TECHNICAL UNIVERSITY OF CRETE
School of Production Engineering and Management

REAL TIME PUBLIC TRANSPORT PRIORITY

A thesis submitted in fulfillment of the requirements for the degree of Master in Production Engineering and Management

by

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CHANIA 2014

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Executive Summary

The development of methodologies for bus priority at traffic signals is a research field that continues to grow since the need to improve public transport (PT) is nowadays higher compared to the previous decades. In cities where road space is limited and traffic congestion is high, one way to improve traffic conditions is to attract citizens to use more often PT means and to provide fast, reliable and frequent services. For PT means, like trams and trains, the design of a precise schedule plan is quite easy, since they are moving on exclusive lanes and they are not affected by external conditions, e.g. traffic congestion, weather or special events. However, in the case of buses moving on mixed lanes, the estimation of their arrival time at each bus stop as well as the estimation of their total travel time may be far from reality. Consequently, the design of a bus priority traffic signal plan in advance is not functional and different methodologies have to be applied.

Several ways have been used to attract people to use PT means more often. These attempts can be separated in two basic categories. In the first category, the goal is to optimize the road network's capacity by changing its structure. This approach includes the addition of exclusive lanes for buses, the construction of queue jumper lanes to the parts of the network where high congestion is observed and the adjustment of bus routes. Some of these efforts could provide good results for the buses' travel time but in most of the cases they are not easily applicable due to the lack of empty space in the network or due to the high cost of constructions needed.

Since public transport priority (PTP) is not satisfactory enough through facility-designed-based measures, a different approach should be used; and this is signal-control-based measures. The goal of this approach is to improve the service of PT vehicles by changing locally or network-wide the signal control so that their total travel time is reduced. To achieve this, these methodologies adjust the current signal control plan of each junction so that a PT vehicle, approaching a signalized junction, crosses the junction as soon as possible. Some of the techniques that are used to provide priority are green extension, stage re-ordering, stage skipping, import of special stages etc. Depending on the traffic condition of the network and the frequency of PT movements, each methodology might have different results and impacts across the network.

Improving the effectiveness of transit signal priority operations has been the subject of considerable research and the results show that the unintended bus delay can be significantly reduced. A major controversy, though, is that these methodologies may bring excessive delays on non-prioritized junctions, as their assigned greens are shortened. Also, a very common dilemma appears is cases where two buses request priority from conflicting directions.

In this thesis a real time PTP methodology is presented and evaluated. This methodology aims to change the signal plan locally in favor of a bus when this bus is detected and priority is requested. The strategy is based on rules while two different priority levels exist. Depending on the position of the bus and the current signal phase, the strategy chooses either to extend the green time or to reduce the red time of the bus. For conflicting priority requests a number of criteria must be taken into account in order to serve both requests, if feasible, otherwise in order to decide which bus should be served first. This strategy can be easily implemented at different road networks. Additionally, when a signal phase is modified for the implementation of a bus priority traffic plan, then it can be easily adjusted to the initial signal plan without affecting the rest of the network. The methodology is implemented in a microscopic simulation environment emulating a part of the urban network of Chania with realistic traffic conditions. The criteria used for the assessment of the methodology are the average delay time, the average harmonic speed and the CO emissions. It is shown that all the criteria for the buses are significantly improved without really affecting the rest of the vehicles in the network. The overall performance is better when the Traffic-responsive Urban Control (TUC) strategy is used instead of a fixed-time plan.

1 Introduction

1.1 Overview of the thesis

The majority of the urban road networks face serious traffic problems, which are the result of the ever growing population in the cities combined with aged road networks. Since such a development was not expected in many cities, during the construction of the network many factors have not been taken into account, e.g. sufficient parking space or exclusive bus lanes for the decongestion of the network. As a consequence of the above, the most serious problems that are noticed are traffic congestion, increased travel time of private and public vehicles and air pollution. There are several incentives for minimizing traffic delays, like environmental factors and high fuel cost. Already an increasing number of researchers have recognized that providing reliable public transportation service is an effective strategy to relieve traffic congestion; however, this calls for an improvement of public transport (PT) services, since, so far, the travel time of PT vehicles, and especially of buses, is much longer than the one of private vehicles. The main reason for the high travel times experienced by buses is that they face significant delays at each bus stop, for boarding and alighting. Additionally, buses have to follow indirect routes. Since these factors cannot be controlled, the aim of the researchers is to favor the movement of PT vehicles compared to private cars at signalized junctions.

Although a series of priority strategies have been developed the last years that aim to change the signal plan locally so as to serve a passing PT vehicle as soon as possible, insufficient research has been done to design priority strategies in response to multiple bus priority requests for conflicting movements at an intersection, which is very common in urban networks. Due to the expansion of the cities, the transit network has become more complex since more and different bus lines have been added and the service frequency of buses has been significantly increased. At centrally located intersections, more than one bus may approach the junction within a signal cycle. As a result, a series of questions arise: which bus should receive priority, is it possible both buses to be served as soon as possible, etc. Most studies have employed the first-come-first-serve policy which provides priority only to the first request. However, in case of a high bus demand it is important to serve, if feasible, all priority requests.

1.2 Aim and objective

The objective of this thesis is the presentation and evaluation of a rule-based public transport priority (PTP) methodology which will be implemented in real time for single or multiple priority requests. The purpose is to test and evaluate a strategy which will provide appropriate priority signal plans for multiple bus requests, as well as to minimize the overall negative impacts to the rest of the network. The strategy will be executed in real time and priority requests might be received in the same cycle from the same or conflicting directions. The priority will be given by changing, if feasible, the signal settings locally for each priority request but without affecting the rules of road safety. Signal priority involves modifying the normal signal operation process in a variety of ways, generally including green extension and red interruption to reduce bus delay time at intersections. It is also important to verify that the strategy will not create major disturbances to the rest of the network. For this reason, apart from the fixed-time strategy combined with PTP, the Traffic-responsive Urban Control (TUC) strategy with PTP will be implemented in order to reduce the delays also for the private vehicles.

Different scenarios will be studied in order to evaluate the effectiveness of the methodology under single or conflicting priority requests. The simulation experiments will be performed with the microscopic simulation software AIMSUN emulating the urban network of Chania, Greece using realistic traffic conditions. The results will be evaluated based on the following criteria: the average delay, the harmonic speed and the pollution emissions. It is assumed that the PT vehicles are moving in mixed-traffic lanes and the detection of the PT vehicle will be done by detectors that are located few dozens of meters upstream of the stop-line at each signalized junction.

1.3 Structure

The organization of the thesis is as follows:

- Chapter 2 starts with some basic notions for the urban networks and reviews the available priority strategies and the ways to provide priority to PT means.
- Chapter 3 presents the PTP methodology, the different rules that are implemented in cases of conflicting priority requests as well as the TUC strategy.
- In Chapter 4, the urban network of Chania is presented and the different scenarios that are studied and their corresponding results are analytically reported.
- Finally, Chapter 5 summarizes the results and presents the main conclusions.

2 Background

In order to present the PTP methodology, a short introduction follows where the priority strategies are categorized and described in detail.

2.1 Basic notions

A *junction* is a location where multiple roads intersect, allowing vehicular traffic to change from one road to another. It consists of a number of approaches, where each approach has one or more lanes and a unique queue. The junctions can be divided into two basic categories: *interchange* and *intersection*. In the first category are those where the roads cross at the same or different elevations, whereas at intersections, roads cross at the same level. Intersections can be furthermore subdivided into signal controlled or uncontrolled.

Each signal controlled junction has a *traffic signal cycle* which is one repetition of the basic series of signal combinations at a junction and its duration is called *cycle time*. A cycle contains a number of *stages*, i.e. a part of the cycle during which a particular set of *phases* receives green, where phase is a set of traffic movements. Finally, the *intergreen* period of a phase consists of both the yellow (amber) indication and the all-red indication. The all-red phase is governed by three separate concepts: stopping distance, intersection clearance time, and pedestrian crossing time, if there are no pedestrian signals.

Traffic conditions can be controlled via traffic lights operations through the following methods (Papageorgiou et al., 2003):

- *Split*: At the signalized junctions each stream has it's green time, so according to the demand of the involved streams, the green durations can be optimized and set on the controller.

- *Cycle time*: The duration of the cycle at each junction is affecting the whole network since a long cycle time increases the junction's capacity but on the other hand increases also the waiting time during red phase.

- *Offset*: This is the stage difference between cycles for successive junctions so that green waves are created in an arterial; clearly, the specification of an offset should ideally take into account the possible existence of vehicle queues.

- *Stage specification*: Some junctions may include a large number of streams therefore, the optimal number and constitution of stages should be specified since it can have a major impact on junction capacity and efficiency.

2.2 Priority strategies

As described elsewhere (Diakaki et al., 2013), there are two basic categories of priority strategies for an urban road network: fixed-time strategies and real-time strategies (see also Figure 1). The first category is based on historic measurements and data. A traffic control plan is created off-line according to the data and it may include adjustment of cycle length, stage splitting, area-wide timing plans, and metering priority. This approach is easy to implement, however, since traffic flow is not constant and bus arrivals at each junction may have big diversifications, these strategies are not efficient for public transport priority. The real-time strategies are operating in real time and require the ability to detect PT vehicles, that are approaching signalized junctions, in real-time. Using measurements from loop detectors that are situated in different places of the network, the real-time methodologies receive a priority request and decide, according to the current phase, what plan to follow and how to serve the specific request.

Furthermore the real time strategies are categorized according to the following criteria (Diakaki et al., 2013):

- **Reactive or proactive**

Reactive strategies are applied at each junction separately and they serve the priority request according to the junction’s current plan without communicating with the rest of the network. Each junction receives isolated treatment for the received priority requests, regardless the traffic condition of the rest of the network.

Proactive strategies are those who receive a priority request one or more signals upstream and a new plan is created to provide priority for the arriving vehicle. Since the priority is requested well in advance, the strategy has the time that is needed to co-ordinate the signal plans of different junctions and to find the most suitable plan for providing priority with minimal disruption to the rest of the traffic. Proactive strategies may be further distinguished as:

- local, when implemented at isolated junctions; versus
- network-wide, when they attempt to improve the progression of PT vehicles within a network, through the adjustment of the coordination timing parameters.

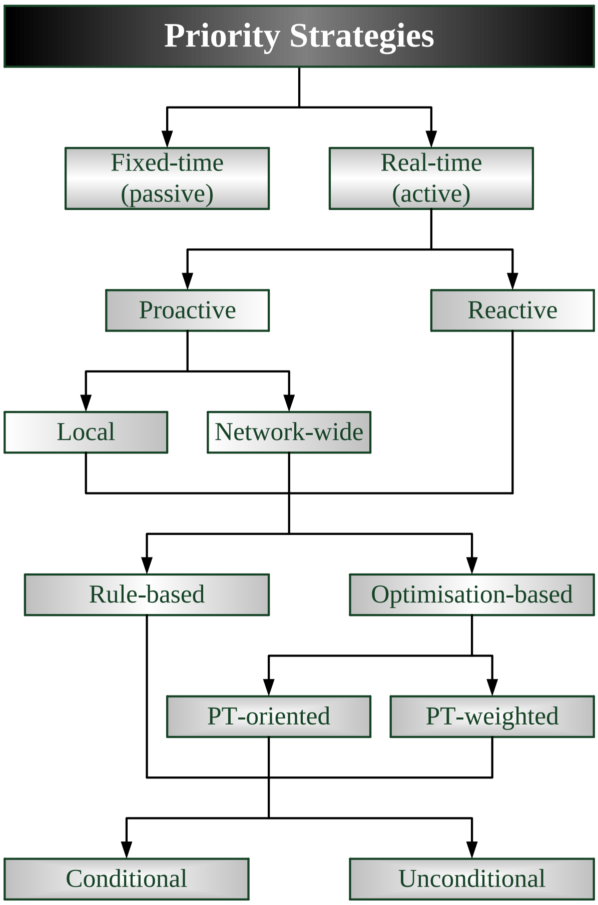


Figure 1: Priority strategies

- **Rule based or optimization based**

The second criterion to distinguish the real-time strategies is rule based versus optimization based. In the first category the decision of whether and how priority will be provided is taken by a set of rules which may include stage extension, stage recall, special stage introduction, etc. As they operate in real-time, they require the ability to detect PT vehicles approaching signalized junctions in real-time, so as to serve them as soon as possible. These strategies are moreover divided in conditional and unconditional strategies.

- ➢ Conditional strategies are those that provide priority if some extra conditions are valid, e.g. if the PT vehicle is behind schedule, or if the downstream network is congested. In order to confirm that the extra conditions are valid, additional real-time information is required regarding the operating status of a detected PT vehicle.
- ➢ Unconditional strategies provide priority for every single request they receive regardless of the network's condition or whether the vehicle really needs to be treated in a special way at its approach to a signal-controlled junction.

Finally, optimization based strategies, have as a main goal the improvement of efficiency for the whole network, and as a result the plan that is chosen is the one that gives the best results for the travel time for all the vehicles. Other criteria that are used are passenger delay, vehicle delay, weighted vehicle delay or combination. These strategies use actual vehicle arrivals as inputs to a traffic model that optimises the current timing in terms of stage durations and stage sequences.

Furthermore, optimisation-based strategies can be distinguished in *PT-weighted* versus *PT-oriented.*

- In *PT-weighted* strategies, PT vehicles receive higher weight comparing with private vehicles while optimizing an appropriate control plan in real time.
- PT-*oriented* strategies are based on the optimisation of an appropriately defined performance index in real time, so as to respond to the received priority requests and provide priority to the detected PT vehicles the soonest possible.

