract the theoretical value of the offset. The distance between two junctions is 30 m and its capacity is 24 vehicles. For the different types of speed, different values have been combined as shown in Table 4-8.

Table 4-8 Speed for theoretical offset

Free speed of network *v* (km/h)	**Speed of queue's movement *w* (km/h)**
15	5
20	8
40	10
50	15

For both decentralized approaches at every second of the simulation, the cycle times are different for every junction, due to their needs for extension of green time. To investigate if there is correlation between two neighboring junctions, firstly the nearest cycle times of each junction must be matched.

In general, the results of the investigations that are presented below did not show obvious correlation between the tested junctions. In some cases it was demonstrated a behavior that befits to the procedure that is followed when an offset is applied. For each case, only the best method is presented.

Each investigation corresponds to the link that receives right of way during the first, the second and the third stage of junction 5, respectively (Figures 4.11, 4.14 and 4.17). All vehicles that exit from the link that receives r.o.w. at the first stage of junction 5 enter to the junction 4. The links that receive r.o.w. during the other two stages disseminate most of their vehicles to the junction 4 and a small rate to other links. The durations of junction 5 correspond to the *red line*, of junction 4 to the *blue line* and the green points correspond to the queue length of junction 4 the moment the junction 5 receives a green light (Figures 4.12, 4.15 and 4.18). These diagrams show the periods before and during the congestion. After matching the nearest cycles between two junctions, it has been calculated the real offset between the tested junctions such as the theoretical offset (Figures 4.13, 4.16 and 4.19).

1st investigation:

The period before the congestion, most of the time, junction 5 has a green light before junction 4 while the queue length of junction 4 is lower than the half of the capacity of the link.

When the traffic conditions become congested, most of the time, junction 5 receives a green traffic light during a green duration of junction 4 and the queue length of junction 4 is higher than the half of the capacity of the link. There are enough moments that junction 5 starts first even the queue of junction 4 is large. In general, this situation could be characterized that has an offset. For the above points, the difference between the real with theoretical offset has been compared, for different values of speed (Figure 4.13).

A closer look at the diagrams shows that only 10 of 32 points of theoretical offset approach the real offset. When the congestion occurs, the points are completely remote to each other. Although it seemed that the junctions form an offset between them, it is proved that many seconds are interrupted.

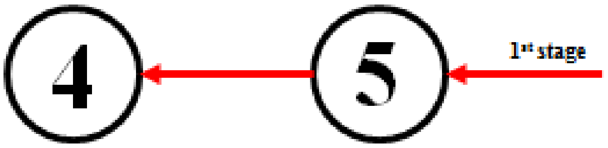


Figure 4.11 - Layout of junctions (1st stage testing)

