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Signal Synchronization of an Urban Corridor with Bus Priority

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Alle mie zie

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1. INTRODUCTION

In the last decade very high vehicular traffic flows characterize many urban areas; consequently, traffic congestion has become a growing problem to be solve. Travel times are strongly influenced by the vehicular density. The challenge of the cities is to minimize the congestion problem and the related environmental concerns through the implementation of traffic control strategies.

Intersections are the most critical points in the network because they accommodate different traffic flow movements. In order to better control the sharing of this space, traffic lights are the most effective means for managing traffic. The signal timing must be set appropriately; in fact, an inadequate setting combined with heavy traffic often brings to oversaturated conditions transforming the intersection in a bottleneck. Thus, massive queues build up with consequent high levels of fuel consumption and pollutant emissions, waiting time increase with the delays and the dissatisfaction of road users who often experience delays at their destination. Extensive studies have been conducted to overcome these impacts and there are many models in the literature developed for isolated intersections and also for junction coordination strategies. Furthermore, recent advances in technology have facilitated the design of real-time signal control that analyses continuously the traffic situations and allows it to be managed more effectively and flexibly.

The crucial problem of road congestion involves not only private cars but also public buses that travel the streets of the city several times a day, remaining very often lined up in traffic. People waiting at bus stops grow, travel times increase, buses are more crowded and this generates inconvenient situations with stress and discomfort both for passengers and bus drivers. The reliability and regularity of the service are negatively impacted by reducing the effectiveness and attractiveness of public transport.

The present work aims at studying state-of-the-art methodologies for traffic control with bus priority and developing an experimental project to improve the performances of an urban corridor, Via Prenestina, located in Rome. The applied methodology consists in synchronizing the timing of the successive intersections along the artery and implementing transit signal priority. A software routine developed by Sapienza University to solve this specific problem, named SINTAC, is used to optimize the parameters of traffic lights. Subsequently, using an open-source microscopic traffic simulator, SUMO, different design scenarios are compared, evaluating the benefits in terms of total delay reduction, to obtain by the optimal solution.

2. LITERATURE REVIEW

2.1 Urban traffic signal control methods

The first three-colored traffic light appeared in Detroit in 1920 and was invented by a policeman named William Potts. Afterwards, many cities have adopted this device and in Europe it was set for the first time in 1926 in England. Thanks to the rise of computer in America in the 1950s, traffic light control improved to the modern traffic signal system with control depending on the volume, density and traffic speed [1].

Traffic lights influence what happens on the roads, they control traffic, improve road safety and increase the quality of traffic flow and they are programmed with different timing setting:

- Fixed-time signals
- Actuated signals
- Adaptive signals

2.1.1. Fixed-time control

Fixed-time signal control uses preset time intervals that are the same every time the signal cycles, regardless of changes in traffic volumes. The phase sequence, phases splits, cycle length and offset for each signal are fixed based on historical traffic information. Some fixed-time systems use different preset time intervals for morning rush hour, evening rush hour, and other busy times.

The disadvantage of these systems is that they assume that traffic volumes are stable, which is rare and this implies a degradation of the performances in case of traffic variability.

2.1.2. Actuated control

Actuated signals have the capability to respond to the presence of vehicles or pedestrians at the intersection. The controllers, using the information of traffic demand obtained from vehicle detectors, are capable of varying the cycle length and green times for each phase. Although they are adaptable to short-term fluctuations in traffic flow reducing delay and increasing capacity, they are more expensive to install and they require careful inspection and maintenance to ensure proper operation.

Traffic-actuated control can be of two types, semi-actuated and fully actuated control, depending on the traffic approaches to be detected [2].

The semi**-actuated control** is used at intersections where a major street having relatively uniform flow is crossed by a minor street with low volumes. Detectors are placed only on the minor street. The green is on the major street at all times unless a call on the side street is noted. The number and duration of side-street green is limited by the signal timing and can be restricted to times that do not interfere with progressive signal-timing patterns along the major street.

The **fully-actuated control** is used at the intersections of streets or roads with relatively equal volumes, but where the traffic distribution is varying. In full actuated operation, all lanes of all approaches are monitored by detectors. A minimum green time duration is provided for each approach during a cycle and this length can be subjected to variations according to the arrival of the vehicle observed by a detection device. The length of each green interval is also constrained by a specification of maximum green time. This form of control is effective for both two-phase and multi-phase operations and can accommodate optional phases.

Much of the benefit of traffic-actuated control is derived from the ability of the controller's proactively responding to the fluctuations in traffic volume, which provides greater efficiency compared to fixed-time control by servicing cross-street traffic only when required. However, actuated traffic signal can only respond to the traffic flow fluctuation to a certain degree. A retiming is needed after a period of time to ensure its efficiency.

2.1.3. Adaptive control

Adaptive traffic signal control is a relatively new method: research began in the 1970's and has only recently been increasing. In this system, the traffic signal is optimized every several seconds based on predicted traffic state. The installed detectors allow to count the queue lengths formed behind the red light and the headway between two successive vehicles passing the sensors, so the volume of traffic existing at the intersection can be estimated. The signal controller utilizes an algorithm to compute optimal signal timings based on detected traffic volume and simultaneously implement the timings in real-time. This real-time optimization allows to react to volume variations, which results in reduced vehicle delay, shorter queues, and decreased travel times [2].

For greater system efficiency, two sensors per lane per link are used to predict future flow.

2.2 Signal timing optimization for isolated intersection

The most appropriate adjustment of traffic signal timings at intersection is an important element which can reduce the number of stops, delays, emissions, fuel consumption and queue lengths by increasing intersection capacity and level of service.

The design of traffic signal at an isolated intersection can be performed by neglecting the relationship with other nearby intersections. In the past years, numerous studies have been conducted to develop various models for optimizing the signal setting, with different objectives.

2.2.1 Fixed-time strategies

In the fixed-time signal control two main optimization methods are used: stage-based approach and phase-based (or group-based) approach [3].

In the **stage-based control method**, the cycle of a signal plan is divided into a sequence of periods called stages consisting of a set of compatible traffic movements that all have green. In this method the stage sequence, the inter-green time between stages, the traffic flows and the saturation flows are defined before optimization. Then a number of constraints, for defining the optimization problem, are considered: a minimum for green duration, an adequate capacity and a cycle duration range. The optimal green splits and cycle time for the stages are calculated. The most common objective functions used are delay minimization and capacity maximization.

Webster (1958) was the first that investigated the undersaturated conditions for isolated intersection and he developed the first empirical formula to estimate the average delay of vehicles and determine the optimum cycle length to minimize total delay for all approaches in the junction. However, this method is not suitable in case of complex intersection [4].

Allsop (1971, 1972) presented a more specific treatment of the isolated signal optimization problem and he formulated the calculation of signal settings as a convex mathematical programming problem to minimize the total delay using Webster's formulation (SIGSET) [5]. He also extended the problem to determine the signal setting that maximizes the intersection capacity and formulated the problem as a linear program (SIGCAP) [6].

Gazis and Potts (1965) were the first to consider oversaturated traffic conditions and in their method at first the maximum green is allocated to the major road and the minimum green to the minor road, then the green time is switched between these two to balance the residual queues [7].

Michalopoulos and Stephanopoulos (1977) modified Gazis' approach and optimized single intersections with queue length constraints switching the signals if the queue reaches its bound [8].

A different approach is in **phase-based optimization**, where stage sequence isn't maintained with specific structure and the signal timing is allocated directly to individual phases, separating mutually incompatible phases by sufficient inter-green times for safe operation.

Improta and Cantarella (1984) specified the cycle-structure by a set of binary variables relating to incompatible signal groups and formulated the problem as a Binary- Mixed-Integer-Linear-Program (BMILP). They solved simultaneously the problem to optimize the stage sequences and green durations [9].

Heydecker & Dudgeon (1987) showed the benefits obtained with this method in case of complex junction, even if it is required a greater number of variables and constraints [10].

Lam et al. (1997) and Wong and Wong (2003) [11] have extended the group-based approach to lane-based, where the lane permitted movements are considered as binary variable.

To more easily solve complex calculations of the optimization problem, some off-line software has been developed such as OSCADY (Burrow, 1987) that is a tool able to model capacity, queues and delays at isolated junction [12].

2.2.2 Traffic-Responsive strategies

Traffic-responsive strategies provide a very high level of control and the optimization of signal timing permits to continuously allocate the optimal signal with respect to changing traffic conditions using real-time measurements provided by inductive loop detectors. Many approaches to real-time signal optimization have been proposed by various authors.

Miller (1963) proposed a dynamic self-optimizing strategy in which the decision to extend a phase is made at repeatedly fixed intervals basing on the examination of a delay-based control function [13].

Robertson and Bretherton (1974) developed a dynamic programming model to find the best sequence of signal timings based on knowledge of traffic arrivals for a finite horizon length [14].