2.3 Priority methods

In real-time strategies a priority request can be received and served directly through appropriate adjustment at the current phase durations and phase sequence at a signalized junction. Various ways are proposed and developed aiming to modify the background traffic signals so as to accelerate the passage of public transport vehicles and these methodologies can be applied at either rule-based or optimization-based strategies.

The most common methods that are used are the following (Diakaki et al., 2003):

- *Green extension:* When a bus is approaching the stop-line at the moment that green time ends the controller gives extra time to extend the green time so that the bus can cross the junction without stopping (see Figure 2). This method is commonly used in urban networks where the bus loop detectors are relatively close to the priority junction and is subject to constraints like maximum extension time, minimum green-time for non-priority stages, etc.

- *Red interruption*: If a bus is approaching the junction during its red time, the controller reduces the green time of the competitive streams so that the waiting time of the bus will be minimized (see Figure 3). As green extension, red interruption is also commonly used where the detection is relatively close to the priority junction.

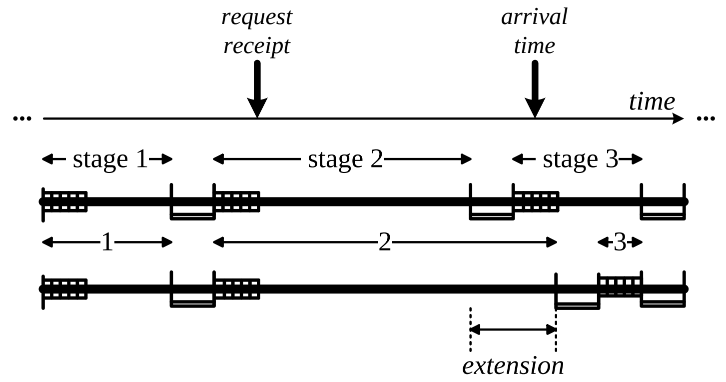


Figure 2: Green extension

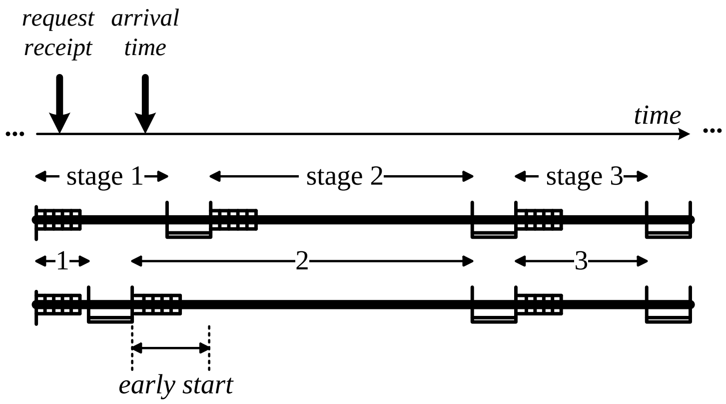


Figure 3: Red interruption

- *Stage skipping:* If a bus arrives at the junction's stop-line during its red time then some of the intermediate stages can be skipped so the green phase for the bus will start earlier and the waiting time will be reduced.

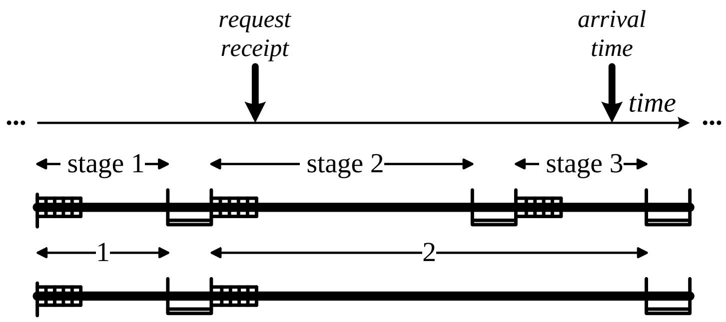


Figure 4: Stage skipping

- *Stage re-ordering:* In extreme cases where the previous methodologies cannot reduce the PT vehicle's waiting time, one other approach is to modify the normal sequence, i.e. to activate a stage which is later in the order, so that the approaching PT vehicle to be served as soon as possible.

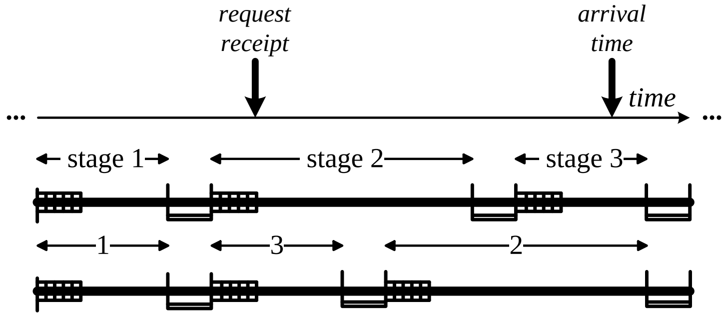


Figure 5: Stage re-ordering

Other methods may include:

- *Special stage:* In order to serve a received priority request, a special stage is introduced into the normal sequence at the first available opportunity that can provide extra green time at a PT vehicle. When the special stage is introduced, the other phases may have to be truncated to their minimum green times or skipped, i.e. this methodology is a combination of stage re-ordering and stage skipping.

- *Offset modification:* When a fixed-time plan is implemented to control all the junctions of the network, the start time of each phase are fixed i.e. the offset duration is stable, so when modifying the offsets, green waves are created in order to reduce the difference between the detection time of a PT vehicle and the ideal time in the cycle for the vehicle to arrive at the detection point (Gardner et al., 2009).

3 A Public Transport Priority Methodology

In this Chapter, the proposed PTP methodology is presented and analytically described before the application and evaluation of the methodology.

3.1 Introduction

Considering that a public transport vehicle is approaching a signalized junction, the following steps are performed.

Step 1: The bus is detected. The detection of the bus is performed either at the beginning of the link or at the moment that the bus is departing from a bus stop. The time required for the bus to travel from the detection point to the stop-line is calculated using the average speed of the vehicle and the distance from the stop-line.

Step 2: According to the junction's current signal plan, the methodology estimates if the bus will approach and cross the junction's stop-line without requiring any change at the current signal plan (i.e. the bus will approach the junction during its green time). In this case there is no need to change the signal plan.

Step 3: If the travel time from step 1 is not enough for the bus to cross the junction, depending on the phase that will be executed at the junction, priority is given by choosing the most appropriate option: green extension, red interruption or stage skipping.

The methods that are used in order to serve the priority requests are described in the following sections.

3.2 Proposed methodology

According to the aforementioned categories of priority strategies (Section 2.1), the proposed methodology is a real-time, reactive, rule-based priority strategy (Dinopoulou et al., 2003). Depending also on the traffic condition and the congestion of the network it can be characterized as conditional or unconditional. In case the network is not saturated, the methodology can be applied without any extra conditions. Priority can be provided for every request without negatively affecting other vehicles since the strategy has the ability to restore the signal control plan to its initial state during the next cycle time. In the opposite case, where the delay time of all the vehicles is already high and extra delay will cause significant queues, one extra criterion can be activated, the downstream occupancy. Measurements for the occupancy of the downstream link can be collected every second, so if a bus requests for priority but the downstream link is congested, then priority is not provided since the bus will be delayed anyway.

The priority requests can be served through green extension or red interruption and the methodology includes two priority options:

Option 1: The cycle time of each junction is given and priority is provided by either green extension or red interruption. The stage sequence is not modified and the PT vehicle's green time is extended, if it's necessary, by reducing the other phases to the permitted minimum time.

Option 2: In this option the duration of the cycle can change only if for the next cycle, which is called recovery, the following rule is applied:

$$C_1 + C_2 = C$$

where C_1 is the changeable cycle, C_2 is the recovery cycle and C is the initial cycle.

With this option, a phase is reduced or extended to serve the bus as soon as possible without modifying the stage sequence. However, if a bus arrives at the stop-line during its red time then the cycle will be reduced or if the bus needs extra time to cross the junction the cycle is increased. In any case if there is a second request for priority during the recovery cycle, then it is served only with Option 1 so that the duration of cycle will not change.

To estimate the arrival time at the junction's stop-line bus, detectors are used which can provide only bus passage information. So, it is important to make an accurate estimation of the travel time from the moment that a bus is detected until the moment that it will cross the junction. If the buses are moving on exclusive bus lanes then the travel time can be easily calculated based on the vehicles' nominal speed; but in case of mixed lanes, like the ones studied here, other factors may have to be considered, e.g. exact speed of the bus or an estimate of the travel time based on the occupancy of the link.

To avoid high deviation between the estimated arrival time and the actual arrival time, the location of the bus detectors is an important issue. If the detectors are located two or three links upstream of the stop-line then the arrival time cannot be predicted reliably since many things may change in the links after the bus detection. On the other hand, if the bus detectors are just a few meters upstream of the stop-line then it may be very late for the controller to change at that moment the running traffic plan. Therefore, to avoid the aforementioned problems, the bus detectors are placed at the upstream end of the signalized approach and the travel time is calculated using the distance between the detector and the stop-line and a nominal speed. In this case, the presence of other cars on the link does not affect significantly the arrival time of the bus since, in case of green extension, these cars are moving at the same speed, and, in case of red interruption, the use of higher speed compared to reality will just cause an earlier interruption or no-priority, to respect minimum green constraints.

Finally, in order to evaluate the estimated travel time at each junction, several tests have been conducted as follows: at the links that are connected with the junctions that provide priority, bus detectors have been placed at the beginning and the end of those links and the time that is needed for a bus to cross the link is measured. Figure 6 shows the distribution of travel times of the buses at a specific junction in the network. In the methodology the estimated travel time is defined to be equal to 8 seconds and as Figure 6 shows, 55% of the buses need 8 seconds to cross the junction. For the buses that are approaching the junction's stop-line during their red time, their travel time differs since they have to wait until the green phase starts. As a consequence in Figure 6 we can see different values of the travel time. Also, when the link is not congested, the buses can move with higher speed and their travel time is less than 8 seconds.

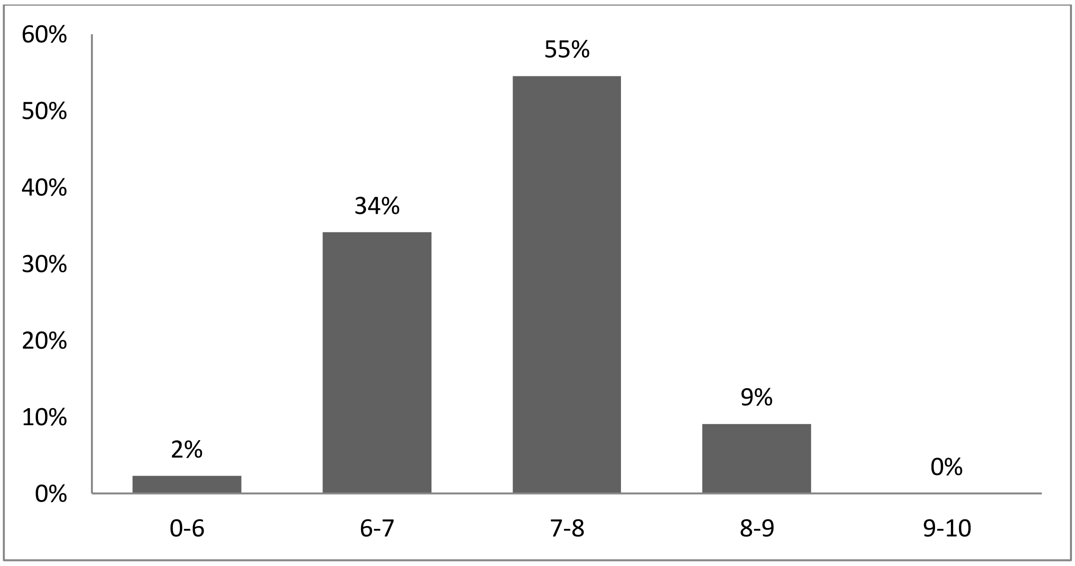


Figure 6: Distribution for buses' travel time from the moment that are detected until they cross the junction

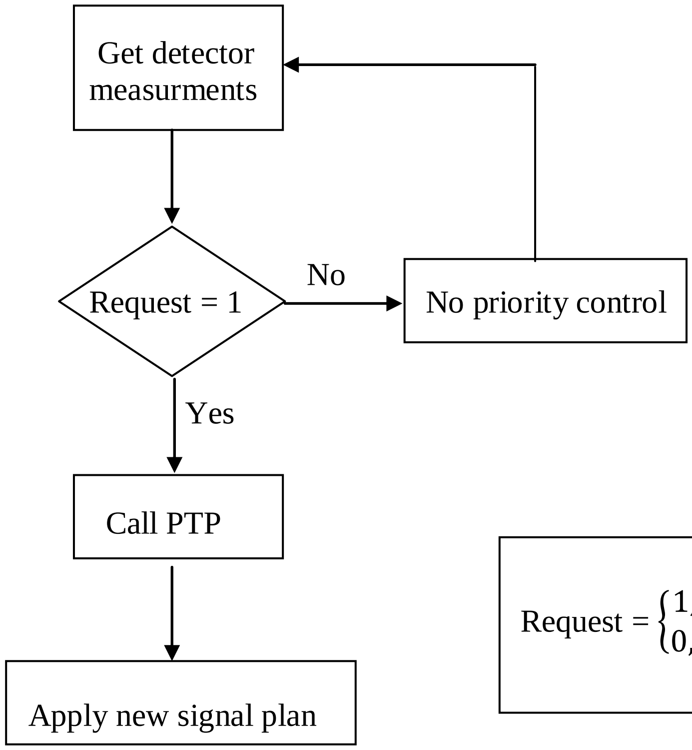
Another approach that is used in this methodology to solve the problem of underestimation or overestimation of the travel time from the upstream end of the signalized approach to the junction's stop-line is the installation of extra detectors between the first set of detectors and the stop-line at specific junctions. If the travel time is underestimated or the link is congested and the queue in not moving then the priority plan that is applied based on detection from the first set of detectors might not be satisfactory. In case of green extension, the extra time that the first detectors will provide will not be enough for the bus to cross the junction so the subsequent set of detectors will apply again the PTP methodology and a new decision will be taken. So if the bus needs a few more seconds to cross the junction then these detectors will provide them. If the travel time is overestimated and red interruption is applied, then the red time of the bus will be reduced by reducing the cycle time if Option 2 is activated or by reducing the green time of the other phases. When the bus will cross the second detector, depending on the current phase, a new decision will be taken if it is necessary.