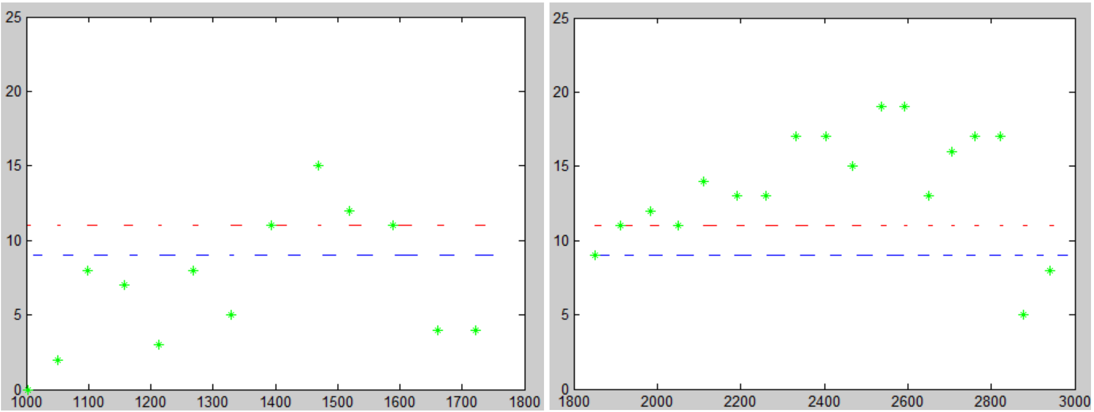


Figure 4.12 – Durations of 1st stage of max pressure algorithm

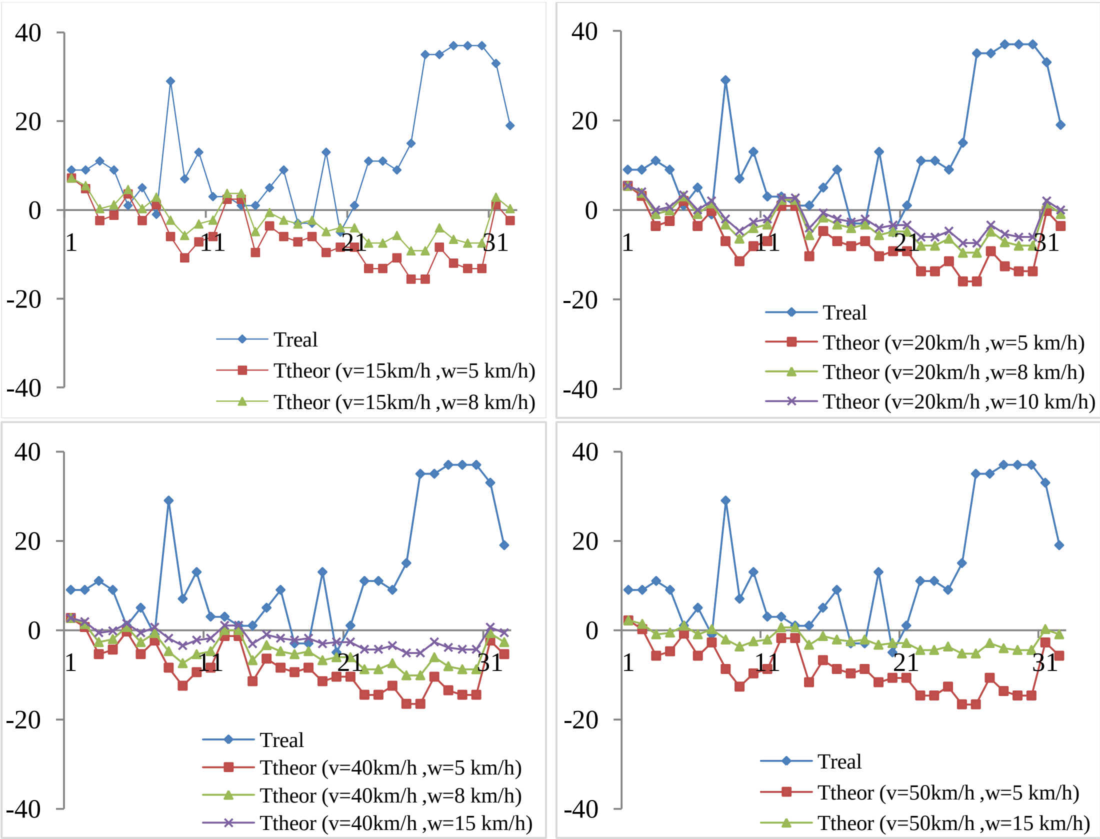


Figure 4.13 - Comparison of real and theoretical offset between junctions 4 and 5 of max pressure algorithm of 1st stage

2nd investigation:

Concerning the second investigation, when the traffic conditions are dense, before congestion period, and the queue length is higher than the half of the capacity of the link, junction 5 has a green traffic light before junction 4. The opposite procedure also happens when the queue is small. During the congestion many times that junction 4 has firstly a green light when the queue length is large. Observing the charts that compare the theoretical with the real offset (Figure 4.16), it is obvious that only 5 of the 32 points are close enough, so there is no correlation between them.

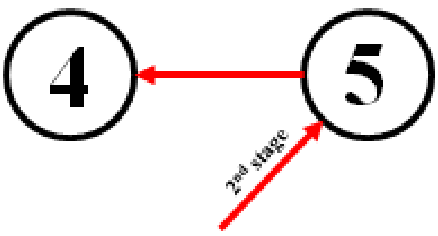


Figure 4.14 – Layout of junctions (2nd stage testing)