Bang (1976) further developed Miller's theory introducing a system called Traffic Optimization Logic (TOL) that used a control function to estimate the benefit of extending the green by h sec. or terminating it immediately [15]. Both Miller and TOL methods provides short-term optimization and they do not guarantee that an overall optimal control is obtained.

Gartner (1983) proposed a rolling horizon approach in the OPAC model. [16] The on-line signal optimization algorithm is design to identify the optimal signal switching sequence for a future-time period knowing as optimization horizon. This time period is divided into time intervals: for the first intervals (head portion) the flow data is known by the detectors and for the next intervals (tail portion) the flow data are based on predictions considering an average flow rate. Then feasible switching sequences for the entire time intervals are identified and the optimal alternative is chosen basing on performance function that considers the total delay. The optimal switching plan is the one that minimizes this function. Though OPAC was originally designed for signal control at isolated intersection, it was then extended for coordinated control of intersections in a network.

Vincent and Young (1988) developed MOVA algorithm designed purposely for isolated intersection. It elaborates the data from detectors thanks to an online microprocessor and the duration of the green is regulated by a delay- and-stops minimizing logic or by a capacity-maximizing process in case of approaches congested. Latest versions of MOVA are also capable of linking two or more junctions when they are not considered as isolated [17].

2.3 Signal timing optimization for coordinated intersections

Signal coordination at network level is a strategy to improve the level of service of the roads. In particular, synchronization is a regulation method of traffic signal for a road artery: it consists in coordinating the timing of successive intersections clearing as many vehicles as possible at safety speed and with minimum delay and stops. A good coordinated traffic signal plans can be reduced some problems such as traffic congestion, fuel consumption and emission of gases, but in general it is a complex problem to solve.

Synchronization can be formulated as an optimization problem and several models by various authors have been proposed in the literature. The main approaches consider as objective function:

- bandwidth maximization
- delay minimization
- the combination of both: minimum delay and maximum bandwidth.

The first is a quasi- concave problem, so a global optimal solution can be found analytically with specific algorithms, while total delay minimization is a non-convex problem, thus only suboptimal solutions can be determined with different approaches [18].

2.3.1 Bandwidth maximization

The bandwidth is the share of cycle time in which a vehicle can leave the first intersection and travel, at preassigned speed, up to the last junction without stopping. Maximizing the bandwidth allows increasing the number of vehicles for which stopping is avoided and the creation of the so called *green waves* (progression of green lights) is the main approach used in traffic lights synchronization.

The oldest methods in the literature for maximizing the bandwidth are mostly graphical and the first computer program was developed by Morgan and Little in 1964 [19]. They considered a two-way street with n traffic signals ($S_1, . . . , S_n$) and they maximized the inbound and outbound bandwidths ($\bar{b}$ and b). The method at first computes the maximal equal bandwidth for the both directions and then shifted the total bandwidth from one direction to the other basing on platoon length.

An extension of this first work was published by Little (1966), who formulated the problem as a mixed-integer linear program (MILP) [20]. He introduced a branch and bound algorithm for the maximal bandwidth problem that divide all the feasible solutions into smaller subsets and define for each the bound. These smaller subsets can then be evaluated systematically until the best solution is found.

After, Little et al. (1981) developed MAXBAND program that computes cycle time, offsets, speeds, and left-turn phase sequence to maximize the weighted combination of bandwidths [21]. One option in MAXBAND is that in the input the green splits can be provided or alternatively, setting traffic volume and capacity information, the program is able to compute the green splits basing on theory of Webster.

Messer et al. (1974) developed a program, PASSER II, that introduces left-turn movements in the optimization and is therefore designed for arterial roads with protected left-turn arrows [22]. This program combines the advantages of maximum bandwidth and minimum delay ensuring a solution of maximum bandwidth and calculating a solution of minimum delay within the limits of the invariable bandwidths.

Gartner (1990) introduced MULTIBAND model, an extension of MAXBAND, based on traffic-dependent criterion and it is able to define an individual bandwidth for each road section, generating a variable bandwidth progression [23]. This model overcomes the limitation of the previous bandwidth-based programs that do not consider different traffic volumes in the various arterial sections but take on a uniform platoon.

An extension of the single arterial MULTIBAND was developed by Stamatiadis and Gartner (1996) with the name of MULTIBAND-96 and it was designed for a multiarterial grid networks.

Also new versions of MAXBAND and PASSER are present, knowing as MAXBAND-86 by Messer et al. (1988) [24] and PASSER IV by Messer and Chaudhary (1993) [25] : both improved to manage multiarterial networks.

More recently, Papola and Fusco (1998) has presented a new algorithm to solve the maximal bandwidth problem based on the periodicity features of the bandwidth function [26].

2.3.2 Delay minimization

The minimum delay problem of a synchronized artery was first treated by Robertson (1969), who proposed a method called TRANSYT [27]. This platoon dispersion model selects the optimal signal offsets and green times to minimize delay or stops of the whole networks, assuming that the cycle time, green times, flows and saturation flows are known. The good convergence of the optimum solution is obtained by a hill climbing optimization procedure. TRANSYT has consisted of two main parts: a traffic flow model and an optimization model and in practice performs sequential offset adjustments based on the improvement of a performance index which includes total delay on networks and eventually also the number of stops. The adjustment procedure continues until no improvement of the performance index are obtained. The program was enhanced by the University of Florida Transport Center in 1981 with the new TRANSYT-7F version and continued to undergo further development.

Foy et al. (1992) implemented a genetic algorithm (GA) that uses an heuristic probabilistic search procedures to find a near-optimal timing strategies and it is a well suitable tool to optimize complex problem [28]. Successively the use of this algorithm was studied in combination with TRANSYT (Hady and Wallace, 1993) [29].

Park et al. (1999) developed a genetic algorithm-based signal optimization program that can handle oversaturated signalized intersections [30].

Lo (1999) introduced the model of cellular transmission to solve the critical problem of blocking the lane owing to the queue that spill back from upstream intersection [31]. The enhancement of this model was performed by subsequent research (Li, 2011; Zhang et al., 2012; Zhang et al., 2013) and it was also included in the latest version of TRANSYT, named TRANSIT- 7F (Binning et al. 2008).

Colombaroni et al. (2009) [32] presented a synchronization method based on a mixed genetic-hill climbing algorithm, which applies a platoon-based delay model that generalizes the analytical model developed by Papola and Fusco (2000). This model was subsequently extended to simulate bus movements and synchronize artery signals with real-time bus priority strategies.

2.3.3 Adaptive signal control systems

All the previous models utilize an off-line signal control strategy based on historical data, but the availability of real-time data has led to the development of on-line models for a real-time coordination of traffic flows on the network. The main programs commercially adopted and currently used in many locations around the world are shown below.

SCATS was implemented by Sims and Dobinson (1980) in Sidney with the aim to improve the movements on arterial roads reducing delay [33]. This system was subsequently widely implemented worldwide.

Robertson et al. (1982) introduced the well-known SCOOT, an effective and efficient tool for signal coordination with the objective to minimize the sum of the average queues and therefore the delay of the vehicles in the network [34]. It is considered as the traffic- responsive version of TRANSYT and is widely used in many cities in the UK. SCOOT obtains information on traffic flows from detectors and works repeatedly in real time estimating the effect of a small adjustment in signal timings through a performance index and assesses whether the existing action time should be advanced, retarded or remain the same. New versions of SCOOT have been released that incorporate the bus priority function and other improvements.

Henry, Farges and Tuffal (1983) developed the hierarchical algorithm PRODYN able to solve the optimization problem and provide in real time the best signal setting with respect to the delay criterion. It uses the technique of decompose the initial complex problem into smaller problems by solving them with dynamic programming and then solves the global problem with iterative calculations [35].

REALBAND (Dell'Olmo and Mirchandani, 1995) is a model able to identify the platoons and predict, for a given time horizon, their movement in the network using the traffic information in real time and sets the signal in such a way that the predicted platoons have appropriate green times with the aim of optimizing a specific performance criterion [36].

UTOPIA (Mauro and Di Taranto, 1990) is a hierarchical and decentralized traffic control systems installed for the first time at Torino. The main feature of this algorithm is the assignment of priority to public transport and the improvement of private traffic at the intersection. At first it decomposes the overall problem at intersection level solving the subproblems for each traffic light intersection and then finds rules to define the interaction between these intersections to guarantee the stability at network level [37].

RHODES (Mirchandani and Head, 2001), like the previous model, is a hierarchical algorithm that decomposes the problem into subproblems, then predicts future vehicle flows based on real-time measurements of traffic streams and optimizes the signal in response to these predictions [38].