3.3 Conflicting priority requests

Consider now that two buses are approaching a signalized junction within the same cycle period from conflicting directions. If both buses request priority but are served from different phases, the methodology will be applied for both requests aiming to serve both requests.

One of the following cases can be applied in order to serve these priority requests:

Case 1: Both buses will be served in the same cycle but this bears the risk that the second priority request might destroy the first bus's priority.



$$\text{Request} = \begin{cases} 1, \text{there is a new request to be served} \\ 0, \ \text{else} \end{cases}$$

Figure 7 : Case 1 for multiple priority requests

Figure 7 describes the main steps of the methodology. Every one second the methodology checks if there is a new request for priority. If *Request = 0* then no bus has been detected and no changes are implemented on the current signal plan. Otherwise, when *Request = 1,* the PTP methodology is implemented and a new signal plan is applied. The new signal plan will be created using one of the two priority options that are implemented in this methodology. Finally, the bus will be served (if feasible) through green extension or red interruption.

In general, the first bus that is detected is the one that will be served first. However, if during this period a second bus requests for priority then the signal plan will change again and a new priority plan will be applied.

There are two possible scenarios:

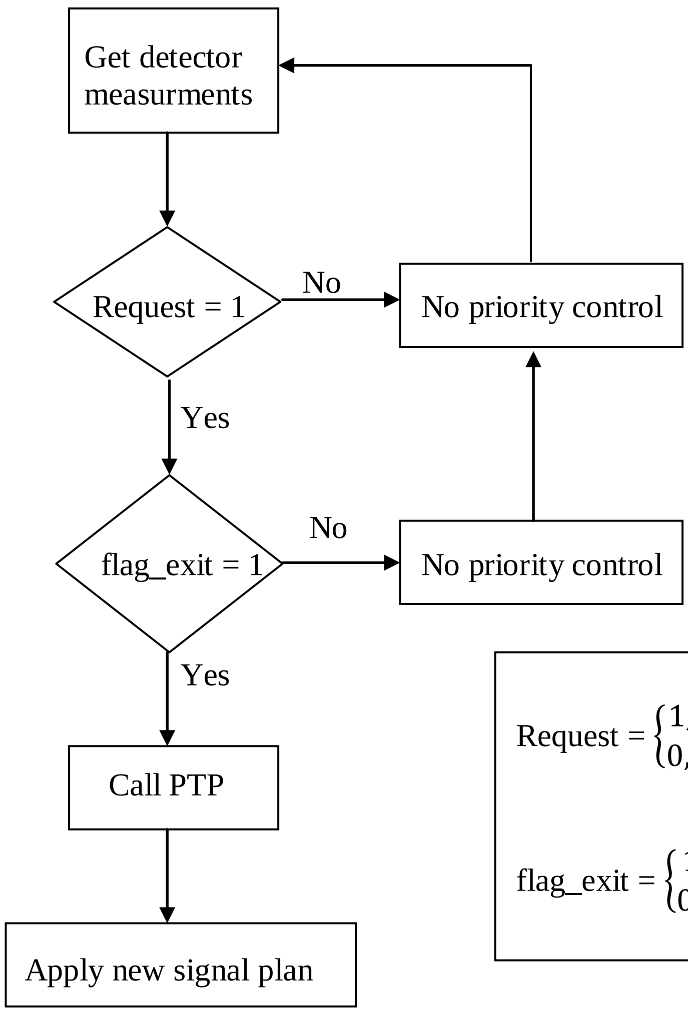
- Both buses can be served if the second priority plan is applied immediately after the first bus has crossed the junction.
- Only the second bus will be served if the second priority plan interrupts the first's bus green time.

One extra criterion can be checked in this option in order to decide which bus has a higher priority, the downstream occupancy. The occupancy of the downstream link for each direction is measured and compared so that the bus which will be delayed anyway due to the congestion of the downstream link will not receive priority.

Case 2: The second priority request will be served in the same cycle only if the first bus has crossed the junction.

To make sure that the first bus is served and has crossed the junction extra detectors are placed at the exit of each studied junction, at the beginning of the next link, so only if the first bus has passed the exit detectors the second bus can request priority. With these detectors there is no risk of destroying the first's bus priority.

As Figure 8 shows, when a bus is detected and requests for priority, the methodology checks whether there is already a bus inside the junction or inside the link approaching the junction. If the *flag_exit* is not equal to one, then there is already a priority request to be served, to wit there is already a bus close to the junction so the other requests will not be served. Otherwise, if *flag_exit = 1* then the previous bus that requested for priority has crossed the junction and a new control plan can be applied. Bus passage measurements are collected every second.



$$\text{Request} = \begin{cases} 1, & \text{there is a new request to be served} \\ 0, & \text{else} \end{cases}$$

$$\text{flag\_exit} = \begin{cases} 1, & \text{if there is no other bus within the junction} \\ 0, & \text{else} \end{cases}$$

Figure 8: Case 2 for multiple priority requests

Case 3: Exit detectors and extra detectors between the first detectors of the link and the stop-line of the junction.

With the use of exit detectors, many priority requests will not be taken into account, since, if there is already a priority plan on the controller for the first bus that has been detected, the second bus cannot request a priority until the first one has crossed the junction. In order to serve the majority of the priority requests, extra detectors can be placed between the first set of detectors and junction's stop-line.

These detectors have two purposes: First, if the travel time from the moment that a bus is detected until the time that passes the junction is not estimated correctly, due to congestion or extra queues, then the second detectors will give a new priority plan aiming to reduce the bus's delay time. Second, if the controller has received a priority request from the first detectors of the link but there is already a bus in the competitive direction that has not crossed the exit detectors, then the second bus has a second chance to request priority when it arrives at the second detectors of the link. If at that moment the first bus has already been served then the second bus can be served as well.

Case 4: Finally, the criteria downstream occupancy, number of passengers and schedule deviation can be applied also with the exit detectors for each priority request. If the first bus that is detected requests for priority, but the occupancy of the downstream link is high, then priority will not be provided, since the bus will be delayed anyway. So, the next bus that is approaching can request priority even if the first bus has not crossed the exit detectors.

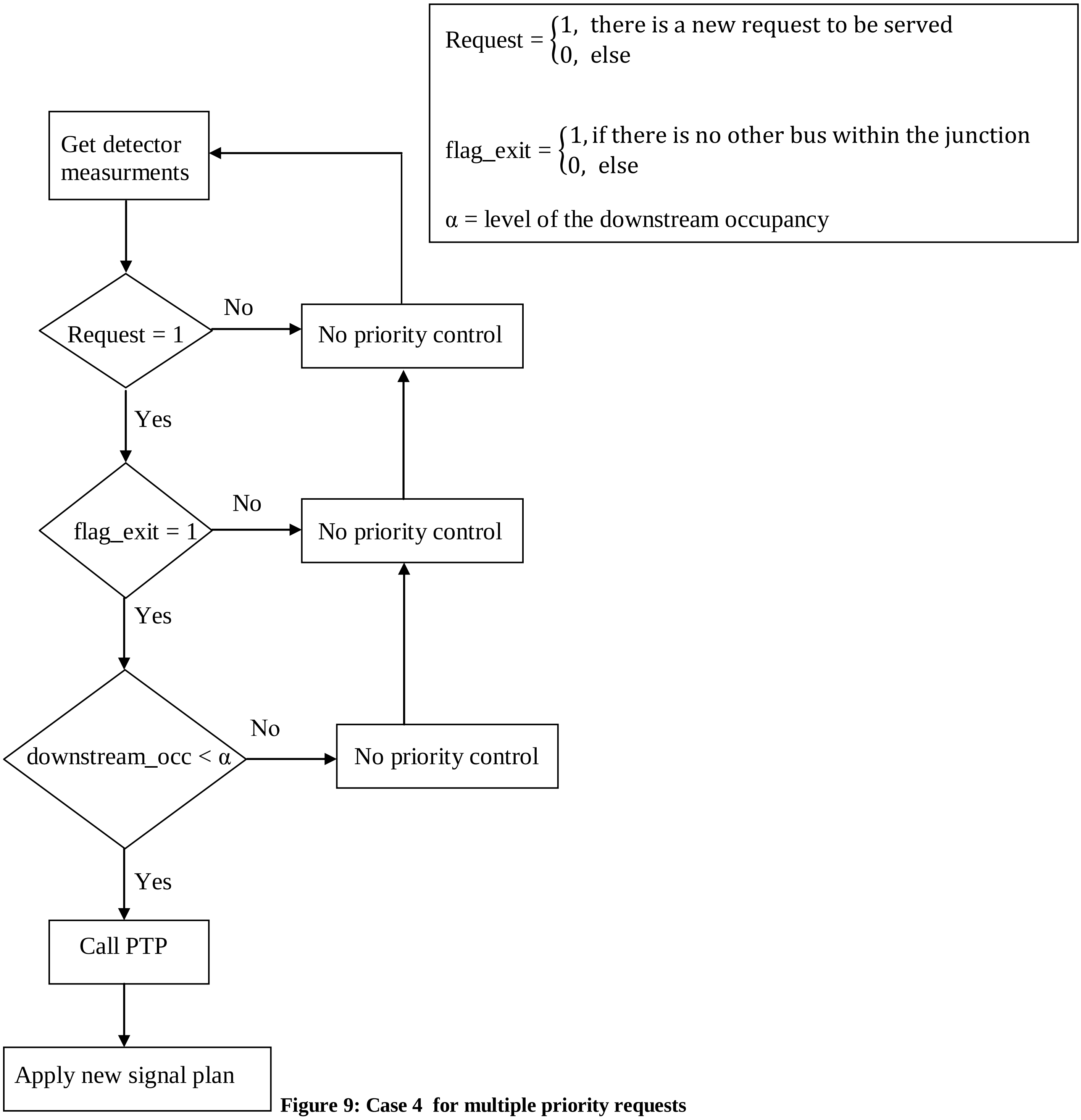


Figure 9: Case 4 for multiple priority requests

As Figure 9 shows, every second the methodology checks if there is a new priority request. If *Request = 1*, a bus is approaching a signalized junction and has been detected by the loop detectors. First the methodology checks if the *flag_exit* parameter is equal to 1. If there is no other bus already in the junction waiting to be served, priority can be requested. Afterwards, if the parameter *downstream_occ* is smaller than a pre-specified value, then the methodology applies the PTP control and a new signal control plan is implemented on the controller.

Similar decisions can be taken if for the two buses that request priority, the number of passengers inside each bus is compared and the bus that serves higher number of passengers must be served first. Also, the bus that is behind schedule can be served first, regardless if it has requested first or second priority or if the previous bus has not crossed the exit detectors.

3.4 A traffic-responsive urban control strategy

Public transport priority control improves the travel time for the buses by changing the signal plan at each junction. However, an important issue that should be noticed is the effect of these control actions to the rest of the network. In congested networks, where the travel time of private cars is already high, these changes on the signal plan in favor of the public transport vehicles may cause extra disturbances to the rest of the network and bigger queues. For this reason, the Traffic-responsive Urban Control (TUC) strategy can be implemented with aim to optimize the flow and the travel time of all the vehicles in the network. Since the basic methodology of TUC is described elsewhere (Diakaki et al., 2003), only a short summary is presented.

The TUC strategy consists of three parts:

- **Split control:** Minimizes the risk of queue spillback and oversaturation

To achieve its objective, split control approaches the urban traffic control problem as an LQ optimal control problem and varies suitably the green-phase durations of each stage without changing the cycle times or the offsets.

- **Cycle control:** Modifies the cycle time of the network to the observed maximum saturation level

The duration of the cycle at each junction is affecting the whole network since a long cycle time increases the junction's capacity but on the other hand increases also the waiting time during red phase. So depending on the traffic conditions, the cycle time should be modified and this is effectuated in TUC by a feedback algorithm that increases or decreases the cycle time using as a criterion the current maximum saturation level.

- **Offset control:** Creates green waves, taking into account the possibility of existing vehicle queues

This part of the TUC strategy is specifying the offset between successive junctions so that green waves are created in an arterial. To accomplish this, offset control is performed in a decentralized way so for each couple of successive junctions the control changes the starting time of a specific stage of the upstream junction.