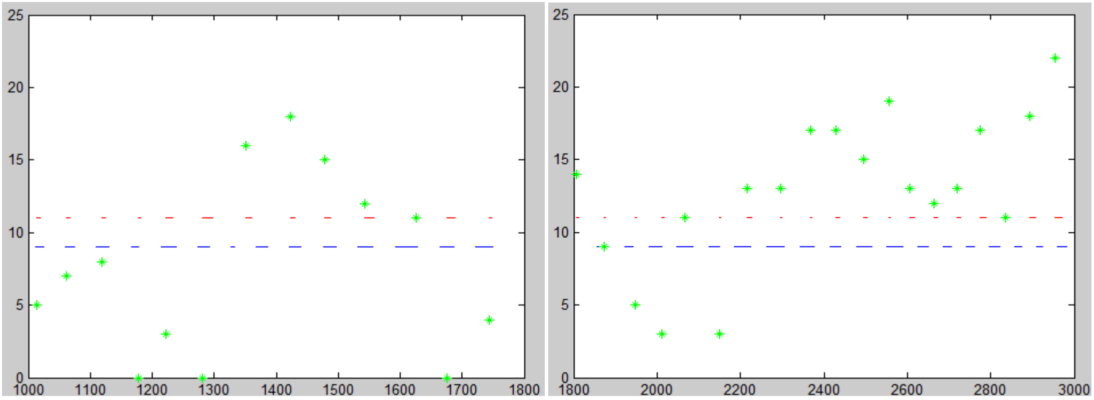


Figure 4.15 Durations of 2nd stage of max pressure algorithm

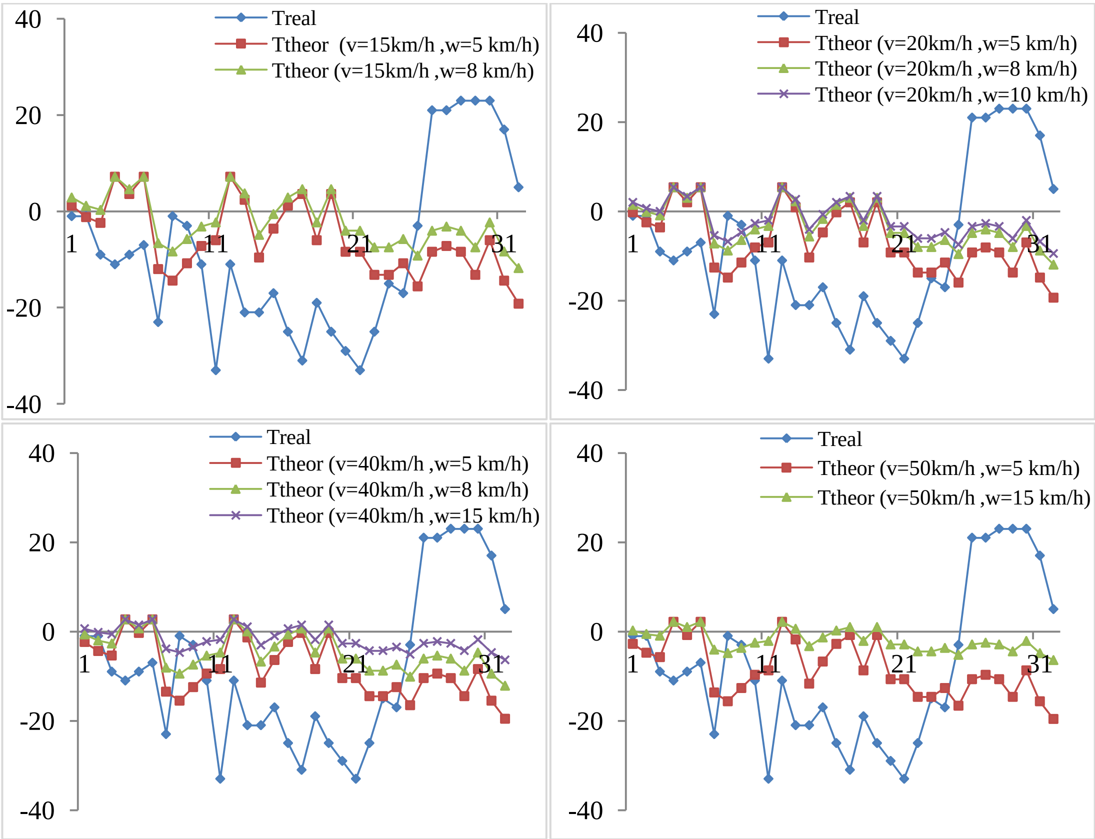


Figure 4.16 - Comparison of real and theoretical offset between junctions 4 and 5 of max pressure algorithm of 2nd stage

3rd investigation:

Finally, for the third stage there is less correlation between the start times of green light for the two junctions. Most of the time the green duration of junction 5 starts and ends between two green durations of junctions 4. The comparison between theoretical and real offsets presents large scale's differences (Figure 4.19).