2.4 Priority at traffic signals

The concept of providing bus priority at signals is not new and it has attracted considerable attention in the research. As early as 1962 an experiment was conducted in Washington, D.C. in which the offset of a signalized network was adjusted to better match the lower average speed of buses [39]. The first bus-actuated, or active, signal priority experiment occurred in Los Angeles in 1970 and was followed by other similar demonstrations across the U.S. [40]. Since then, transit signal priority strategies have grown not only in the United States, but all over the world. Various approaches have been proposed in the literature, which explore different aspects of the priority problem and some of these studies are reported below.

Skabardonis (2000) developed an optimal signal timing for bus operations by minimizing a combination of delays and stops offline [41]. Weighting factors for delays and stops, that implicitly accounted for passenger loads, were included to favor the buses. Later in 2008, together with Geroliminis [42] proposed a strategy with the aim to minimize the adverse impacts to the rest of the traffic. Based on real-time monitoring of traffic conditions and bus arrivals, the priority was guaranteed through special stage, green extension or stage recall considering queue presence, schedule adherence, green ratio and bus route progression.

Liu, et al. (2003) developed an approach whereby a linear program (LP) is first used to optimise the departure flow rates. The optimized rates are then converted into appropriate signal parameters and compared with the currently signal timings to determine whether a replacement is necessary. To take into account priority requests, the arrival of a bus is represented by weighting the arrival demand of the associated approach with a factor that is defined based on traffic demands, queuing conditions at every junction approach and information on the potential bus delay [43].

Lee et al.(2005) used online microsimulation-based arrival prediction models in developing dynamic TSP systems. The developed method consisted of two major components: an online microsimulation travel time prediction model and a priority operation model. When a transit vehicle is detected, the prediction model is activated to retrieve signal-timing information and traffic data from the upstream and downstream sensors. The priority operation model consisted of a library of six priority plans that would be evaluated by the arrival prediction model. Once the travel time of each priority plan has been evaluated, the most appropriate plan with the least travel time is selected and sent to the signal controller [44].

Stevanovic et al. (2008) presented a Genetic Algorithm model that works in a micro-simulation environment to optimize four basic signal timing parameters (i.e., cycle length, offset, splits, and phase sequence) and transit priority settings. The objective of the optimization is the sum of total delay and weighted number of stops for all vehicles. Two TSP strategies are made possible by optimizing the transit priority parameters: green extension and red truncation. Taking advantage of the random seeds in the micro-simulation, the stochasticity characteristics of vehicle arrivals are implicitly addressed [45].

Ekeila, et al. (2009) proposed an approach, which, using a linear model to predict arrival times, responds on a FIFO basis to the received priority requests via green extension, stage recall, or cycle extend. The prediction model that has been used to test and evaluate this approach has been developed based on simulation-obtained data for dwell and travel times [46].

Li et al. (2011) presented an adaptive TSP optimization model that optimizes green splits for three consecutive cycles to minimize the weighted sum of transit vehicle delay and other traffic delay, considering the safety and other operational constraints under the dual-ring structure of signal control. By computing not only the green but also the red time for each phase, the model was able to capture the evolution of TSP-induced queues and their delays using deterministic queuing theory. Due to the nonlinear nature of phase red-time and vehicle delays, the optimization model is Mixed Integer Nonlinear Programming (MINP) [47].

Christofa and Skabardonis (2011) presented a traffic responsive signal control system for signal priority on conflicting transit routes that also minimizes the negative impacts on the auto traffic based on person delay. The vehicle delays are estimated using deterministic queuing theory, where arrivals and departures are constant. The position of a bus in a vehicle queue is explicitly modeled to obtain the bus delay. In addition, the passenger load of each bus is used as the weighting factor among multiple priority calls as well as between bus and passenger vehicles [48].

Ma et al. (2012) developed a TSP control framework that uses a dynamic programming approach to determine a timing plan with minimal bus delays. In a multi-request scenario, each request is weighted by bus occupancy and schedule deviations. Three active priority strategies are explicitly modeled: green extension, red truncation, and phase insertion. Although the delay to non-transit vehicles are not computed, the degree of saturation is set as a constraint to ensure the impact to other traffic is not too large. The framework further implements a rolling horizon approach to enhance its real-time control capability. A simulation study showed up to a 30 percent reduction of bus delays compared to fixed time control with no TSP implementations [49].

He et al. (2012) proposed a unified platoon-based framework called PAMSCOD that considers multiple models of travel, excluding pedestrian and bicyclists. The framework includes a Mixed Integer Linear Programming (MILP) model that searches the optimal signal plan by feeding priority requests and phasing data to signal controller in real-time. The objectives of the optimization model are to minimize the total of bus and platoon delays and to maximize the slack green time. The slack green is the extra green time available for a typical actuated controller to extend phases until gap-outs or max-outs. This method addresses the shortcoming that an adaptive signal controller usually operates on a fixed split basis, which cannot take advantages of industrial-standard controllers that are based on vehicle actuations [50].

Again Hu et al. (2015) proposed a person-delay-based optimization method for an intelligent Transit Signal Priority logic that enables bus/signal cooperation and coordination among consecutive signals under the Connected Vehicle environment. The problem is formulated as a Binary Mixed Integer Linear Program which is solved by standard branch-and-bound method [51].

In addition, many of the real-time signal control systems mentioned above, such as PRODYN, SCOOT, UTOPIA, have embedded bus priority logic into the software. These systems, using the traffic measurements available from the detectors, estimate the arrival time of PT vehicles and select the appropriate signal control treatments.

3. BUS PRIORITY AT TRAFFIC SIGNAL

3.1 The need of bus priority

The continued growth of the population in many towns in the world and the increased need for mobility of people and goods in the developed Countries have led to a significant increase in the number of cars traveling on our roads. Traffic congestion problems have become one of the most difficult challenges to solve today and many researches have been conducted to design an efficient transport system and improve mobility in urban areas. Usually optimization strategies for signal setting of intersection have the objective of minimizing the average delay for all motor vehicles. However, since buses and trams normally carry much higher number of passengers need to be handled differently in order to minimize the overall delay per person. Prioritizing transit vehicles, makes the public transport service more reliable, efficient and faster, but also more attractive and competitive than the car, so that more travelers will utilize buses freeing up space on our streets and reducing problems on air quality and fuel consumption.

3.2 Transit Signal Priority (TSP)

Transit signal priority (TSP) is a strategy to enhance the performance of transit systems by modifying the signal control logic to give buses priority at signalized intersections, without deteriorating the overall traffic conditions. The preferential treatment of public vehicles at the junction allows to facilitate their movement, improving schedule adherence and reducing delay and travel time.

3.2.1 Priority methods

The figure illustrates the delay of public transport without transit priority. The vehicle trajectory is plotted on the space-time diagram and the horizontal band represents the signal times: if the transit vehicle encounters a red traffic signal, the delay accumulates until the light turns green and the vehicle can proceed. Signal priority strategies attempt to reduce the delay in two ways: by reducing the probability that a transit vehicle will encounter a red signal and, if this occurs, reducing the waiting time to the green signal.

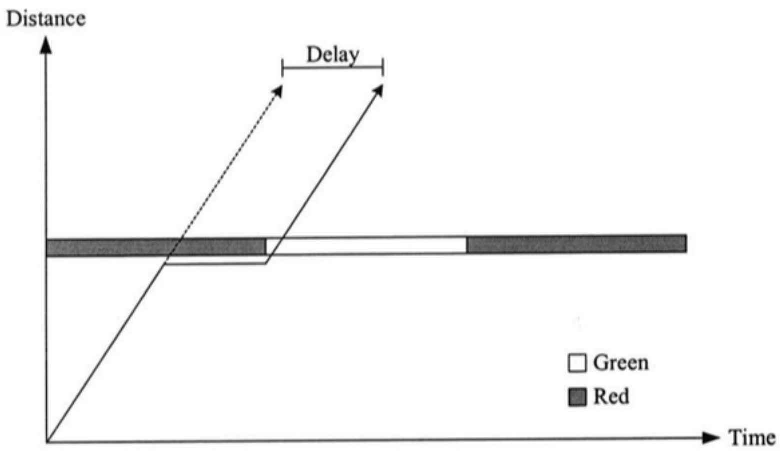


Figure 1 - Vehicle trajectory without signal priority

Priority can be awarded by various methods of signal modification and the most adopted actions are:

- green extension: method to extend green time for priority movement, usually used when the bus will arrive the intersection just after the end of normal green. the elongation of the signal is limited by a maximum value. Figure 2
- red truncation (or early green): strategy that prematurely interrupts all the other phases to accelerate the return to green for the priority vehicle serving phase. It is used when a bus arrives to the intersection during a red indication. Figure 3
- phase insertion: when a short green phase is inserted within the normal signal sequence. Figure 4

Other measures can be [52]:

- phase rotation: modification of the normal sequence to provide priority, i.e. the activation of a certain phase that is later in the order.
- phase skipping: omission of one or more phases from the normal phase sequence. This strategy is allowed only if the skipped phase demand is low.
- phases splitting: repeating for priority vehicles the green twice in the same cycle. The length of the cycle can remain unchanged if each of the two green phases is half the length of the original phase.
- adjustment of cycle length: reduction of the cycle time and decrease of the waiting time until the next green. This strategy leads to a reduction in the delay but also in the capacity of the intersection due to the increase in lost time
- signal synchronization: procedure to create a signal progression along an artery, favoring public transport and designing the green band based on the average bus speed instead of the average private cars speed.