TUC may be implemented together with the PTP methodology in order to optimize both buses' and cars' travel time. When using TUC, the cycle time and the offset are changing every 10 minutes. As a result, in case of option 2 for the PTP methodology, the recovery cycle has to take into account possible changes of the cycle length in order to make sure that the offset between consecutive junctions is not affected.

4 Simulated Scenarios

4.1 Network description

For the implementation of the PTP methodology, a part of the urban network of Chania, Greece, has been modeled in the microscopic simulator AIMSUN 7.0. The network contains 22 signalized junctions (red and green points in Figure 10), from which 6 (red points in Figure 11) have been programmed to provide priority to the buses.

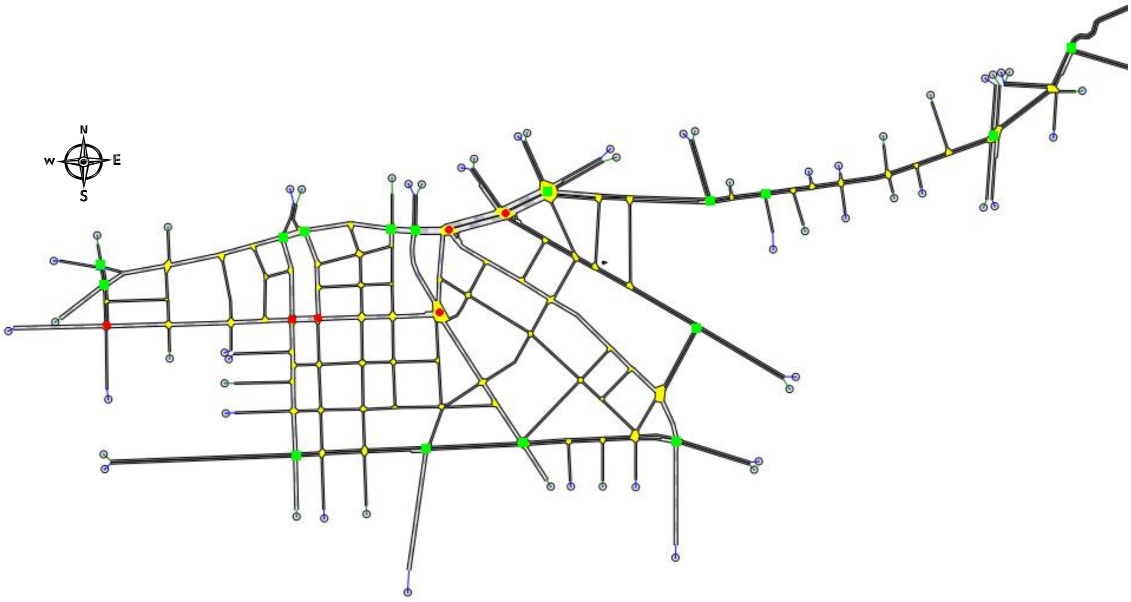


Figure 12: Chania urban network in AIMSUN.

The junctions that have been chosen are located in the center of the network and serve a high volume of private and PT vehicles. The specific junctions are connected with a bus line (red line in Figure 13) that enters the network at the west side, crosses the center of the city and exits the network at the south-east end. The second bus line that is studied (green line in Figure 13) enters the network at the south-east side, crosses the central junctions of the city and exits at the south end. As shown in Figure 13, there are three junctions in the network where the bus lines intersect and conflicting priority requests are received in the same cycle.

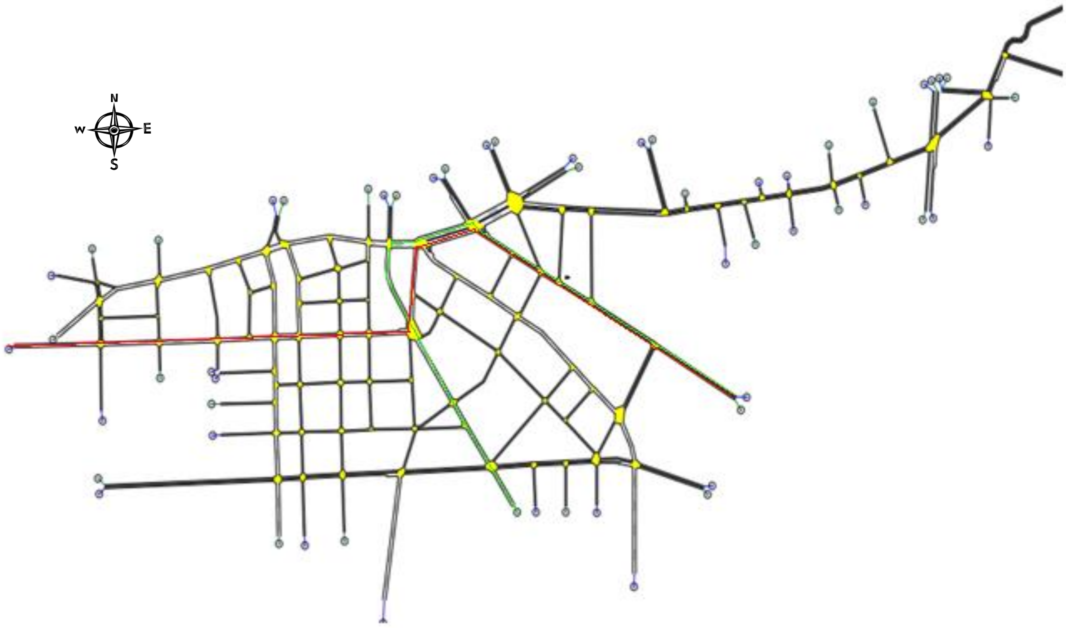


Figure 13: The two studied bus lines.

Buses are moving on mixed lanes. Bus detectors have been installed at the upstream end of the signalized approaches. These detectors are used in order to detect buses and request priority from the PTP system installed locally for each junction. Bus passage measurements from these detectors are collected every second. Bus stops are being placed upstream of these detectors to avoid any impact on the estimation of the arrival time at the junction's stop-line. The network is simulated using realistic dynamically varying demand for a period of four hours, from 12:00 to 16:00, i.e. the early afternoon peak. In the case of a fixed plan, some junctions are saturated during the peak, but no queue over-spilling occurs. As it concerns the bus schedule utilized, frequent bus departures (one per five minutes on average, with a maximum deviation of 1 minute) are considered and, as a consequence, the controller receives quite often a priority request and has to change almost every five minutes the current signal plan in favor of the bus movement.

In the following sections, results are presented with either a fixed-time plan or the TUC strategy applied for all the junctions of the network while the PTP methodology is applied for the junctions that receive multiple priority requests from the same or competitive directions. Section 4.2 presents the results with a fixed-time plan and three different cases are used to serve conflicting priority requests. Three scenarios are produced with the same demand profile and at each one, one of cases 1,2,3 described in Section 3.2 is applied. Case 4 is not tested since the network is not over-saturated so the criterion of downstream occupancy does not affect the methodology and information for the number of passengers or schedule deviation are not provided in the version of AIMSUN used.

In section 4.3 the same scenarios are created for the priority requests but TUC strategy is implemented instead of a fixed-time plan for all the signalized junctions in the network.

The same demand data is used for all the studied scenarios while twenty simulation replications have been produced for each scenario. The results will be evaluated based on three criteria averaged over the twenty replications: the average bus delay, the harmonic speed for buses and pollution emissions. The pollutant that is studied is CO and the pollution emission model that is used to simulate the emissions in AIMSUN is QUARTET. The input parameters for the QUARTET model are those provided by the AIMSUN Dynamic Simulators Users Manual v7. Also, it is assumed that the PT vehicles are moving in mixed-traffic lanes and the detection of the PT vehicle will be done by detectors that are located few dozens of meters upstream of the stop-line at each signalized junction.

Finally, hypothesis analysis tests (R. Scheaffer et al., 1995) have been conducted in order to confirm that there is indeed a differentiation between the average delay time, h. speed and CO emissions before and after implementing PTP control. It is shown, through the t-tests with two independent samples, that the difference between the average delay without priority control and the average delay after applying PTP is real and not a false hypothesis due to the random sampling errors. The test statistic value is

$$Z = \frac{(\bar{X}_1 - \bar{X}_2) - D_0}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$$

where $\bar{X}_1$ and $\bar{X}_2$ are the means of two independent samples, σ_1^2, σ_2^2 are their variances respectively and n_1, n_2 is the size of each sample. The degree of freedom is set as $n_1 + n_2 - 2$ and the significance level (a), a probability threshold below which the hypothesis will be rejected, is 5%. The value Z is used as a test statistic for testing $H_0: \mu_1 - \mu_2 = D_0$ versus $H_a: \mu_1 - \mu_2 \neq D_0$ where μ_1, μ_2 are the unknown mean values of each population. For the following t-tests the value D_0 is set equal to zero.

4.2 Fixed-time plan – Public transport priority for multiple priority requests

For the first scenarios that are studied, a fixed-time plan is applied for all the junctions of the network and the PTP methodology applied for the junctions that receive priority requests. Both priority options are applied and compared to the case of no priority control. Three different scenarios are simulated for cases where conflicting priority requests are received in one junction in the same cycle. As discussed already, there is a bus departure every five minutes, with a maximum deviation of 1 minute.

4.2.1 PTP methodology with a fixed-time plan – Case 1

The following tables (Tables 1-3) present the average results for the first scenario. The analytical results for all the simulations/replications conducted using the AIMSUN microscopic simulator, are included in the Appendix. Table 21 of the Appendix shows the simulation results with no priority control (NO_PTP), while Tables 22 and 23 show the simulation results with the first (PTP1) and second (PTP2) priority option, respectively.

Each priority request is served with green extension or red interruption and when two requests are received in the same cycle the first can be served with PTP1 or PTP2 whereas the second can be served only with PTP1.

The results of Table 1 show that the delay time for the buses has been significantly reduced when PTP is applied; there is a 37.34% improvement with the first priority option and a 38% improvement with the second priority option, compared to the case with no priority control. As it concerns the delay time for the cars, there is also a 2.19% and 1.58% improvement with the first and the second priority option, respectively. This improvement may be explained as the studied priority methodology is applied on approaches with a high demand; when the signal control changes in favor of a bus then other vehicles on the same approach may also be benefited.

The average delay time for all the vehicles in the network is improved by 2.44% for the first priority option and 1.85% for the second priority option. As a result, the conclusion of the first scenario studied is that the methodology serves effectively the priority requests without affecting negatively the overall traffic conditions for the network.

Table 1 : Average delay time with a fixed-time plan and case 1

Delay (sec/km)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	119.93	75.15	74.36	-37.34	-38.00
Car	97.36	95.23	95.82	-2.19	-1.58
All	97.49	95.11	95.69	-2.44	-1.85

Table 2 shows that the harmonic speed for the buses is increased by 29.84% for PTP1 and by 30.60% for PTP2, compared to the no priority control. Also, there is an improvement of the harmonic speed for the cars, and as a result for all the vehicles in the network for both priority options.

Table 2 : Average h. speed with a fixed-time plan and case 1

H. Speed (km/h)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	18.53	24.06	24.20	29.84	30.60
Car	21.83	22.12	22.04	1.33	0.96
All	21.81	22.13	22.05	1.47	1.10

Table 3 : CO emissions with a fixed-time plan and case 1

CO Emissions (g/s)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	1.92	1.57	1.59	-18.23	-17.19
Car	241.04	239.67	240.50	-0.57	-0.22
All	242.96	241.24	242.09	-0.71	-0.36

Finally, the results shown in Table 3 indicate that there is a decrease in the CO emissions for the buses of 18.23% with the first priority option and 17.19% with the second. This is expected since the total travel time of the buses is reduced when applying the PTP methodology and as a consequence the CO emissions are reduced. However, overall the change in negligible either applying the first or the second option.

As mentioned already, hypothesis tests have been conducted in order to ascertain whether the number of replications is sufficient to provide an accurate average. For the average delay time of the buses in Table 1 with PTP1 two samples are used: the first set includes the results of all the replications without PTP control, whereas the second sample includes the results with PTP1. The average of the first sample is $\bar{X}_1$ =119.93 and the standard deviation $\sigma_1 =$ 6.27, while for the second sample $\bar{X}_2$ =75.15 and σ_2 =3.69. The samples have the same size $n_1 = n_2 = 20$ and the standard error s_d is calculated as follows:

$$s_d = \sqrt{\frac{(n_1 - 1) \cdot \sigma_1^2 + (n_2 - 1) \cdot \sigma_2^2}{n_1 + n_2 - 2}} \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$$

Here, s_d =1.63. The t-test value, is equal to 27.5 while the t-critical equals to 2.02. Since the value of t-test is higher than the t-critical the hypothesis $H_0: \mu_1 - \mu_2 = 0$ is rejected. As a consequence, from these samples it can be concluded that the average delay time with PTP1 is indeed lower compared to the no control case. Similar results for the buses' delay time are observed in Tables 1-18.

4.2.2 PTP methodology with a fixed-time plan – Case 2

For the second scenario, exit detectors are used to confirm that a priority request is served before a new priority plan is applied on the controller. The demand utilized as well as the bus arrivals are the same with those considered for scenario 1. Tables 24-25 in the Appendix present the analytical results for this scenario. The average results are presented in following tables (Tables 4-6).