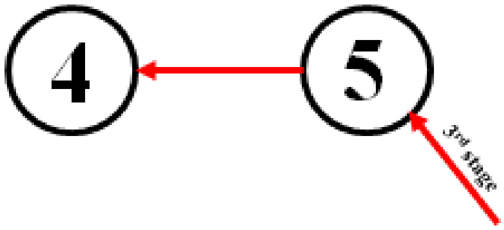


Figure 4.17 - Layout of junctions (3rd stage testing)

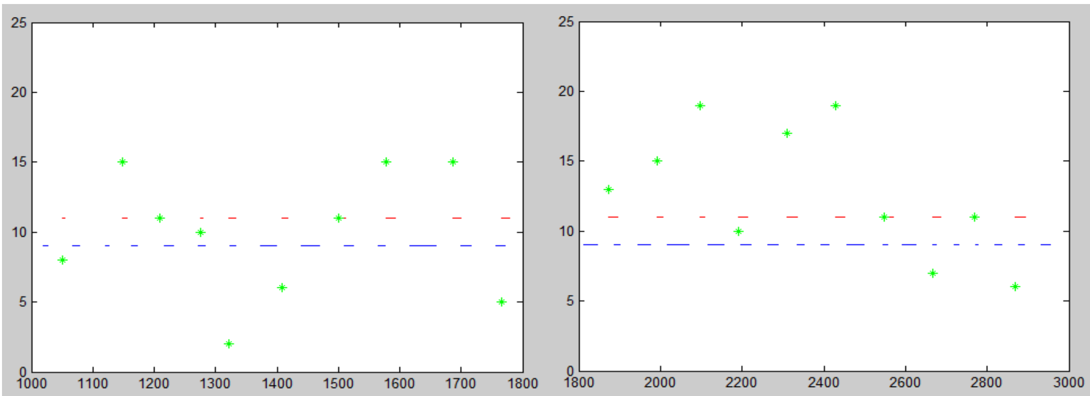


Figure 4.18 - Durations of cycles of 3rd stage of job scheduling algorithm

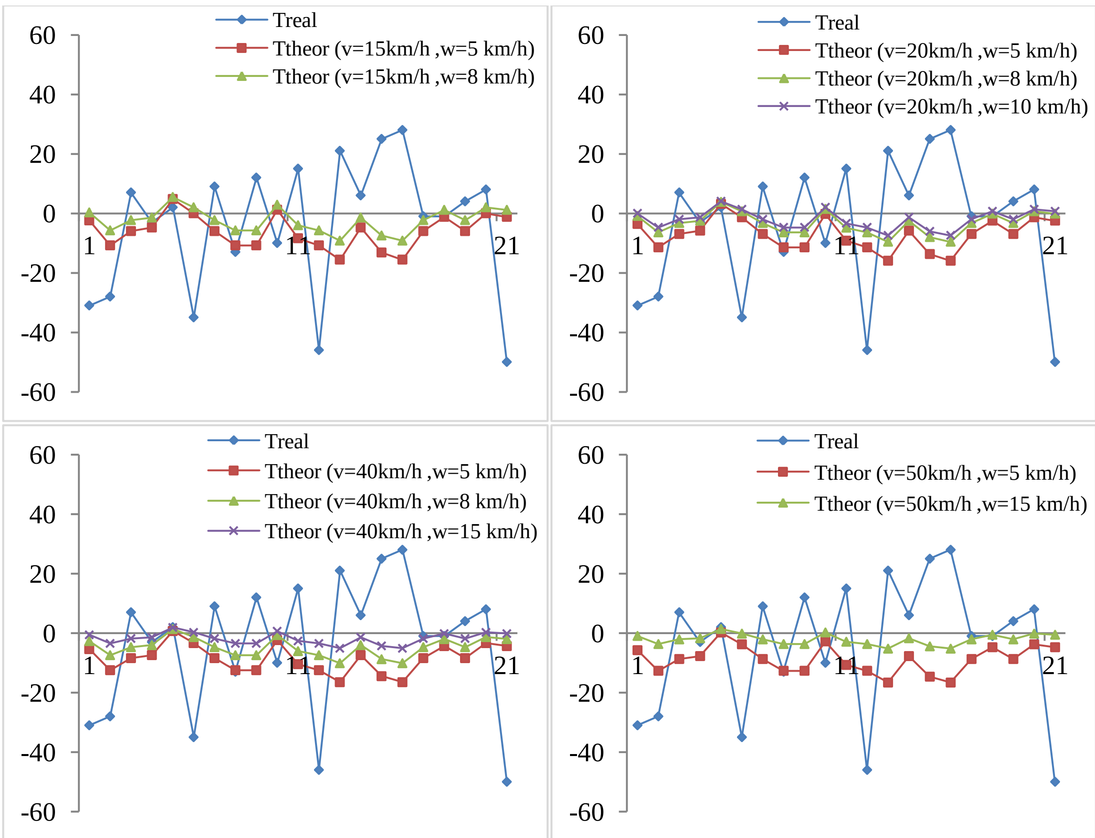


Figure 4.19 - Comparison of real and theoretical offset between junctions 4 and 5 of job scheduling algorithm of 2nd stage.

In order to compare the three stages to each other, the difference of real and theoretical offset has been calculated. The corresponding diagrams (Figures 4.20 and