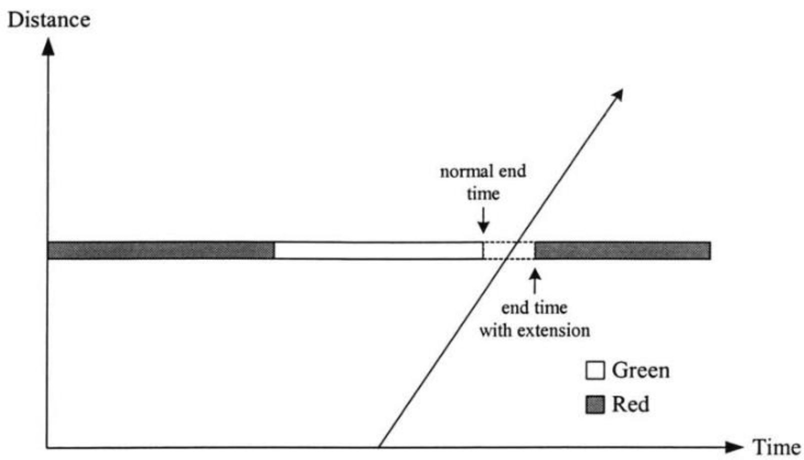


Figure 2 - Vehicle trajectory with green extension method

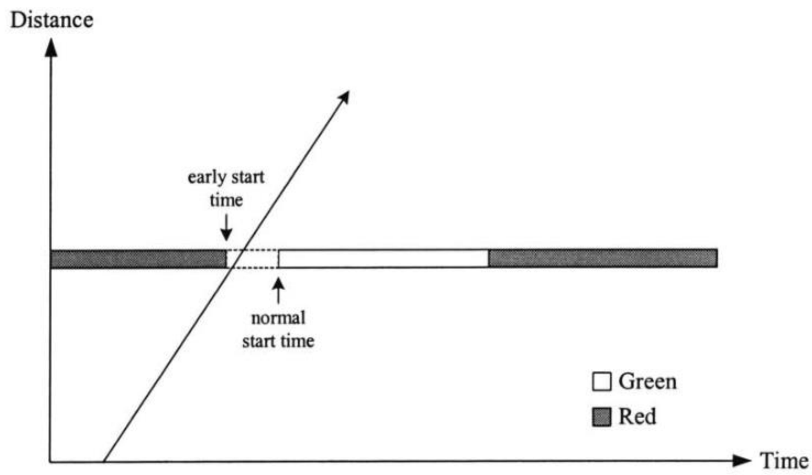


Figure 3 - Vehicle trajectory with red truncation method

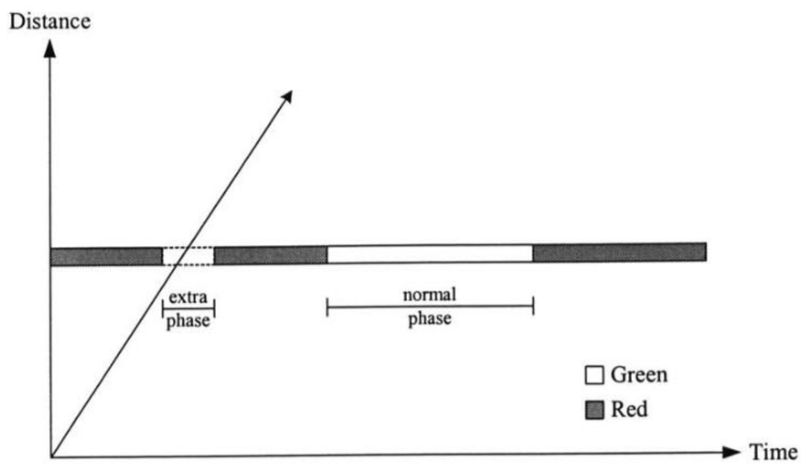


Figure 4 - Vehicle trajectory with phase insertion method

3.3 Priority strategies

The strategies can be classified, according to different signal priority treatments, into three main categories: passive, active and adaptive. These different approaches are described below [52].

3.2.1 Passive priority

Passive priority techniques are based on fixed-time plans and do not require the presence of the transit detection system to be active. The predetermined timing plan is developed offline based on historical data and it is an efficient form of TSP when transit operations are predictable, bus frequencies are high and traffic volumes are low.

3.2.2 Active priority

Active priority strategy requires a vehicle detection system and when a bus is actually present, priority measure is activated and the signal setting is altered to pass the bus through the intersection. This strategy applies signal priority only when necessary and it can give larger benefits to transit vehicles compared to passive method. Active priority can be:

- unconditional, if the priority status is assigned to each public transportation vehicle. The disadvantage of this strategy is the fact that priority could be granted to any public vehicle, which might not need it, as for example a vehicle in advance with respect to its schedule.

- Conditional, if the priority status is granted on the basis of certain criteria such as schedule adherence (i.e. priority required for the transit vehicle with a delay of 5 minutes respects its schedule), vehicle frequency, passenger waiting time at bus stop, bus occupancy or cross-street traffic conditions.

3.2.3 Adaptive priority

Adaptive Signal Control System gives priority to the transit vehicle using optimization-based control schemes, which means that it provides priority treatment for public transport and at the same time tries to minimize the negative effects on the other traffic. Considering the delay of public transport together with the delay of all the other vehicles, the control system calculates the optimal signal setting defining how to better distribute the green time between the approaches. This strategy doesn't apply specific priority actions, like the extension or the truncation of a phase, but changes continuously the duration of green according to the demand [53]. The implementation of the adaptive strategy requires the following components: 1) vehicle detection system to predict in real time its arrival time at the intersection; 2) communication links between vehicle, priority request system and signal controllers; 3) signal control algorithm that regulates the signals to provide priority, explicitly considering the impacts on the rest of the traffic and ensuring pedestrian safety.

Priority strategies for public transport can be combined with existing adaptive control systems, giving more weight to public transport vehicles in the optimization process.

4. OPTIMIZATION WITH BUS PRIORITY

4.1 SINTAC Software

SINTAC (Sincronizzazione del Traffico per l'ATAC) is a mathematical tool and computer software for analysis and design of signalized urban arteries, developed by Department of Hydraulics, Transportation and Roads of Sapienza University of Rome on behalf of ATAC Spa [54]. The model was subsequently extended to introduce the synchronization and optimization of traffic lights with priority to public transport [55]. In this work, the latest version of SINTAC 4.6.1 was used.

The software integrates the two traditional approaches of traffic signals synchronization: the creation of the so-called green wave and the delay minimization. An algorithm based on equivalent systems is used for the first optimization problem, while for the latter a hybrid resolution method has been adopted that applies in series a genetic algorithm and a hill climbing algorithm.

4.1.1 Bandwidth maximization problem

For the bandwidth maximization problem, the software adopts the model developed by Fusco and Papola (1998a) [56] which introduces the concept of ideal equivalent system to obtain the value of the maximum bandwidth of two real nodes. The approach of maximizing the green bandwidth for traffic signals synchronization, offers the advantage, from a mathematical point of view, of being a concave problem for which, resolutive methods are known to determine the optimal solution. Moreover, it provides an effective graphic representation of the solution, which allows an immediate visual interpretation of the goodness of the solution found.