Table 4 : Average delay time with a fixed time plan and case 2

Delay (sec/km)	**NO_PTP**	**PTP1**	**PTP2**	**% Change of PTP1 compared to NO_PTP**	**% Change of PTP2 compared to NO_PTP**
Bus	119.93	80.82	78.74	-32.61	-34.35
Car	97.36	95.21	95.86	-2.21	-1.54
All	97.49	95.12	95.75	-2.43	-1.78

As shown in Table 4, both priority options reduce the average delay time for all the vehicles. Comparing these results with Table 1, the improvement of the buses' delay time is smaller and this can be explained since when two buses are approaching a junction from opposite directions, the second bus will be served only if the first bus has left the junction. So as it is expected many priority requests are not served but in these cases there is no risk of destroying the first's bus priority. As for the other vehicles in the network the improvement is almost the same as in Table 1.

Table 5: Average h. speed with a fixed-time plan and case 2

H. Speed (km/h)	**NO_PTP**	**PTP1**	**PTP2**	**% Change of PTP1 compared to NO_PTP**	**% Change of PTP2 compared to NO_PTP**
Bus	18.53	23.20	23.50	25.20	26.82
Car	21.83	22.12	22.03	1.33	0.92
All	21.81	22.13	22.04	1.47	1.05

The harmonic speed for the buses is improved with both priority options, 25.20% with PTP1 and 26.82% with PTP2, as well as for the cars that are moving in the same links with the buses so they are benefited by the changes at the signal plan.
Since the average delay time of all the vehicles in the network has been improved, a decrease on the CO emissions is also expected. Indeed, as Table 6 shows, the emissions are decreased by 15.63% with PTP1 and 15.10% with PTP2.

Table 6 : CO emissions with a fixed-time plan and case 2

CO Emissions (g/s)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	1.92	1.62	1.63	-15.63	-15.10
Car	241.04	239.92	240.54	-0.46	-0.21
All	242.96	241.53	242.17	-0.59	-0.33

4.2.3 PTP methodology with a fixed-time plan – Case 3

Aiming to improve the results when exit detectors are implemented and serve more priority requests, extra detectors are placed in some junctions between the first detectors of the link and the stop line. With these detectors a second opportunity to request priority is given to a bus that is approaching second a signalized junction.

Tables 26-27 in the Appendix present the analytical results for this scenario. The average results are presented in following tables (Tables 7-9).

Table 7 : Average delay time with a fixed-time plan and case 3

Delay (sec/km)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	119.93	71.97	72.66	-40.00	-39.41
Car	97.36	94.01	94.40	-3.44	-3.04
All	97.49	93.87	94.27	-3.71	-3.30

Table 8: Average h. speed with a fixed-time plan and case 3

H. Speed (km/h)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	18.53	24.57	24.47	32.60	32.06
Car	21.83	22.29	22.23	2.11	1.83
All	21.81	22.30	22.24	2.25	1.97

Table 9: CO emissions with a fixed-time plan and case 3

CO Emissions (g/s)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	1.92	1.54	1.58	-19.79	-17.71
Car	241.04	237.47	238.85	-1.48	-0.91
All	242.96	239.02	240.43	-1.62	-1.04

Table 7 shows that the extra detectors improve the delay time for all the vehicles in the network with higher percentage compared to Table 4. There is a 40% improvement for the delay time of the buses with the first priority option and 39.41% with the second. The results are also better if they are compared with Table 1 where exit detectors are not implemented. It is concluded that a higher number of buses is served with priority comparing to the previous scenarios, and for that reason the delay time decreases.

Table 8 shows the results for the harmonic speed. The improvement for the buses after applying priority control is 32.60% for the PTP1 case and 32.06% for the PTP2 case. There is also a small increase on the harmonic speed for the cars. Furthermore, comparing these results with the corresponding results from scenarios 1 and 2 (presented in Tables 3 and 6, respectively), we can conclude that the harmonic speed for the cars is higher with case 3 for each priority option.

According to Table 9, the CO emissions of the buses have been significantly reduced when PTP is applied; there is a 19.79% decrease with the first priority option and a 17.71% improvement with the second priority option, compared to the case with no priority control. Compared to the first two scenarios studied (sections 4.2.1, 4.2.2), the achieved improvement is better for both priority options and not only for the buses but even overall.

4.3 TUC strategy – Public transport priority for multiple priority requests

Since the number of private vehicles in urban networks is increasing it is important to reduce the delay time for all the vehicles in the network, not only to provide priority for the buses. As shown in Section 4.2, with the PTP methodology there is an improvement on the delay time for the cars but the percentage is not so high. Aim of this section is to show how TUC strategy manages to reduce the delay time at a satisfactory level both for private and for public vehicles.

TUC applies split control using data from all the links approaching a junction. Additionally, cycle and offset control are applied every ten minutes. For the buses, PTP control will be activated every time that priority is requested but at the same time TUC control will be active aiming to reduce the average delay time and to increase the harmonic speed for all the vehicles in the network. Also the CO emissions will be compared in order to evaluate the methodology with environmental criteria.

As in section 4.2, both priority options are compared with the case of no priority control and three scenarios are simulated, each with a different plan for the conflicting priority requests and the same demand scenario as in section 4.2.

4.3.1 PTP methodology with TUC – Case 1

Table 10 shows that the delay time for the buses is reduced by 3.92% with the first priority option and by 7.01% with the second priority option. The average delay time for the cars is increased by 1.70% with PTP1 and by 2.29% with PTP2. However, comparing with Table 1, there is an improvement on the delay time for the cars since this is 95.23 sec/km when a fixed-time plan is applied and 87.75 sec/km when TUC is applied, both for the case of PTP1. An improvement is also noticed for the case of PTP2; the delay for the cars is 95.82 sec/km when a fixed-time plan is applied and 88.26 sec/km when TUC is used instead. So according to Table 10, priority control keeps reducing the delay time for the buses while TUC reduces the delay time for all the vehicles in the network.

Table 10: Average delay time with TUC and case 1

Delay (sec/km)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	81.65	78.45	75.93	-3.92	-7.01
Car	86.28	87.75	88.26	1.70	2.29
All	86.26	87.69	88.19	1.66	2.24

Table 11: Average h. speed with TUC and case 1

H. Speed (km/h)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	23.06	23.54	23.93	2.08	3.77
Car	23.40	23.19	23.11	-0.90	-1.24
All	23.40	23.19	23.12	-0.90	-1.20

Table 12: CO emissions with TUC and case 1

CO Emissions (g/s)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	1.60	1.61	1.60	0.63	0.00
Car	232.53	235.29	236.46	1.19	1.69
All	234.12	236.91	238.06	1.19	1.68

Table 11 shows that the harmonic speed is increased for the buses while the impact on the other vehicles of the network is insignificant. Comparing with Table 2, we can conclude that TUC manages to increase the harmonic for all the vehicles of the network even when priority control is not applied. The percentage of improvement for the buses is higher with a fixed-time plan, as shown in Table 2, but the overall harmonic speed is better when TUC is applied since from 22.05 km/h with a fixed-time plan is 23.12 km/h with TUC, both for PTP2.

As Table 12 shows there is a negligible increase of the CO emissions of the buses when PTP1 is used and when PTP2 is applied the level of emissions has been kept stable. For the other vehicles in the network there is a minor increase for both priority options but comparing these results with the ones achieved when a fixed-time plan is used instead of the TUC strategy (section 4.2.1, Table 3), it is obvious that the overall emissions have now been decreased.

Tables 28-30 in the Appendix present the analytical results for this scenario.

4.3.2 PTP methodology with TUC – Case 2

When exit detectors are added at the exit of the junction to confirm that a bus has crossed the junction, the delay time for the buses was increased compared to case 1 with a fixed-time plan as Tables 1 and 3 show. Similar results are noticed with the

TUC strategy. The average results are presented in following tables (Tables 13-16), while Tables 31-32 in the Appendix present the analytical results for this scenario.

Table 13 shows that there is 3.43% improvement for the buses' delay time with the first priority option and 3.10% with the second but comparing with Table 10, the exit detectors cause a small increase to their delay time. The impact of the PTP methodology to the other vehicles in the network is negligible for both priority options.

Table 13: Average delay time with TUC and case 2

Delay (sec/km)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	81.65	78.85	79.12	-3.43	-3.10
Car	86.28	87.15	87.94	1.01	1.92
All	86.26	87.10	87.89	0.97	1.89

Table 14: Average h. speed with TUC and case 2

H. Speed (km/h)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	23.06	23.48	23.44	1.82	1.65
Car	23.40	23.27	23.16	-0.60	-1.07
All	23.40	23.27	23.16	-0.56	-1.03

Table 14 shows that there is a 1.82% increase of the harmonic speed for the buses when PTP1 is used and a 1.65% increase when PTP2 is applied. For the other vehicles there is a minor decrease but comparing these results with the ones achieved when a fixed-time plan is used instead of thee TUC strategy, it is obvious that the overall speed has now been increased.

Table 15: CO emissions with TUC and case 2

CO Emissions (g/s)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	1.60	1.60	1.63	0.00	1.87
Car	232.53	234.46	235.77	0.83	1.40
All	234.12	236.05	237.40	0.82	1.40

When applying PTP1, the CO emissions of the buses is reduced, compared to no control, by 0.63%, but with PTP2 there 1.87% increase. Furthermore, the PTP methodology when is applied with TUC, causes a minor decrease on the emissions overall, but if it is compared with the results from a fixed-time plan (section 4.2.2, Table 6) it is obvious that TUC reduces satisfactory the emissions since from 241.53 g/s with PTP1 and a fixed-time plan now the emissions have the value 236.05 g/s with PTP1 for all the vehicles.

4.3.3 PTP methodology with TUC – Case 3

In the studied scenarios with a fixed-time plan controlling all the junctions of the network and case 3 implemented for priority requests received from conflicting directions in the same cycle, the average results was better comparing with cases 1 and 2. Similar results are expected when the TUC strategy is applied.

As Table 16 shows, the average delay time for the buses is decreased by 5.7% when PTP1 is applied and by 7.74% when PTP2 is used. Comparing these results with Tables 10 and 13, it can be concluded that the extra detectors serve a higher number of priority requests and the delay time for the buses is lower. The delay time for the cars is almost at the same level as in Table 10 which means that even if the signal plan changes more often in favor of the buses, the rest of the vehicles in the network are not affected negatively.

Table 16: Average delay time with TUC and case 3

Delay (sec/km)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	81.65	77.00	75.33	-5.7	-7.74
Car	86.28	87.74	88.26	1.69	2.29
All	86.26	87.67	88.18	1.63	2.23

Table 17: Average h. speed with TUC and case 3

H. Speed (km/h)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	23.06	23.77	24.04	3.08	4.25
Car	23.40	23.19	23.11	-0.90	-1.24
All	23.40	23.19	23.12	-0.90	-1.20

Table 18: CO emissions with TUC and case 3

CO Emissions (g/s)	NO_PTP	PTP1	PTP2	% Change of PTP1 compared to NO_PTP	% Change of PTP2 compared to NO_PTP
Bus	1.60	1.59	1.58	-0.63	-1.25
Car	232.53	235.59	236.13	1.32	1.55
All	234.12	237.18	237.72	1.31	1.54

Table 17 shows that both priority options increase the harmonic speed of the buses without really affecting the situation of the rest of the vehicles. Again, comparing these results with Tables 11 and 14 it can be concluded that the harmonic speed values are higher when extra detectors are included in the network between the first detectors of the link and the stop-line of the junction.

Finally, conserving the CO emissions, Table 18 shows that both priority options reduce the level of emissions, 0.63% with PTP1 and 1.25% with PTP2 for the buses, while for the cars the cars a minor increase is observed. However, comparing these results with Table 9 when a fixed-time plan is used instead of TUC it is clear that TUC manages to maintain in lower level the CO emissions.

5 Conclusions

5.1 Average delay time with public transport priority methodology

A public transport priority methodology that can serve multiple and conflicting priority requests has been developed and tested. In total, six scenarios have been created in order to evaluate the PTP methodology. The scenarios have been categorized based on the following criteria: for the first three a fixed-time plan was controlling all the junctions in the network and the PTP methodology was used to control the junctions that provided priority with three different cases to be implemented in order to manage the conflicting priority requests. In the next three scenarios instead of a fixed-time plan, TUC strategy was used to control the junctions also with the PTP methodology.

This section gathers and compares the final results. The goal of the following comparisons is to conclude which is the most satisfactory priority option and which case is most satisfactory for the conflicting priority requests that are received in one junction during the same cycle.

The impact on the rest of the network has to be taken into account since the priority methodology should not disturb largely the network. In the following Tables only the average delay time is used to evaluate the methodology since, as discussed already, if the overall delay time is reduced then the CO emissions are also decreased and the harmonic speed is increased.

Table 19: Comparison table for the average delay time with a fixed-time plan.

Delay (sec/km)	**Vehicle Type**	**Case 1**	**Case 2**	**Case 3**
PTP1	Bus	75.15	80.82	71.97
	Car	95.23	95.21	94.01
	All	95.11	95.12	93.87
PTP2	Bus	74.36	78.74	72.66
	Car	95.82	95.86	94.90
	All	95.69	95.75	94.27

Table 19 shows the average delay results when a fixed-time plan is used, for both priority options and all the cases that are used to serve buses that are approaching a signalized junctions from conflicting directions. The best results are observed when the first priority option is applied with case 3. With the first priority option the duration of the cycle is not changed, so the PTP methodology will provide directly a priority plan on the controller without affecting the rest of the network since the duration of the cycle will be the same. If the bus that is approaching a junction needs a few more seconds to cross the stop-line then its green time will be extended, while if it is approaching during its red phase then the duration of the red will be reduced. Case 3 performs better than cases 1 and 2 because with the exit detectors in place, every bus that requests priority will be served unhindered and with the extra detectors in the same link more buses can request priority and consequently reduce their delay time. Furthermore, with the extra detectors that are used in case 3, the PTP methodology performs better since in cases where the travel time of a bus is under or over – estimated the second detectors will provide a more sufficient priority plan on the controller.