4.21) have only a few points that not exceed 5 seconds, which could be a feasible difference between the real and the theoretical offset. Depending on the above observation, none of the stages of junction 5 forms an offset with the junction 4.

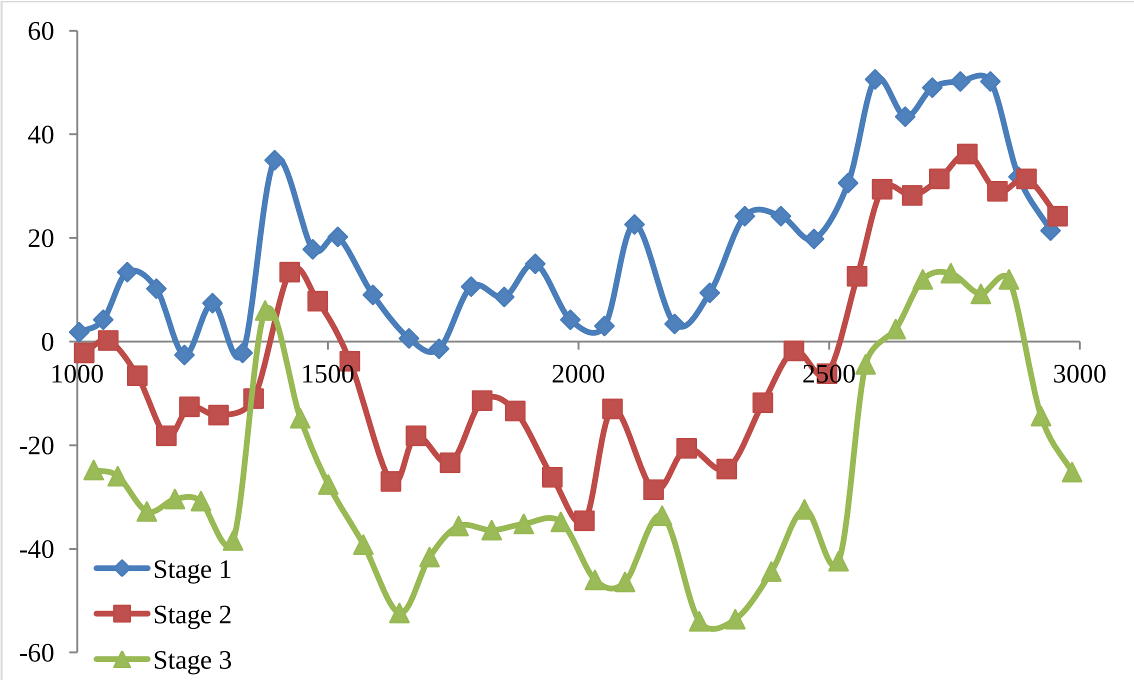


Figure 4.20 - Difference between real and theoretical offset for network free speed 15km/h and movement speed 5km/h, for max pressure algorithm.