4.1.1.1 Ideal synchronization

With reference to a given sequences of nodes with the following characteristics:

- all nodes are equally spaced: $l_{i,j} = A,\ \forall i \neq j,\ \ i = 1,2,\dots,n$
- all nodes have same cycle length and green time $g_i = g_j = b$;
  $C_i = C;\ \ \forall i,j$

it is possible to realize an *ideal synchronization* that is a practice to adjust the offset θ of the nodes to realize a progression of vehicles which travel at constant speed without to stop at intersections. Assuming that the speeds (called synchronization speed) are the same in both directions $v_1 = v_2 = v$ and considering two contiguous nodes, the interval between the green start in the two nodes is equal to the travel time between these:

$$t_{ij} = t_{ji} = \frac{A}{v} + \frac{A}{v} = C,\ \ C = \frac{2A}{v}$$

From this follows that the offset between two contiguous nodes is half cycle, that is:

$$\theta = 0{,}5C \quad (i = 1,2,\dots,n)$$

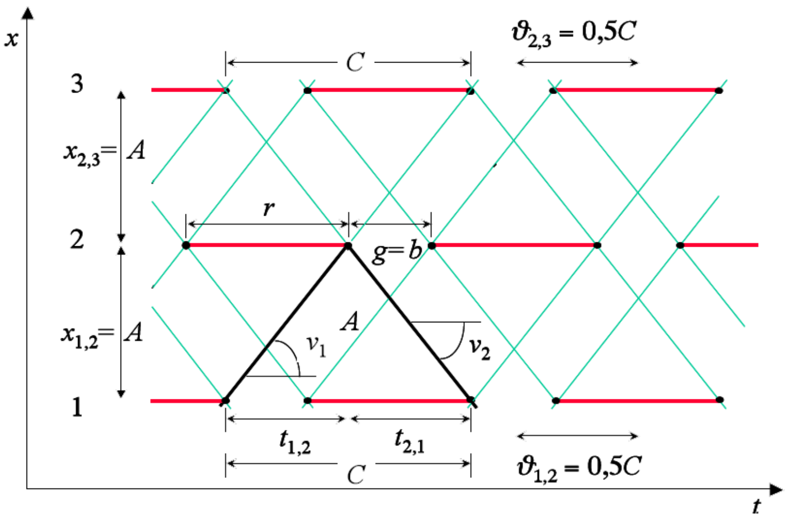


Figure 5 - Scheme of the ideal synchronization in the space-time plan

In the formulation of the problem it is necessary to introduce some constraints on the variables:

$$v_{min} \leq v \leq v_{max}$$

$$C_{min} \leq C \leq C_{max}$$

The lower and upper limits on the speeds respectively guarantee a minimum service level, below which the synchronization would not be more convenient and ensure safe driving conditions. Instead, the limits on the cycle length ensure compliance with the capacity conditions on the artery approaches (lower bound) and the need to limit the duration of the red time within values tolerable by users (upper bound).

An important property of the synchronization scheme is that of being periodic in time with period C and in space with period $2A$. It follows that, taken as a reference of the times half of the duration of the red of the first node, the nodes placed at distance equal to an odd multiple of A are in phase with the first node, while the nodes placed at a distance equal to an even multiple of A are in phase opposition:

$$\theta = 0 \quad if \quad \frac{x_i - x_0}{2A} = m, \quad m = 0,1,2, \dots$$

$$\theta = 0{,}5 \quad if \quad \frac{x_i - x_0}{2A} = \frac{2m+1}{2}, \quad m = 0,1,2, \dots$$

4.1.1.2 Formulation of maximal bandwidth problem

The green bandwidth is defined as the set of possible trajectories at constant speed, not interrupted along the entire artery. This concept can be applied in the case of nodes having a different duration of green and in the case of nodes placed at any distance between them. In the first case the bandwidth will be equal to the smaller green of the artery, while in the second case the bandwidth will be generally less than the green duration. The maximal bandwidth problem can be formulated as the search of the offset that maximize the sum of the bandwidths in the two directions taking into account the constraints on the cycle length, the speed and value of the variables. The mathematical formulation is:

$$max = (b + b')$$

Subject to:

$$b > 0, b' > 0$$

$$0 \leq \theta < C$$

$$v_{min} \leq v \leq v_{max}$$

$$max_i(C_{min,i}) \leq C \leq C_{max}$$

$$C_{min,i} = \frac{L_i}{(1 - max_h(y_{i,h}) - max_k(y_{i,k}))}$$

This is defined as Problem B, that is a quasi-concave problem and admits infinite optimal solutions.

Replacing the non-negativity constraint $b > 0, b' > 0$ with that of equality $b = b'$, the problem of maximum symmetrical bandwidth (Problem B1) is obtained. It is subject to:

$$b = b' > 0$$

$$\theta = 0 \; or \; C/2$$

$$v_{min} \leq v \leq v_{max}$$

$$max_i(C_{min,i}) \leq C \leq C_{max}$$

$$C_{min,i} = \frac{L_i}{(1 - max_h(y_{i,h}) - max_k(y_{i,k}))}$$

This last problem is strictly concave and therefore admits a unique solution. Furthermore, Problem B1 presents an analogy with the ideal synchronization, which, as will be seen, allows to express its any solution through an ideal equivalent system, consisting of a succession of infinite ideal nodes with green time equal to the bandwidth, placed at distance *A* from each other.

4.1.1.3 Synchronization of a pair of nodes

As shown in the previous paragraph, the synchronization of a pair of nodes with a maximum symmetrical band admits two possible solutions for the offset: $\theta = 0$ (in phase) or $\theta = 0{,}5$ (in phase opposition), having set *C = 1*. The choice between these two values depend on the distance between the two nodes. The following relationships are valid:

$$\theta = 0 \quad if \quad 0 \leq \frac{x_i - x_0}{2A} < 0{,}25 \;\; \cup \;\; 0{,}75 \leq \frac{x_i - x_0}{2A} < 2A$$

$$\theta = 0{,}5 \quad if \quad 0{,}25 \leq \frac{x_i - x_0}{2A} < 0{,}75$$

4.1.1.4 Equivalent system

It is possible to demonstrate that the value of the maximum bandwidth of a pair of real nodes i and j can be obtained by using the equivalence between the two given nodes and a pair of ideal nodes having the length of green time equal to the maximum bandwidth between the nodes i and j and the distance A equal to the ratio $vC/2$ (Figure 5).

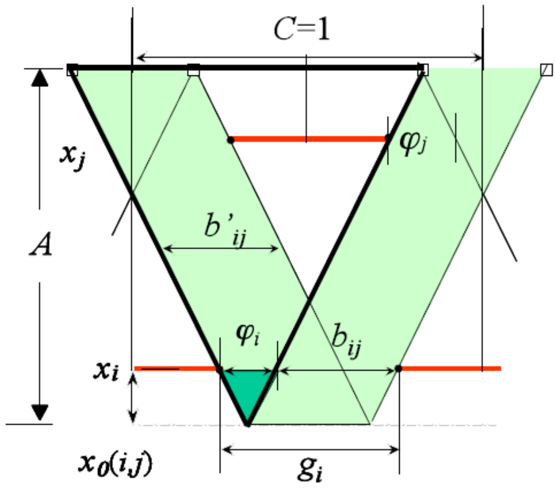


Figure 6 - Ideal synchronization scheme in space-time plan: in each node the green starts when the first platoon arrives and ends immediately after the passage of the last vehicle

It is possible to see that the two real nodes and the ideal nodes of the system obtained by extending the bands in the two directions produce the same solution, that is the same bandwidth. Therefore, they can be considered equivalent.

Considering the similarity between the two triangles highlighted in Figure 6: the green triangle with height $x_i - x_0$ and base φ_i and the other one with thickest line having height A and base C, the following relationships can be written:

$$x_i - x_0(i,j) = A\varphi_i$$

$$b_{ij} = b'_{ij} = g_i - \varphi_i$$

From the first equation it is possible to obtain the abscissa of the ideal node x_0, given the module $A = vC/2$, the abscissa x_i and the bandwidth b_{ij}. This relationship allows to determine the ideal equivalent system to the first pair of nodes.

Synchronization of two nodes

1) CASE: $x_i - x_0 \leq \frac{A}{2}$; $\theta = 0$

In the case the two nodes have distance less than $\frac{1}{2}A$, the offset is chosen equal to 0 and the nodes are in phase. Respect to the ideal system one node will be under the ideal node and the other one will be above the ideal node, as illustrated in Figure 7.

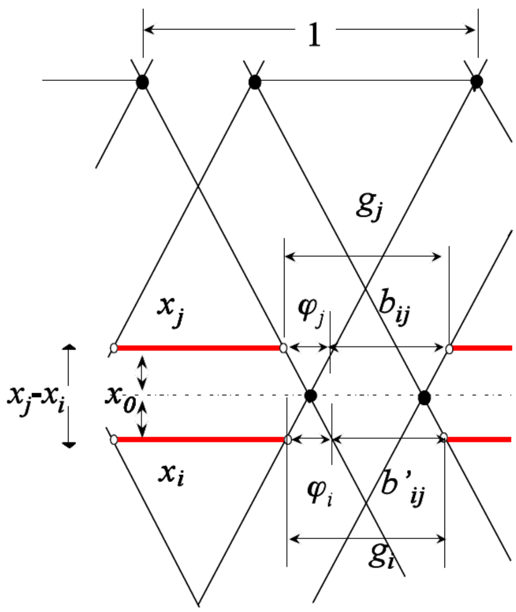


Figure 7 - Synchronization of two nodes at a distance less than A/2

Applying the previous relations to node i is obtained for the triangle with base φ_i:

$$x_0 - x_i = A\varphi_i$$

$$b'_{ij} = g_i - \varphi_i$$

Explaining the first equation with respect to φ_i and replacing it in the second one, the following expression of the bandwidth is extracted:

$$b'_{ij} = g_i - \frac{x_0 - x_i}{A}$$

Adopting the same procedure for the node j it obtains, as objective function, sum of two bands, the following relationship:

$$f = b_{ij} + b'_{ij} = g_i + g_j - \frac{x_j - x_i}{A}$$

The maximum bandwidth of two nodes, having a distance less than A/2 and $\theta = 0$, is equal to the following equation:

$$b_{ij} = b'_{ij} = \frac{1}{2}\left(g_i + g_j - \frac{x_j - x_i}{A}\right) \qquad if\ \theta = 0$$

2) *CASE:* $x_i - x_0 > \frac{A}{2}$; $\theta = 0{,}5$

In the case the two nodes have distance greater than $\frac{1}{2}A$, the offset is chosen equal to 0,5 and the nodes are in opposite phase. The ideal nodes are not placed between the real nodes, but one ideal node is above the node j and the other one is under node i (Figure 8).