Table 20: Comparison table for average delay time with the TUC strategy

Delay (sec/km)	**Vehicle Type**	**Case 1**	**Case 2**	**Case 3**
PTP1	Bus	78.45	78.85	77.00
	Car	87.75	87.15	87.74
	All	87.69	87.10	87.67
PTP2	Bus	75.93	79.12	75.33
	Car	88.26	87.94	88.26
	All	88.19	87.89	88.18

When TUC strategy is applied the second priority option with case 3 gives better results for the buses' delay time. However, as Table 20 shows the average delay time for all the vehicles in the network is lower when case 3 is applied with the first priority option.

Comparing the results of Tables 19 and 20 we conclude that PTP1 with case 3 is more efficient for buses when a fixed-time plan is used instead of TUC, however, as it concerns all the other vehicles, TUC leads to better results and smaller delays even when priority measures are taken into account.

5.2 Overall conclusions

In this thesis, a PTP methodology was presented and evaluated aiming to change the signal plan locally in favor of the PT vehicles. The methodology can be implemented in real time, detect a bus that is approaching a signalized junction and adjust the signal plan in order to reduce buses' delay time by extending its green time or reducing its red time. In case of conflicting priority requests during the same cycle, four different cases were presented in order to serve, if feasible, both requests.

The methodology was implemented in a microscopic simulation environment emulating the network of Chania with realistic traffic conditions, aiming to provide priority to the buses in signalized junctions changing the current signal plan locally. Two bus lines were considered in the network, therefore there were cases where two buses requested for priority at a junction during the same cycle.

The criteria used for the assessment of the methodology are the average delay time, the average harmonic speed and the CO emissions. It was shown that all the criteria for the buses are significantly improved without really affecting the rest of the vehicles in the network. Also the PTP methodology could serve sufficiently the cases of conflicting requests and as a consequence it reduced by a significant percentage buses' delay time.

Finally the overall performance was better when the TUC strategy was used instead of a fixed-time plan.

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Appendix

Table 21: Fixed-time plan – No priority control

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	112.28	19.31	6.18	1.85	94.60	22.21	666.44	236.41	94.71	22.19	672.62	238.26
2	119.81	18.51	6.46	1.94	98.46	21.70	678.43	239.46	98.59	21.67	684.89	241.40
3	124.60	18.04	6.58	1.98	99.79	21.51	697.17	245.77	99.94	21.48	703.75	247.74
4	121.24	18.35	6.38	1.88	96.56	21.93	680.64	240.95	96.71	21.91	687.02	242.84
5	116.44	18.82	6.29	1.89	93.48	22.36	669.17	237.39	93.61	22.34	675.46	239.28
6	127.38	17.85	6.65	2.00	101.48	21.29	703.44	246.67	101.63	21.27	710.09	248.67
7	119.75	18.52	6.37	1.91	97.72	21.78	678.41	240.11	97.85	21.76	684.78	242.02
8	118.83	18.62	6.46	1.91	100.42	21.44	697.84	245.83	100.53	21.42	704.31	247.74
9	131.11	17.53	6.89	2.05	100.78	21.38	697.42	244.67	100.96	21.35	704.30	246.72
10	116.36	18.86	6.43	1.92	96.35	21.96	664.13	235.24	96.48	21.94	670.56	237.16
11	109.72	19.61	6.22	1.87	94.72	22.19	668.21	237.10	94.81	22.17	674.43	238.97
12	114.21	19.10	6.23	1.89	94.04	22.27	670.16	238.40	94.16	22.25	676.39	240.29
13	132.24	17.37	6.91	2.03	99.48	21.55	700.50	247.04	99.67	21.52	707.42	249.07
14	124.13	18.13	6.62	2.00	97.89	21.76	682.48	240.87	98.05	21.73	689.10	242.87
15	121.63	18.27	6.52	1.98	95.84	22.04	667.43	236.39	96.00	22.01	673.95	238.37
16	126.84	17.89	6.52	1.93	97.48	21.82	687.86	242.91	97.65	21.79	694.38	244.85
17	112.52	19.27	5.93	1.79	95.15	22.13	666.17	236.25	95.25	22.11	672.10	238.05
18	118.18	18.73	6.31	1.92	95.95	22.01	681.72	241.50	96.08	21.99	688.03	243.41
19	117.64	18.70	6.32	1.88	97.66	21.79	689.95	243.87	97.77	21.77	696.28	245.75
20	113.63	19.10	6.25	1.87	99.34	21.57	689.93	243.99	99.42	21.55	696.18	245.85
Average	**119.93**	**18.53**	**6.43**	**1.92**	**97.36**	**21.83**	**681.88**	**241.04**	**97.49**	**21.81**	**688.30**	**242.96**

Table 22: Fixed-time plan – First priority option – Case 1

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	82.00	22.88	5.32	1.60	96.29	21.97	684.40	242.42	96.20	21.97	689.72	244.02
2	81.48	23.19	5.40	1.68	94.23	22.27	674.77	239.87	94.15	22.27	680.17	241.55
3	69.52	24.97	4.89	1.52	92.64	22.47	661.11	235.70	92.50	22.48	666.01	237.22
4	78.71	23.52	5.12	1.55	97.15	21.85	680.73	240.78	97.04	21.86	685.85	242.33
5	73.61	24.16	5.02	1.57	94.97	22.19	663.11	234.89	94.84	22.20	668.13	236.46
6	76.80	23.86	5.03	1.55	94.41	22.23	674.77	239.75	94.31	22.24	679.81	241.30
7	68.39	25.18	4.90	1.55	95.61	22.06	666.36	236.45	95.45	22.08	671.26	238.00
8	73.67	24.34	5.09	1.59	93.84	22.30	657.45	233.52	93.71	22.31	662.54	235.11
9	75.77	23.93	5.08	1.58	93.42	22.37	676.79	240.87	93.31	22.38	681.87	242.46
10	78.28	23.66	5.13	1.64	98.01	21.74	692.46	244.70	97.89	21.75	697.59	246.34
11	74.86	24.12	5.13	1.54	93.69	22.33	671.16	238.71	93.58	22.34	676.29	240.25
12	76.61	23.83	5.05	1.57	97.32	21.83	688.72	243.72	97.20	21.84	693.77	245.29
13	70.58	24.88	5.00	1.60	94.84	22.17	668.88	237.28	94.70	22.18	673.87	238.88
14	75.07	24.07	4.99	1.58	95.16	22.13	683.34	242.82	95.05	22.14	688.32	244.40
15	75.26	23.90	5.03	1.55	95.35	22.10	681.19	241.58	95.23	22.11	686.22	243.13
16	77.12	23.73	4.94	1.54	93.92	22.30	675.65	239.70	93.83	22.31	680.59	241.24
17	77.77	23.60	5.09	1.58	95.88	22.03	680.08	241.30	95.78	22.04	685.17	242.88
18	70.68	24.83	4.83	1.54	94.62	22.19	672.36	239.05	94.48	22.21	677.18	240.58
19	75.00	24.04	5.14	1.59	98.29	21.71	692.81	245.03	98.15	21.73	697.94	246.62
20	71.86	24.53	4.98	1.56	94.93	22.16	662.37	235.15	94.79	22.18	667.35	236.71
Average	**75.15**	**24.06**	**5.06**	**1.57**	**95.23**	**22.12**	**675.42**	**239.67**	**95.11**	**22.13**	**680.48**	**241.24**

Table 23: Fixed-time plan – Second priority option – Case 1

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	76.02	23.86	5.11	1.61	96.57	21.93	694.79	246.18	96.45	21.94	699.90	247.79
2	73.01	24.43	5.11	1.60	95.51	22.09	668.33	236.95	95.37	22.10	673.43	238.56
3	71.16	24.75	4.92	1.58	93.43	22.36	663.98	236.78	93.30	22.37	668.90	238.35
4	72.85	24.49	4.95	1.56	98.75	21.65	691.41	244.94	98.60	21.66	696.36	246.50
5	76.46	23.81	5.05	1.64	94.08	22.28	661.94	235.51	93.97	22.29	666.99	237.14
6	80.35	23.29	5.12	1.64	95.20	22.13	674.11	238.76	95.11	22.13	679.22	240.40
7	70.52	24.85	4.96	1.60	94.98	22.15	666.80	236.62	94.83	22.16	671.76	238.22
8	72.39	24.65	5.01	1.57	93.90	22.29	659.87	234.52	93.77	22.30	664.88	236.09
9	79.95	23.28	5.19	1.62	92.65	22.48	673.67	240.03	92.58	22.48	678.87	241.65
10	73.25	24.42	4.94	1.55	99.71	21.52	697.26	245.87	99.55	21.53	702.20	247.41
11	68.55	25.29	4.84	1.51	94.38	22.24	675.47	239.61	94.23	22.25	680.31	241.12
12	71.08	24.65	4.98	1.59	100.36	21.43	704.80	249.04	100.19	21.45	709.77	250.63
13	73.77	24.30	5.08	1.63	95.55	22.07	679.70	240.68	95.42	22.08	684.78	242.32
14	75.75	23.96	5.00	1.61	95.63	22.06	685.11	243.20	95.51	22.07	690.11	244.81
15	77.67	23.61	5.11	1.59	96.12	21.99	685.92	243.16	96.01	22.00	691.03	244.74
16	75.35	23.95	4.90	1.55	93.58	22.34	661.52	235.23	93.47	22.35	666.42	236.78
17	71.22	24.70	4.85	1.56	95.61	22.06	669.86	236.93	95.47	22.07	674.71	238.48
18	75.70	23.92	4.94	1.54	94.90	22.15	675.08	239.37	94.78	22.16	680.01	240.91
19	74.30	24.23	5.07	1.61	98.57	21.68	698.22	246.77	98.42	21.69	703.29	248.38
20	77.80	23.58	5.15	1.66	96.83	21.91	676.89	239.87	96.72	21.92	682.04	241.53
Average	**74.36**	**24.20**	**5.01**	**1.59**	**95.82**	**22.04**	**678.24**	**240.50**	**95.69**	**22.05**	**683.25**	**242.09**

Table 24: Fixed-time plan – First priority option – Case 2

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	88.97	21.95	5.55	1.70	95.15	22.12	683.37	242.74	95.11	22.12	688.92	244.43
2	77.59	23.77	5.24	1.65	94.40	22.24	673.00	239.12	94.30	22.25	678.24	240.77
3	77.67	23.71	5.13	1.61	94.06	22.27	672.56	239.15	93.96	22.28	677.69	240.76
4	81.55	23.08	5.25	1.63	97.19	21.86	686.62	243.84	97.10	21.86	691.86	245.47
5	83.06	22.80	5.31	1.66	93.29	22.39	660.49	234.83	93.23	22.39	665.80	236.49
6	86.25	22.46	5.29	1.60	94.90	22.16	671.65	237.60	94.85	22.17	676.94	239.21
7	75.46	23.93	5.14	1.62	95.15	22.12	667.36	236.58	95.03	22.13	672.50	238.19
8	77.29	23.85	5.16	1.60	93.46	22.35	656.34	233.37	93.36	22.36	661.50	234.97
9	79.98	23.33	5.21	1.63	92.22	22.53	671.08	238.77	92.14	22.54	676.28	240.40
10	82.27	22.99	5.25	1.61	99.13	21.60	693.51	244.73	99.03	21.61	698.76	246.34
11	78.09	23.57	5.23	1.57	93.51	22.35	674.31	239.65	93.42	22.36	679.55	241.22
12	81.75	23.02	5.23	1.61	95.76	22.04	684.55	242.92	95.68	22.05	689.78	244.53
13	80.45	23.25	5.30	1.67	94.81	22.17	674.88	239.38	94.72	22.18	680.18	241.06
14	78.37	23.55	5.08	1.59	95.74	22.05	682.89	242.70	95.64	22.06	687.97	244.29
15	81.39	23.11	5.17	1.61	95.94	22.01	687.09	243.87	95.85	22.02	692.26	245.48
16	85.29	22.46	5.18	1.57	93.26	22.39	668.06	237.28	93.21	22.39	673.24	238.86
17	82.95	22.94	5.21	1.65	94.16	22.26	669.11	237.87	94.09	22.26	674.32	239.52
18	76.81	23.79	5.07	1.53	95.02	22.14	672.09	238.05	94.91	22.15	677.17	239.58
19	77.28	23.69	5.19	1.58	98.75	21.66	697.00	246.42	98.63	21.67	702.19	248.01
20	83.86	22.71	5.29	1.62	98.26	21.72	680.76	239.51	98.18	21.73	686.05	241.13
Average	**80.82**	**23.20**	**5.22**	**1.62**	**95.21**	**22.12**	**676.34**	**239.92**	**95.12**	**22.13**	**681.56**	**241.53**