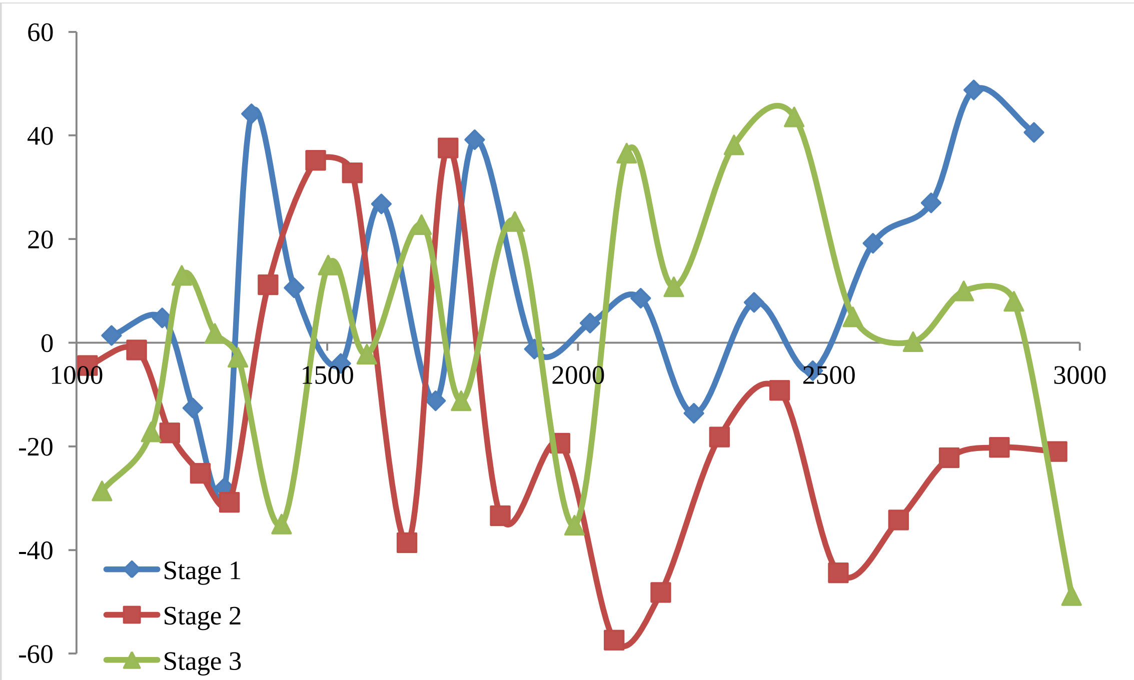


Figure 4.21 - Difference between real and theoretical offset for network free speed 15km/h and movement speed 5km/h, for job scheduling algorithm.

5 Conclusions

5.1 Conclusions

The aim of this thesis is to demonstrate and compare three signal control strategies under realistic traffic conditions. The centralized control strategy TUC has been created in order to provide coordinated traffic responsive signal control in large-scale urban network. The decentralized control is represented by the job scheduling algorithm of the SURTRAC system and the max pressure algorithm. In order to investigate the potentials of each method in a real network, two demand scenarios have been developed. The first one corresponds to dense traffic conditions and the other corresponds to congested traffic conditions.

The simulation results denote both centralized and decentralized approaches, under both demand scenarios, have better performance than fixed time control. A high performance under both considered scenarios is achieved only by TUC and the max pressure algorithm. However, TUC outperforms under congested traffic conditions and max pressure algorithm under dense traffic conditions. The job scheduling algorithm has comparable output with TUC under dense traffic conditions, while in congested traffic conditions is degraded over the other. Concerning the cycle times that arise during high traffic loads and demands, it has been observed that the avoidance of wasted green time and the usage of offsets, depending on the method, can lead to positive effects.