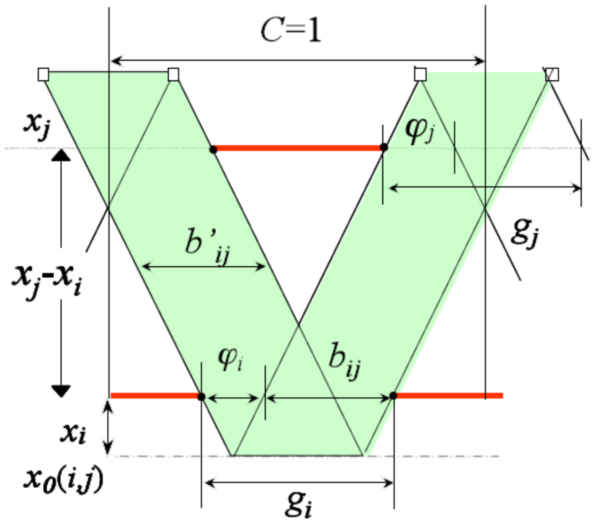


Figure 8 - Synchronization of two nodes at a distance greater than A/2

For the node *i*, above the ideal node, the following relations are considered:

$$x_i - x_0 = A\varphi_i$$

$$b_{ij} = b'_{ij} = g_i - \varphi_i$$

from which:

$$b_{ij} = g_i - \frac{x_i - x_0}{A}$$

The node j is placed respect the ideal node of a value equal x0 + A. For this reason applying the law corresponding to the similarity of the triangles, it obtains:

$$x_0 + A - j = A\varphi_i$$

$$b'_{ij} = g_j - \varphi_j$$

$$b'_{ij} = g_j - 1 + \frac{x_j - x_0}{A}$$

The objective function is given by:

$$f = b_{ij} + b'_{ij} = g_i + g_j - 1 + \frac{x_j - x_i}{A}$$

and the maximum bandwidth of two nodes, having a distance greater than A/2 and $\theta = 0{,}5$ is equal to:

$$b_{ij} = b'_{ij} = \frac{1}{2}\left(g_i + g_j - 1 + \frac{x_j - x_i}{A}\right) \qquad if\ \theta = 0{,}5$$

Identification of the ideal equivalent system to a pair of nodes

As explained above, if the nodes have a distance less than A/2, the ideal node is between the two real nodes, while if the distance is more than A/2, the ideal nodes are one under the node i and one above the node j, so it is possible choosing indiscriminately one of the two ideal nodes. According to these assumptions, the abscissa of the ideal node can be determined by:

$$x_0 = x_i + (g_i - b'_{ij})A \qquad if\ \ \frac{x_j - x_i}{A} \leq 0{,}5$$

$$x_0 = x_i - (g_i - b'_{ij})A \qquad if\ \ \frac{x_j - x_i}{A} > 0{,}5$$

If the two nodes are at distance $d > A$, since the system is periodical and symmetric, it is possible to return in the interval [0,A) by making the following substitution:

$$\frac{x_j - x_i}{A} \quad \rightarrow \quad man\left[\frac{x_j - x_i}{A}\right]$$

The *mantissa* operator gives only the decimal part of a real number and ensure to remain in the interval [0,1).

4.1.1.5 Synchronization of urban artery

If a third node r must be coordinated with the first pair of nodes, it is sufficient to coordinate it with the ideal equivalent system associated to them (Figure 9). In this case the nodes to be synchronized are only two: the ideal node and the third node, so the expressions previously defined for a pair of nodes can also be used in this situation. The ideal system, therefore, is a useful tool to solve the problem because it avoids to consider all the possible combination between the nodes. The width of the maximum band after the synchronization of the third node r of the artery is:

$$b_{ij;r} = b'_{ij;r} = \frac{1}{2}\left(g_r + b_{ij} - man\left[\frac{x_r - x_0(i,j)}{A}\right]\right) \quad if \;\; 0 \leq man\left[\frac{x_r - x_0(i,j)}{A}\right] < 0,5$$

$$b_{ij;r} = b'_{ij;r} = \frac{1}{2}\left(g_r + b_{ij} - 1 + man\left[\frac{x_r - x_0(i,j)}{A}\right]\right) \quad if \;\; 0,5 \leq man\left[\frac{x_r - x_0(i,j)}{A}\right] < 1$$

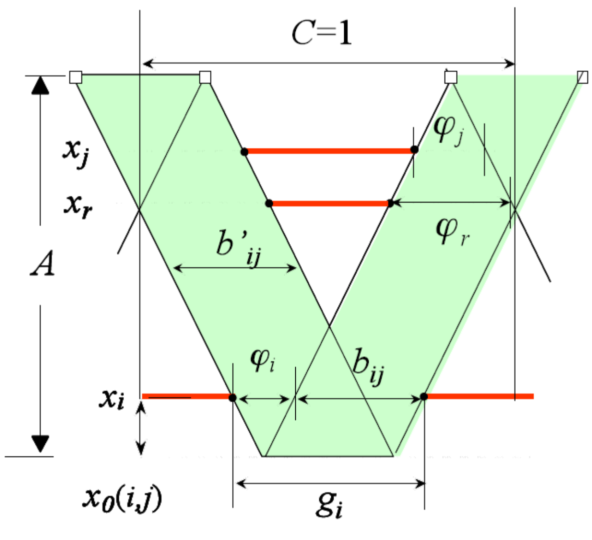


Figure 9 – Synchronization of a third node r with the pair of nodes i and j

In the first case the node r will be placed in phase with the ideal node, while in the second it will be in phase opposition. The synchronization of the node r reduces the width of the band, producing an ideal grid displacement, as shown in Figure 10.

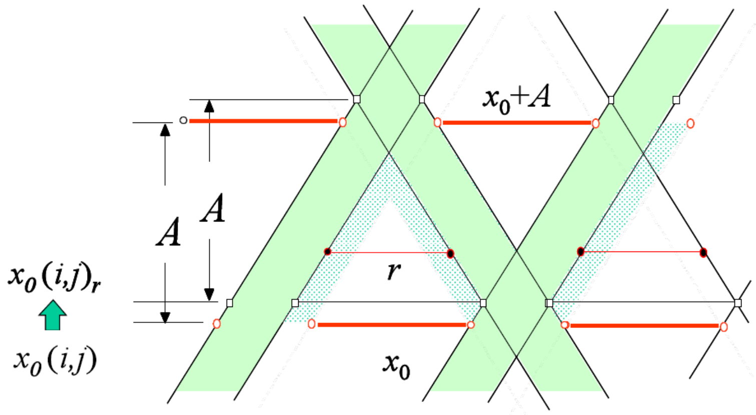


Figure 10 - Reduction of bandwidth and translation of the ideal system after the synchronization of a third node r with the pair of nodes i and j

In general each node is put in phase with the ideal node near and its synchronization, decreasing the band, leads to a reduction of the distance with the ideal node. After to determinate the position of the new equivalent ideal system it is possible to coordinate a fourth node with this new ideal system and so on until the last node of the artery.

The procedure of resolution of synchronization of the urban artery requests the following several steps:

- coordination of a first pair of nodes $S_i(x_i, g_i)$ and $S_j(x_j, g_j)$;
- identification the ideal system $S_0(S_i, S_j)$, equivalent to the first pair of nodes;
- coordination of the third node $S_r(x_r, g_r)$ in the ideal system;
- identification of the new ideal equivalent system to the succession of the coordinate nodes;
- extension of the procedure to the all nodes.

The solution depends on the order of the node synchronization and the optimal solution must be found considering all $\binom{n}{2}$ possible combinations of first two nodes and the (n - 2)! permutations of the followings.

Note that the solution obtained from the maximal bandwidth problem can be effectively used as an initial search point for the solution of minimum delay problem.

4.1.2 Minimum delay problem

In the previous chapter the model of signal synchronization, according to the criterion of maximizing the band, has been illustrated. In the following section, the algorithm used by the software for solving the problem of minimum delay will be presented.

4.1.3 Platoon simulation model

4.1.3.1 The analytical model

To solve the problem of minimum delay, the software applies a mixed genetic-hill algorithm that performs an artery simulation in each phase of the search procedure. The simulation model adopted is a generalization of the model developed by Fusco and Papola (2000) [57].