Table 25: Fixed-time plan – Second priority option – Case 2

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	75.01	24.12	5.09	1.60	94.15	22.26	662.95	235.60	94.03	22.27	668.04	237.19
2	79.35	23.28	5.22	1.62	95.19	22.11	683.11	242.50	95.10	22.12	688.33	244.12
3	76.65	23.85	5.24	1.66	94.44	22.23	667.39	236.93	94.33	22.24	672.64	238.60
4	78.40	23.53	5.13	1.64	93.68	22.33	667.72	237.86	93.59	22.34	672.85	239.50
5	76.02	24.00	5.02	1.60	96.50	21.94	676.70	240.17	96.37	21.96	681.72	241.76
6	87.16	22.21	5.40	1.71	95.63	22.07	671.73	237.48	95.58	22.07	677.13	239.20
7	84.82	22.64	5.29	1.62	94.26	22.25	668.02	237.05	94.20	22.25	673.31	238.67
8	76.80	23.71	5.17	1.64	93.96	22.29	661.94	235.15	93.85	22.30	667.11	236.79
9	79.83	23.24	5.16	1.65	92.45	22.50	675.08	240.32	92.38	22.51	680.24	241.97
10	79.68	23.38	5.12	1.60	99.31	21.57	698.68	246.22	99.20	21.58	703.80	247.82
11	75.71	23.95	5.08	1.59	96.56	21.94	683.75	241.67	96.44	21.95	688.84	243.26
12	79.75	23.39	5.20	1.66	99.14	21.59	701.22	247.84	99.03	21.60	706.42	249.50
13	72.73	24.54	5.02	1.64	94.75	22.18	664.75	236.17	94.61	22.19	669.77	237.81
14	82.14	23.05	5.16	1.62	94.97	22.15	682.49	242.08	94.90	22.15	687.65	243.69
15	80.37	23.12	5.16	1.64	97.09	21.86	686.52	243.09	96.99	21.87	691.69	244.72
16	84.20	22.84	5.08	1.58	96.12	22.00	679.71	240.67	96.05	22.00	684.80	242.24
17	77.66	23.62	5.06	1.60	95.19	22.12	671.93	238.77	95.09	22.13	676.99	240.37
18	78.55	23.42	5.07	1.59	94.99	22.14	677.87	240.75	94.89	22.15	682.94	242.35
19	73.45	24.21	5.07	1.63	101.51	21.30	709.09	249.91	101.34	21.32	714.16	251.54
20	76.57	23.86	5.08	1.64	97.26	21.85	680.53	240.68	97.14	21.86	685.61	242.32
Average	**78.74**	**23.50**	**5.14**	**1.63**	**95.86**	**22.03**	**678.56**	**240.54**	**95.75**	**22.04**	**683.70**	**242.17**

Table 26: Fixed-time plan – First priority option – Case 3

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	69.94	24.95	4.94	1.53	92.72	22.45	661.59	235.99	92.58	22.47	666.54	237.52
2	67.47	25.29	4.88	1.50	93.19	22.40	666.42	237.11	93.04	22.42	671.30	238.61
3	74.42	24.03	5.06	1.56	94.61	22.21	658.76	234.52	94.49	22.22	663.81	236.08
4	74.08	24.26	5.01	1.58	96.62	21.93	680.62	242.02	96.49	21.94	685.63	243.59
5	66.12	25.54	4.75	1.50	94.20	22.25	665.65	237.16	94.03	22.27	670.40	238.66
6	71.49	24.67	4.92	1.56	90.37	22.80	662.04	237.21	90.26	22.81	666.97	238.77
7	78.67	23.54	5.13	1.55	97.54	21.80	685.85	241.89	97.43	21.81	690.97	243.44
8	71.43	24.61	4.87	1.53	95.11	22.13	667.92	237.45	94.97	22.14	672.79	238.98
9	72.89	24.42	5.07	1.58	98.32	21.71	689.90	244.44	98.16	21.73	694.96	246.02
10	74.05	24.31	5.08	1.62	93.90	22.30	662.04	236.01	93.78	22.31	667.12	237.63
11	76.08	23.75	5.15	1.56	93.21	22.39	666.76	237.94	93.11	22.39	671.91	239.50
12	70.07	24.86	5.04	1.57	92.94	22.44	657.90	234.77	92.80	22.45	662.94	236.34
13	72.62	24.44	5.02	1.59	91.26	22.67	655.53	234.36	91.15	22.68	660.55	235.94
14	71.67	24.68	4.93	1.54	95.34	22.10	672.38	239.26	95.19	22.11	677.32	240.80
15	70.92	24.74	4.92	1.57	92.01	22.57	648.22	231.22	91.88	22.58	653.13	232.78
16	70.63	24.79	4.89	1.49	92.92	22.44	667.85	237.66	92.79	22.45	672.74	239.15
17	67.05	25.39	4.87	1.52	92.99	22.42	652.27	232.46	92.83	22.44	657.14	233.98
18	70.83	24.82	4.83	1.53	95.39	22.09	678.16	240.32	95.25	22.11	682.98	241.86
19	72.22	24.51	4.93	1.52	93.61	22.34	667.03	237.95	93.49	22.35	671.95	239.46
20	76.87	23.84	4.92	1.53	93.86	22.31	674.28	239.71	93.76	22.32	679.19	241.23
Average	**71.97**	**24.57**	**4.96**	**1.54**	**94.01**	**22.29**	**667.06**	**237.47**	**93.87**	**22.30**	**672.02**	**239.02**

Table 27: Fixed-time plan – Second priority option – Case 3

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	71.99	24.47	5.01	1.59	93.44	22.35	676.55	241.10	93.31	22.36	681.55	242.69
2	73.50	24.43	5.15	1.67	93.96	22.30	666.48	237.80	93.84	22.31	671.63	239.47
3	72.36	24.48	5.00	1.62	92.52	22.48	663.47	236.91	92.40	22.50	668.47	238.53
4	75.10	24.08	5.05	1.57	96.61	21.93	680.51	242.07	96.48	21.94	685.56	243.64
5	77.08	23.81	5.09	1.66	94.06	22.28	664.48	236.41	93.96	22.29	669.58	238.07
6	70.01	24.93	4.84	1.52	93.90	22.31	664.85	236.86	93.75	22.32	669.69	238.38
7	68.18	25.15	4.90	1.54	92.87	22.44	649.61	231.35	92.72	22.45	654.52	232.89
8	75.94	24.04	5.11	1.61	93.60	22.34	663.26	235.74	93.50	22.35	668.37	237.35
9	71.65	24.68	4.93	1.59	90.87	22.73	661.20	236.23	90.76	22.74	666.13	237.82
10	75.28	24.11	5.04	1.61	97.31	21.83	685.50	242.61	97.18	21.84	690.53	244.22
11	74.37	24.14	5.05	1.56	94.10	22.27	671.19	238.15	93.98	22.28	676.24	239.70
12	71.68	24.55	4.93	1.58	95.93	22.02	685.34	243.80	95.79	22.03	690.27	245.38
13	76.02	24.07	5.12	1.67	93.85	22.30	659.18	235.17	93.74	22.31	664.30	236.83
14	70.24	24.90	4.82	1.53	94.80	22.17	683.00	242.61	94.66	22.19	687.81	244.14
15	70.81	24.73	4.85	1.56	94.99	22.14	680.31	242.03	94.85	22.16	685.17	243.59
16	68.98	25.01	4.68	1.51	92.40	22.50	662.96	236.63	92.27	22.52	667.64	238.14
17	72.10	24.52	4.90	1.60	93.09	22.41	659.64	235.45	92.97	22.42	664.54	237.05
18	72.46	24.51	4.87	1.52	94.76	22.17	678.43	241.34	94.63	22.18	683.29	242.86
19	69.18	25.02	4.92	1.57	98.53	21.68	690.91	244.60	98.36	21.70	695.83	246.16
20	76.28	23.85	5.10	1.63	96.29	21.98	676.42	240.15	96.17	21.99	681.52	241.78
Average	**72.66**	**24.47**	**4.97**	**1.58**	**94.40**	**22.23**	**671.16**	**238.85**	**94.27**	**22.24**	**676.13**	**240.43**

Table 28: TUC strategy – No priority control

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	86.61	22.37	5.39	1.60	88.50	23.08	649.66	234.88	88.49	23.07	655.05	236.48
2	79.08	23.42	5.22	1.59	87.44	23.23	658.57	237.94	87.39	23.23	663.79	239.53
3	82.42	22.86	5.31	1.63	86.14	23.43	640.02	231.89	86.12	23.42	645.33	233.52
4	82.58	22.92	5.37	1.63	83.84	23.77	624.38	226.68	83.84	23.76	629.75	228.31
5	84.21	22.78	5.35	1.65	86.79	23.32	650.79	235.14	86.77	23.32	656.14	236.79
6	84.15	22.68	5.45	1.69	85.87	23.45	634.40	229.82	85.86	23.45	639.85	231.51
7	81.37	23.12	5.21	1.63	87.49	23.21	649.87	235.09	87.46	23.21	655.08	236.72
8	82.15	22.94	5.33	1.64	84.81	23.62	624.72	226.18	84.80	23.62	630.05	227.82
9	77.62	23.71	4.92	1.46	87.94	23.15	652.41	235.42	87.88	23.15	657.33	236.88
10	80.14	23.24	5.14	1.56	88.21	23.10	642.51	232.07	88.16	23.10	647.65	233.62
11	83.39	22.77	5.23	1.57	86.10	23.42	648.54	234.84	86.08	23.42	653.78	236.41
12	82.77	22.84	5.29	1.63	83.04	23.91	622.51	226.53	83.04	23.91	627.80	228.15
13	82.73	22.95	5.25	1.57	86.78	23.33	643.72	232.77	86.76	23.32	648.97	234.34
14	79.68	23.37	5.33	1.62	85.84	23.48	642.68	232.75	85.81	23.48	648.01	234.37
15	76.03	23.92	5.00	1.56	86.73	23.33	652.16	235.98	86.67	23.33	657.16	237.54
16	82.58	22.95	5.21	1.60	83.73	23.79	627.57	228.00	83.72	23.79	632.78	229.60
17	84.05	22.65	5.37	1.61	89.96	22.84	655.60	236.31	89.93	22.84	660.97	237.92
18	80.32	23.13	5.18	1.57	85.61	23.50	640.06	232.37	85.58	23.50	645.24	233.94
19	78.66	23.55	5.14	1.57	84.53	23.68	644.42	233.94	84.50	23.68	649.56	235.51
20	82.44	22.93	5.31	1.58	86.28	23.40	640.05	231.92	86.26	23.40	645.37	233.51
Average	**81.65**	**23.06**	**5.25**	**1.60**	**86.28**	**23.40**	**642.23**	**232.53**	**86.26**	**23.40**	**647.48**	**234.12**

Table 29: TUC strategy – First priority option – Case 1

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	75.64	23.89	5.12	1.55	91.45	22.63	661.47	238.16	91.36	22.64	666.58	239.71
2	74.87	24.11	5.20	1.67	88.21	23.12	658.35	238.83	88.13	23.13	663.55	240.50
3	81.09	23.11	5.23	1.64	86.58	23.35	645.87	234.81	86.55	23.35	651.10	236.45
4	80.31	23.21	5.24	1.61	88.46	23.07	650.40	234.81	88.41	23.07	655.64	236.43
5	76.98	23.75	5.17	1.60	84.53	23.67	624.56	226.99	84.48	23.67	629.73	228.59
6	83.04	22.88	5.32	1.64	88.90	23.02	650.01	234.95	88.86	23.02	655.34	236.59
7	74.61	24.10	5.11	1.58	89.59	22.91	660.52	237.73	89.50	22.92	665.64	239.31
8	79.01	23.54	5.21	1.63	84.71	23.64	628.30	228.38	84.67	23.64	633.50	230.00
9	81.00	23.11	5.23	1.60	85.24	23.56	641.22	233.10	85.21	23.56	646.44	234.71
10	70.49	24.91	4.87	1.52	87.59	23.19	650.74	235.09	87.49	23.20	655.61	236.61
11	82.12	23.01	5.34	1.62	92.75	22.46	672.61	240.52	92.68	22.47	677.95	242.14
12	78.31	23.51	5.21	1.59	88.20	23.11	661.45	239.03	88.14	23.12	666.66	240.63
13	75.81	24.00	5.20	1.65	86.82	23.31	642.78	232.70	86.75	23.32	647.98	234.35
14	82.64	22.97	5.20	1.64	85.65	23.50	648.02	235.16	85.63	23.50	653.22	236.80
15	79.96	23.29	5.18	1.63	88.42	23.08	664.58	240.18	88.37	23.08	669.76	241.82
16	81.51	23.10	5.06	1.57	86.63	23.35	648.57	235.50	86.60	23.35	653.62	237.07
17	81.15	23.08	5.20	1.65	85.32	23.54	634.10	230.73	85.30	23.54	639.30	232.38
18	72.29	24.46	4.91	1.54	91.06	22.69	665.21	240.15	90.95	22.70	670.13	241.69
19	79.24	23.34	5.25	1.63	88.71	23.05	658.37	237.26	88.65	23.05	663.62	238.89
20	78.86	23.39	5.28	1.65	86.15	23.43	639.01	231.82	86.10	23.43	644.29	233.47
Average	**78.45**	**23.54**	**5.18**	**1.61**	**87.75**	**23.19**	**650.31**	**235.29**	**87.69**	**23.19**	**655.48**	**236.91**