Considering the above conclusions about the studied control approaches, the max pressure algorithm is the most applicable in networks that consist of junctions with arbitrary geometrical and signal control characteristics. The application in real-time of this approach requires only a limited number of calculations. The other decentralized approach, the job scheduling algorithm, requires calculations that, under particular conditions, can be unworkable in real time. In order to be used and applied in general, some simplifications and assumptions are required. Furthermore, the job scheduling approach can be characterized as demanding, as it needs often accurate queue estimations. That characteristic increases the needs for sensing system. Although, the centralized control TUC, involves simple calculations, to be applied to a network, needs redesign when junctions' topology or signal control changes, due to its central logic. Max pressure algorithm, it can be applied to junctions with arbitrary characteristics. A significant difference between them is that TUC has low needs in sensing infrastructure. Finally, TUC strategy provides a sequence of signal plans without significant differences among each other, to achieve the least disturbances to the common users' network.

5.2 Future work

The system SURTRAC has more capabilities to apply to a network that could be used also in this research. A useful ability of this algorithm is that junctions can be connected to their upstream and downstream junctions. This operation could be helpful in order to gain and provide information about the traffic flow of neighboring junctions.

Concerning TUC strategy, it can be concluded from the results that it performs better for congested networks than in off-peak conditions. In cases of low demand, control of the split could be done with a different way. Hybrid TUC in this study operates satisfactorily, but other formulations of the TUC strategy could be used as well, e.g. the actuated TUC. This formulation of TUC could lead to stage changing in cases of no vehicle detection when the overall demand is low enough. This procedure could manage to lower cycle durations and decrease lost times when the network is empty, which is achieved by the decentralized methods that have been examined in this master thesis.

References

Kluwer Academic Publishers, 2003. 'Handbook of transportation science', Second edition.

Little, J.D.C., Kelson, M.D. and Gartner, N.H., 1981. MAXBAND: A program for setting signals on arteries and triangular networks. *Transportation Research Record* 795, 40-46.

Robertson, D.I., 1969. TRANSYT: Method area traffic control, Transportation Research Board, Vol 11, No 6, pp 276-281.

Hunt, P.B., Robertson, D.L. and Bretherton, R.D., 1982. The SCOOT on-line traffic signal optimization technique. Traffic Engineering & Control 23, 190-192.

Xie, X.,Smith, S.F., Lu, L., Barlow, G.J., 2012. Schedule-driven intersection control, Transportation Research Part C 24, pages 168-189.

Smith, S.F., Barlow, G.J., Xie, X., Rubinstein, Z.B., 2013. SURTRAC: Scalable Urban Traffic Control, Compendium of Papers of 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., USA.

Varaiya, P. 2013. Max pressure control of a network of signalized intersections, Transportation Research Part C 36, pages 177-195.

Kouvelas, A., Lioris, J., Fayazi, S., Varaiya, P., 2014. Max-Pressure Controller for Stabilizing the Queues in Signalized Arterial Networks. Traffic Flow Theory and Characteristics 2014, Volume 1. Transportation Research Record: Journal of the Transportation Research Board 2421, 133–141.

Gregoire, J., Frazzoli, E., de La Fortelle, A., Wongpiromsarn, T., 2014. Back-Pressure Traffic Signal Control with Unknown Routing Rates. Preprints of the 19th World Congress, The International Federation of Automatic Control, Cape Town, South Africa.

Dinopoulou, V., Diakaki, C., Papageorgiou, M., 2002. Applications on the urban traffic control strategy TUC. Proc., 9th Meeting of the EURO Working group on Transportation, Bari, Italy, pp. 366-371.

Diakaki, C., Dinopoulou, V., Aboudolas, K., Papageorgiou, M., Ben-Shabat, E., Seider, E., Leibov, A., 2003. Extensions and new applications of the traffic-responsive urban control strategy: Coordinated signal control for urban networks, Transportation Research Record: Journal of the Transportation Research Board, 1856, 202-211.

Kouvelas, A., Aboudolas, K., Kosmatopoulos, E.B., Papageorgiou M., 2011. Adaptive Performance Optimization for Large-scale Traffic Control Systems. IEEE Transactions on Intelligent Transportation Systems 12(4), 1434–1445.

TTS-Transport Simulation Systems, 2004. 'Aimsun 5.1 Microsimulator User's Manual'.

Manolis, D., Diakaki, C., Papamichail, I., Papageorgiou, M., 2015. Comparative evaluation of two alternative approaches for the decentralized real-time signal control of urban networks, 4th International Symposium and 26th National Conference on Operational Research, pages 196-200.