The delay at nodes is defines as the excess travel time relative to travel at the synchronization constant speed. This model provides the delay of a generic platoon based on the arrival time and length of the platoon and also on the start time and duration of the red light. In particular, platoons can be classified into three types:

- Type A *(totally delayed or front-delayed platoon):* Platoon p arrives at node *i* during the time interval necessary to clear the queue (if any) at the end of red time (Figure 11). In this case, all platoon vehicles are delayed by the same amount and the total delay is given by:

$$D_{i,p} = q(v_s)l_{i,p}\left[\vartheta_i + \frac{r_i}{2} + \tau_i - t_{i,p}\right]$$

$$\vartheta_i - \frac{r_i}{2} + \tau_i \leq t_{i,p} < \vartheta_i + \frac{r_i}{2} + \tau_i$$

where:

- ϑ_i is the offset of node i, defined as the difference between the instants of half red time of node *i* and node 1;
- r_i is the effective red time of node *i;*
- τ_i is the time needed to clear the queue at the end of red at node *i*: it is given by the total number of vehicles delayed at node *i*, before the platoon *p* arrives, divided by *q*(*vs*);
- $q(v_s)$ is the traffic flow at the cruise speed along the artery;
- $t_{i,p}$ and $l_{i,p}$ are, respectively, the arrival time and the time length of platoon *p* at node *i;*
- $D_{i,p}$ is the total delay of the vehicles of platoon *p* stopped at node *i*.

The term in square brackets represents the average delay per vehicle.

- Type B (*partially delayed or hind-delayed platoons)*: Platoon *p* arrives at node *i* after the queue (if any) at the end of red time has been cleared and ends after the start of red time, so that the rear of the platoon is delayed (Figure 12):

$$D_{i,p} = q(v_s)l_{i,p}\left[\vartheta_i + \frac{r_i}{2} + \tau_i - t_{i,p}\right]$$

$$\vartheta_i + \frac{r_i}{2} + \tau_i \leq t_{i,p} < \vartheta_i + C - \frac{r_i}{2}$$

- Type C (*no-delayed platoons):* Platoon p arrives at node i after the queue (if any) at the end of red time has been cleared and ends before the start of red time, so that it is not delayed:

$$D_{i,p} = 0$$

$$\vartheta_i + \frac{r_i}{2} + \tau_i \leq t_{i,p} < \vartheta_i + C - \frac{r_i}{2} - l$$

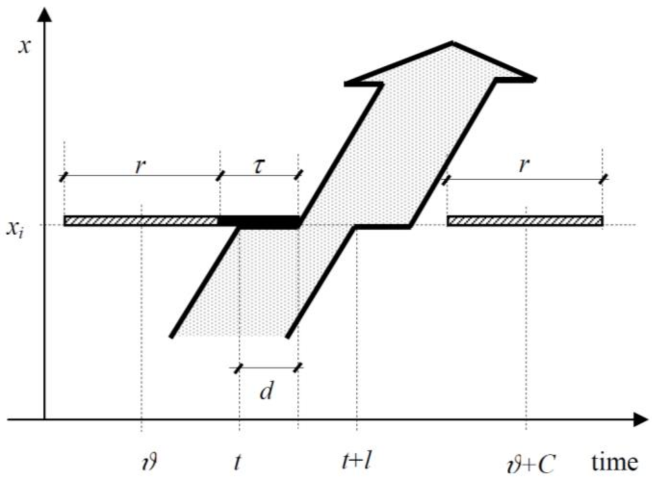


Figure 11 - Example of platoon of type A

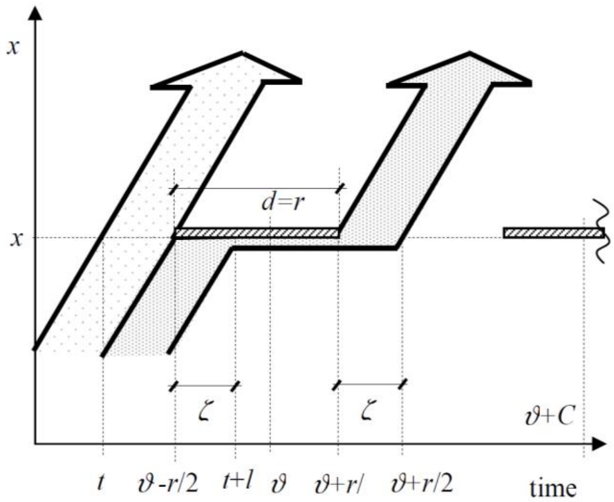


Figure 12 - Example of platoon of type B

4.1.3.2 The algorithm of progression and classification of platoons

To compute the delay at nodes, the algorithm logic follows a cascaded procedure (Figure 13): at the beginning the departure time and the length of each platoon at node *i* are calculated, then the link module computes the arrival times and the time length of each platoon at the downstream node *i+1*. Subsequently the algorithm performs the platoon classification at node *i+1*, necessary to determine the average delay and the number of stopped vehicles. At the node the platoons can recombine through a mechanism exemplified in Figure 14, where two platoons, A-type and B-type, arrive at the node *i* and a third platoon of vehicles entering the artery from side streets starts at the beginning of the effective red time for the artery (i.e., at the beginning of the effective green time for side streets). Since A-type platoon (denoted as 1 in the figure) is split into 2 sub-platoons (1′ and 1″ in the figure) and platoon 2 arrives before the queue has been cleared, it joins platoon 1″. Departures at the node are then composed by platoon 1′, whose starting time coincides with its arrival time; by platoon 2, which starts at the end of the effective red time, and by platoon 3, entering the artery from side streets. The link module computes the arrival times and the time length of platoons at downstream intersection. The arrival time is determined by applying either the synchronization speed or an acceleration rate and verifying if following platoons can catch up the preceding one. The time length is computed by subtracting the vehicles that leave the artery at the upstream node and assuming that all vehicles belonging to the platoon can accelerate, compressing then the platoon. Platoon progression and recombination along the links is illustrated by the example in Figure 15.

The first vehicle of platoon 1 travels at the synchronization speed v_s. Dashed line represents the trajectory of the last vehicle if no vehicle of the platoon had left the artery or if, in any case, it had traveled at the synchronization speed; however, due to exiting vehicles, all vehicles within the platoon can travel at a higher speed, as indicated for the last one, whose speed is indicated as v''. All vehicles of the entering platoon (numbered as 2 in the figure) travel at a speed $v'>v_s$ and may catch up the preceding platoon, depending on the link length and the value of v'', as it occurs in the case of platoon 2. However, platoon 3 starts at the end of effective red time, travels at speed v' and the leading vehicle cannot catch up the tail of platoon 2. Successive vehicles within the platoon can accelerate to fill the empty spaces left by exiting vehicles and such a condition is applied to compute the time length of the platoon at node i+1.

The node delay model computes delays at every approach of the artery by checking, for each arriving platoon, which condition occurs among the A), B), C) cases introduced in the previous section. Since the existence and the length of a queue cannot be determined before all platoons have been analyzed, the delay computation requires an iterative procedure that classifies the different platoons progressively. It is worth noting that such a procedure involves few iterations, because the platoons can both catch up each other along the links and recompose themselves at nodes, when more platoons arrive during the red phase.