Table 30: TUC strategy – Second priority option – Case 1

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	76.18	23.97	5.11	1.60	84.31	23.70	623.95	226.16	84.26	23.70	629.06	227.76
2	69.70	24.97	4.89	1.51	90.24	22.81	665.05	239.43	90.12	22.82	669.94	240.94
3	76.56	23.84	5.25	1.65	86.73	23.35	652.83	236.42	86.67	23.35	658.08	238.07
4	77.55	23.71	5.09	1.59	89.02	22.99	664.73	239.96	88.95	22.99	669.82	241.55
5	78.87	23.43	5.20	1.62	89.45	22.92	661.51	238.54	89.39	22.92	666.71	240.16
6	74.11	24.06	5.06	1.56	84.26	23.72	631.62	229.15	84.20	23.72	636.68	230.71
7	73.88	24.37	4.99	1.58	88.35	23.10	650.91	234.37	88.26	23.11	655.89	235.95
8	74.08	24.16	5.08	1.59	89.30	22.97	652.87	234.94	89.21	22.98	657.95	236.53
9	81.00	23.08	5.28	1.70	87.40	23.23	658.40	238.66	87.37	23.23	663.68	240.37
10	75.56	24.06	4.99	1.56	87.62	23.19	654.16	236.79	87.55	23.20	659.15	238.35
11	83.68	22.71	5.41	1.67	95.13	22.14	682.00	244.10	95.07	22.14	687.41	245.77
12	78.29	23.58	5.13	1.64	87.96	23.15	654.10	236.40	87.91	23.15	659.22	238.04
13	83.91	22.68	5.59	1.76	92.09	22.55	672.01	241.62	92.04	22.55	677.61	243.38
14	76.34	23.84	5.08	1.64	86.74	23.33	650.42	236.00	86.68	23.34	655.50	237.64
15	74.55	24.11	5.00	1.60	86.07	23.43	649.67	235.02	86.00	23.43	654.67	236.62
16	67.78	25.32	4.65	1.45	88.13	23.12	653.24	234.88	88.01	23.14	657.89	236.33
17	76.60	23.81	5.07	1.58	85.93	23.46	641.95	233.07	85.87	23.46	647.02	234.64
18	74.71	24.04	5.03	1.58	90.02	22.84	669.79	241.00	89.93	22.85	674.81	242.58
19	72.88	24.41	5.03	1.56	89.91	22.87	664.84	239.26	89.81	22.88	669.87	240.82
20	72.40	24.47	4.98	1.55	86.60	23.36	644.66	233.40	86.51	23.37	649.63	234.95
Average	**75.93**	**23.93**	**5.09**	**1.60**	**88.26**	**23.11**	**654.93**	**236.46**	**88.19**	**23.12**	**660.03**	**238.06**

Table 31: TUC strategy – First priority option – Case 2

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	74.50	24.07	5.09	1.54	89.36	22.94	658.97	237.71	89.27	22.94	664.06	239.25
2	87.74	22.24	5.64	1.72	86.56	23.37	646.11	234.37	86.57	23.36	651.75	236.09
3	82.73	22.90	5.32	1.60	88.43	23.07	654.81	236.49	88.40	23.07	660.13	238.10
4	80.89	23.17	5.24	1.56	87.76	23.18	649.01	235.07	87.72	23.18	654.25	236.63
5	68.60	25.03	4.96	1.54	84.81	23.63	642.77	232.72	84.71	23.64	647.73	234.25
6	78.21	23.62	5.16	1.62	89.35	22.95	654.95	235.79	89.28	22.96	660.11	237.40
7	81.88	22.96	5.36	1.72	89.88	22.86	656.02	236.51	89.83	22.86	661.38	238.23
8	84.29	22.69	5.40	1.69	84.22	23.71	624.91	227.47	84.22	23.70	630.31	229.16
9	84.99	22.54	5.39	1.68	85.56	23.51	646.72	235.23	85.56	23.50	652.11	236.91
10	72.85	24.53	4.94	1.56	87.59	23.20	651.22	235.46	87.50	23.21	656.17	237.02
11	86.10	22.41	5.46	1.61	88.79	23.03	657.19	236.72	88.77	23.03	662.65	238.33
12	78.48	23.58	5.20	1.58	88.73	23.03	666.06	240.51	88.67	23.04	671.27	242.10
13	74.79	24.00	5.13	1.55	87.10	23.27	642.15	232.16	87.02	23.27	647.28	233.71
14	76.72	23.89	5.03	1.60	85.86	23.47	651.66	235.31	85.81	23.47	656.70	236.91
15	72.65	24.31	4.95	1.51	85.82	23.47	645.82	234.00	85.75	23.47	650.77	235.51
16	77.53	23.68	4.96	1.53	87.18	23.26	646.14	234.06	87.13	23.27	651.10	235.59
17	78.41	23.52	5.13	1.60	84.70	23.64	634.68	230.69	84.67	23.64	639.81	232.29
18	81.36	23.09	5.24	1.60	88.88	23.01	649.22	234.51	88.83	23.01	654.46	236.11
19	77.22	23.75	5.15	1.58	87.37	23.25	651.02	235.42	87.31	23.25	656.17	236.99
20	76.99	23.69	5.15	1.58	84.93	23.62	631.28	228.91	84.88	23.62	636.43	230.49
Average	**78.85**	**23.48**	**5.19**	**1.60**	**87.15**	**23.27**	**648.04**	**234.46**	**87.10**	**23.27**	**653.23**	**236.05**

Table 32: TUC strategy – Second priority option – Case 2

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	73.29	24.28	5.04	1.56	91.31	22.65	668.59	240.57	91.21	22.66	673.63	242.13
2	79.03	23.49	5.29	1.69	84.36	23.71	638.59	232.15	84.33	23.71	643.89	233.84
3	78.95	23.41	5.16	1.61	87.20	23.26	646.57	234.65	87.16	23.26	651.72	236.26
4	78.81	23.43	5.17	1.61	89.18	22.96	656.90	237.42	89.11	22.96	662.07	239.03
5	83.85	22.71	5.37	1.72	85.64	23.50	637.80	231.21	85.63	23.49	643.17	232.93
6	76.57	23.88	5.06	1.57	88.25	23.11	653.41	236.45	88.18	23.12	658.47	238.02
7	79.96	23.21	5.30	1.66	85.99	23.44	638.95	230.91	85.96	23.44	644.26	232.58
8	84.46	22.65	5.40	1.67	86.29	23.39	636.54	230.69	86.27	23.39	641.94	232.36
9	80.82	23.13	5.25	1.65	86.66	23.34	653.80	236.72	86.63	23.34	659.06	238.37
10	76.98	23.79	5.08	1.60	87.66	23.19	652.06	234.97	87.59	23.19	657.14	236.57
11	77.77	23.72	5.18	1.62	91.79	22.60	672.87	241.54	91.70	22.60	678.05	243.16
12	80.01	23.24	5.21	1.65	90.70	22.74	673.30	242.19	90.63	22.75	678.51	243.84
13	83.38	22.77	5.49	1.70	88.92	23.01	656.61	236.04	88.89	23.00	662.09	237.74
14	73.91	24.28	4.99	1.57	84.45	23.68	641.10	232.89	84.39	23.69	646.09	234.46
15	76.02	23.88	5.02	1.54	87.80	23.17	656.68	237.14	87.73	23.18	661.70	238.68
16	76.23	23.82	4.93	1.54	89.18	22.97	664.66	239.61	89.11	22.97	669.58	241.14
17	81.31	23.08	5.26	1.65	85.86	23.47	631.43	229.28	85.83	23.46	636.70	230.93
18	96.22	21.02	5.71	1.82	93.20	22.38	677.04	242.24	93.22	22.38	682.76	244.06
19	77.29	23.69	5.17	1.62	87.91	23.17	655.19	236.41	87.84	23.17	660.35	238.04
20	67.61	25.21	4.86	1.57	86.47	23.38	639.17	232.25	86.36	23.39	644.03	233.83
Average	**79.12**	**23.44**	**5.20**	**1.63**	**87.94**	**23.16**	**652.56**	**235.77**	**87.89**	**23.16**	**657.76**	**237.40**

Table 33: TUC strategy – First priority option – Case 3

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	79.77	23.25	5.30	1.66	91.38	22.64	672.97	241.73	91.31	22.65	678.28	243.39
2	86.24	22.42	5.59	1.76	87.69	23.20	649.95	235.35	87.68	23.19	655.54	237.10
3	81.99	23.10	5.18	1.62	86.44	23.38	645.21	234.62	86.41	23.38	650.39	236.24
4	82.75	22.92	5.34	1.63	89.72	22.90	664.38	239.63	89.68	22.90	669.73	241.26
5	71.62	24.50	5.04	1.58	83.08	23.90	624.30	227.26	83.01	23.91	629.34	228.84
6	74.67	24.17	5.03	1.52	89.29	22.96	652.59	235.22	89.20	22.97	657.62	236.74
7	75.56	23.97	5.17	1.59	87.75	23.18	647.39	233.79	87.67	23.19	652.55	235.38
8	75.66	24.02	5.12	1.58	84.08	23.74	619.95	225.19	84.03	23.74	625.07	226.76
9	78.91	23.47	5.21	1.65	89.63	22.91	672.18	242.70	89.57	22.91	677.39	244.35
10	76.55	23.85	5.10	1.59	86.36	23.39	650.06	235.29	86.30	23.39	655.16	236.88
11	77.82	23.63	5.21	1.54	92.61	22.48	672.40	241.05	92.52	22.49	677.61	242.59
12	78.19	23.62	5.20	1.63	92.48	22.50	686.40	246.82	92.39	22.51	691.60	248.45
13	76.30	23.91	5.21	1.64	87.20	23.26	647.66	234.41	87.13	23.26	652.87	236.05
14	79.64	23.31	5.13	1.60	85.72	23.48	643.59	233.48	85.69	23.48	648.73	235.08
15	77.87	23.52	5.10	1.57	85.89	23.46	641.09	232.97	85.84	23.46	646.19	234.54
16	67.57	25.35	4.68	1.45	86.09	23.43	646.43	234.03	85.99	23.44	651.12	235.48
17	79.84	23.30	5.19	1.64	86.66	23.35	634.83	230.43	86.62	23.35	640.02	232.08
18	77.68	23.63	5.08	1.55	90.04	22.83	662.60	239.15	89.96	22.84	667.68	240.69
19	69.71	24.99	4.98	1.52	87.47	23.23	657.82	238.41	87.36	23.24	662.80	239.93
20	71.68	24.49	5.04	1.55	85.22	23.57	634.64	230.30	85.14	23.58	639.68	231.85
Average	**77.00**	**23.77**	**5.15**	**1.59**	**87.74**	**23.19**	**651.32**	**235.59**	**87.67**	**23.19**	**656.47**	**237.18**

Table 34: TUC strategy – Second priority option – Case 3

	Bus				Car				All vehicles			
Replications	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)	Delay T. (sec/km)	H. Speed (km/h)	TTT (hours)	CO emissions (g/s)
1	73.36	24.31	5.07	1.54	89.17	22.97	661.18	238.83	89.07	22.97	666.25	240.36
2	75.16	24.05	5.18	1.62	86.71	23.35	649.85	234.92	86.64	23.35	655.03	236.54
3	83.49	22.73	5.33	1.67	87.05	23.28	648.85	235.31	87.03	23.28	654.18	236.98
4	83.64	22.80	5.34	1.65	89.56	22.90	660.55	237.96	89.52	22.90	665.89	239.61
5	64.27	25.89	4.72	1.51	84.50	23.68	630.69	229.95	84.38	23.70	635.41	231.47
6	70.49	24.89	4.86	1.50	89.84	22.88	655.74	236.08	89.73	22.89	660.60	237.59
7	69.04	25.05	4.92	1.52	86.71	23.36	639.08	231.33	86.60	23.37	643.99	232.85
8	77.52	23.76	5.18	1.63	85.28	23.55	633.88	229.89	85.23	23.55	639.06	231.52
9	76.18	23.88	5.09	1.59	86.98	23.30	653.69	235.90	86.91	23.31	658.78	237.49
10	82.10	23.06	5.24	1.64	90.30	22.80	667.57	239.62	90.25	22.80	672.82	241.25
11	78.30	23.61	5.20	1.61	92.55	22.49	668.21	240.12	92.47	22.50	673.40	241.73
12	72.75	24.40	5.04	1.57	89.43	22.93	668.58	240.95	89.33	22.94	673.62	242.53
13	76.58	23.83	5.16	1.63	89.70	22.90	657.76	237.48	89.62	22.91	662.92	239.11
14	77.50	23.73	5.08	1.61	85.82	23.47	642.54	232.91	85.77	23.48	647.62	234.52
15	76.43	23.75	5.08	1.57	90.35	22.79	670.56	241.21	90.27	22.80	675.64	242.78
16	72.05	24.59	4.81	1.50	89.47	22.92	663.92	239.27	89.37	22.93	668.73	240.76
17	70.63	24.77	4.94	1.55	85.25	23.56	632.29	229.60	85.16	23.57	637.23	231.15
18	76.70	23.75	5.05	1.56	88.24	23.10	653.69	236.17	88.17	23.10	658.74	237.72
19	74.51	24.09	5.11	1.60	90.08	22.85	667.27	239.64	89.99	22.86	672.39	241.24
20	75.85	23.89	5.11	1.63	88.15	23.12	652.32	235.46	88.08	23.13	657.43	237.10
Average	**75.33**	**24.04**	**5.08**	**1.58**	**88.26**	**23.11**	**653.91**	**236.13**	**88.18**	**23.12**	**658.99**	**237.72**