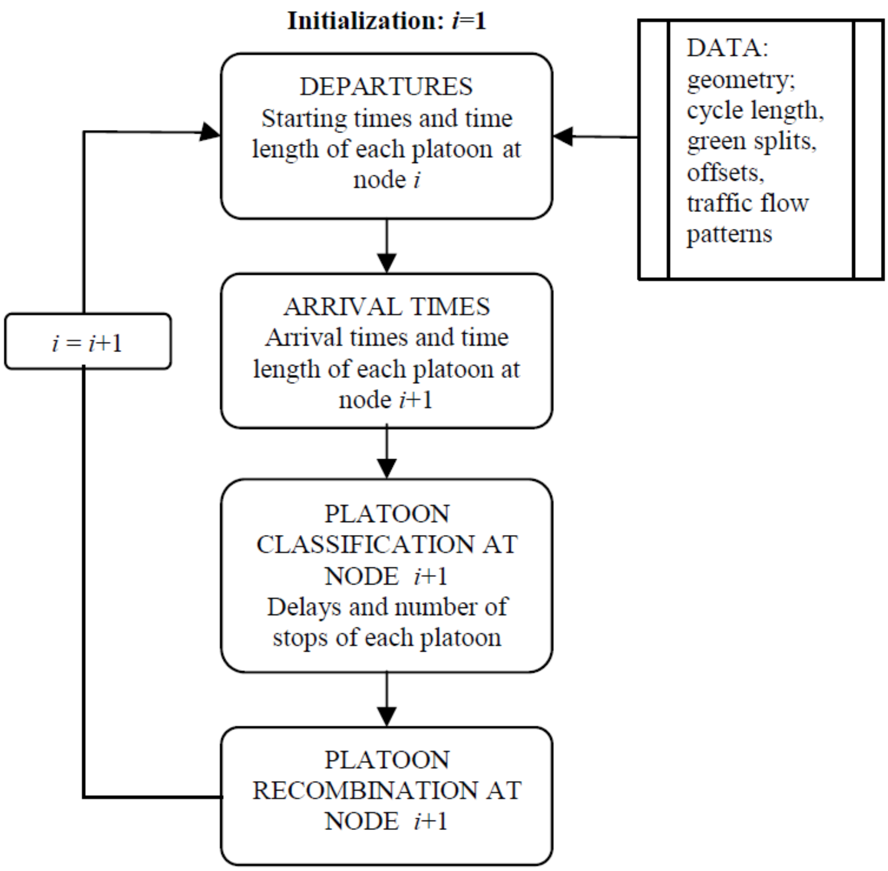


Figure 13 - Flow chart of the algorithm

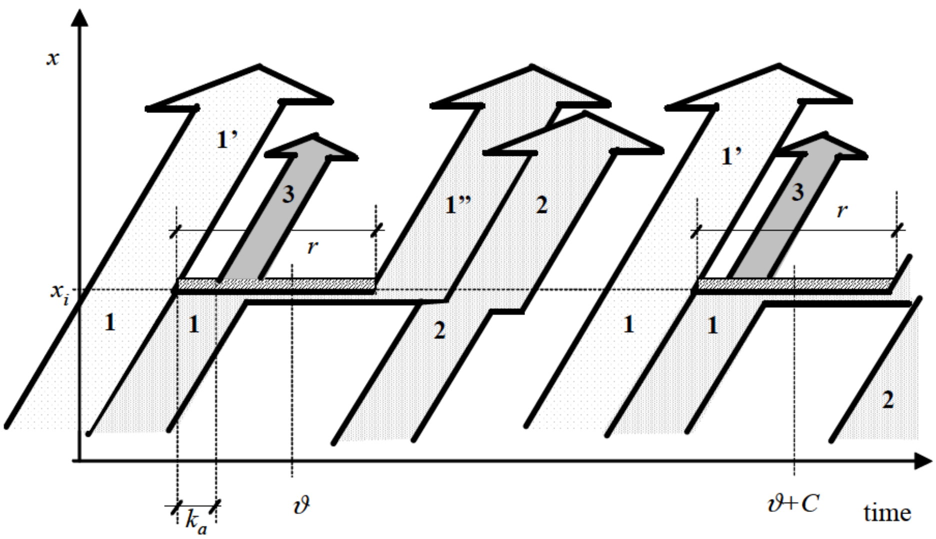


Figure 14 - Example of platoon recombination at node i

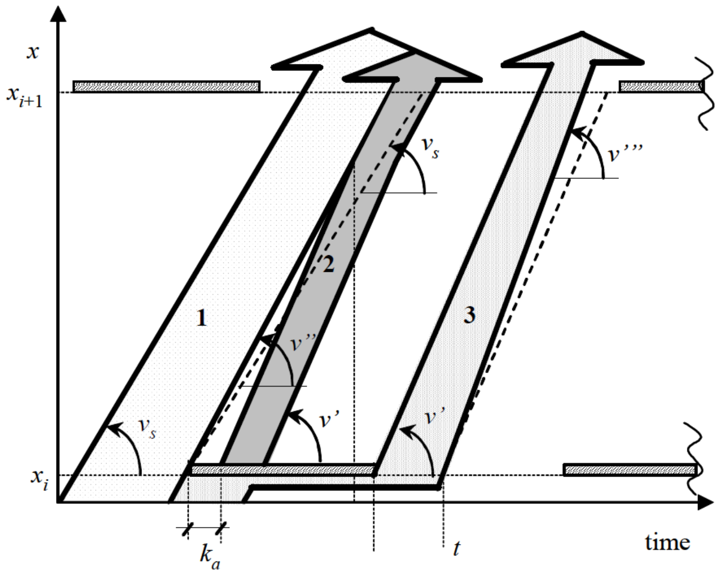


Figure 15 - Example of platoon progression and recombination along a link

4.1.4 Extension of the platoon simulation model

The analytical model described above considers the progression of platoons along a synchronized artery in steady-state traffic. In order to generalize this model in SINTAC these two simplification hypotheses have been removed, going also to consider the case of unsynchronized artery and over-saturation condition [54].

4.1.4.1 Traffic model in stationary traffic conditions and synchronized regulation

Under steady-state traffic conditions, in each cycle the queue is disposed within the green time and for a synchronized artery with a common cycle, the conditions occurred in the previous cycle are repeated in each cycle. In this case it is possible to obtain an analytical formulation of the delays on the entire artery referred to a single cycle, obtained by classifying each incoming platoon according to the overlap with the green time and with the arrival of the other platoons.

4.1.4.2 Stationary traffic conditions and non-synchronized traffic light regulation

In the case of a non-synchronized artery the model is able to treat also the conditions "without project", but the previous advantage of periodicity is lost. So it is no possible to estimate the delay by referring to a single traffic light cycle, but it is essential to refer to a simulation of several cycles, since in general the same conditions do not repeat with a specific period. However, the same formulas for the classification of the platoons used previously, are applied. The calculation procedure is simplified, since it is not necessary to perform an iterative search of the platoons of type A which repeats the classification of the platoons after having updated the duration of disposal of the queue after the arrival of a first platoon of type A, but the procedure is longer, as the classification is repeated for each platoon sequentially throughout the simulation interval.

4.1.4.3 Over-saturation conditions

In the case of an artery under over-saturation conditions, the traffic is naturally non-stationary and, in the general case, it is possible that the capacity conditions are not met in one or more nodes. Regardless if the artery is synchronized or not, it is necessary to simulate the progression of the platoons along the artery and, moreover, it is necessary to verify the respect of the condition of capacity. In the case that these are violated, at least one platoon is disposed of in the subsequent cycle. Since the flow is any, also the following cycle may not be sufficient: the time of disposal of the platoon τ can be even greater than the cycle. The platoon is then classified as type A and the delay is increased by the number of over-saturation cycles. The following platoons are classified considering the value of τ calculated in this way. In addition to the capacity condition with respect to the flow, it is necessary to check the capacity conditions of the arc (or capacity of the number of vehicles in the queue). The propagation of the queue beyond the arc (spillback of the queue) modifies the functioning mechanism of the nodes, in that it commands the free way of the platoons to a node reached by the spillback from the traffic light of the node that generated the spillback.

The instants of free way and of way impeded to a node reached by the spillback are therefore identified by the instants in which the kinematic waves from the downstream node respectively at the beginning and at the end of the green reach the upstream node. In steady-state traffic conditions the simulation has a fixed duration and it is guaranteed that all the flow traveling through the artery during that time interval is served, in case of over-saturation, the simulation may require a longer duration to estimate the time of all the platoons arrived in the established period. The same condition applies to platoons entering the transversal approaches. In this case, since there is no platoon progression, a uniform inlet flow is assumed and the delay can be calculated by generalizing the known expression of uniform arrivals in case of over-saturation.

$$W = W_1 + W_2 = Q_0 r + Q_0 g + q\frac{r^2}{2} + qrg + q\frac{g^2}{2} - s\frac{g^2}{2} = Q_0 C + \frac{1}{2}qC^2 - \frac{1}{2}sg^2$$

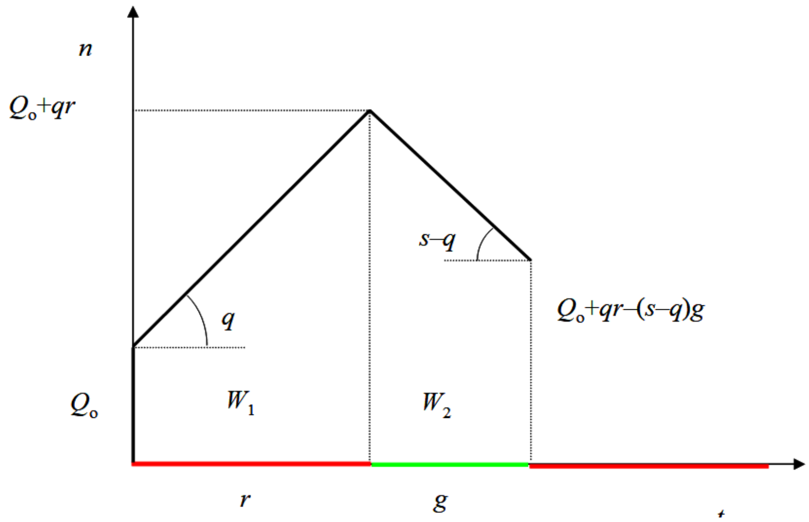


Figure 16 - Graphic interpretation of delay to a transversal approach in over-saturation condition

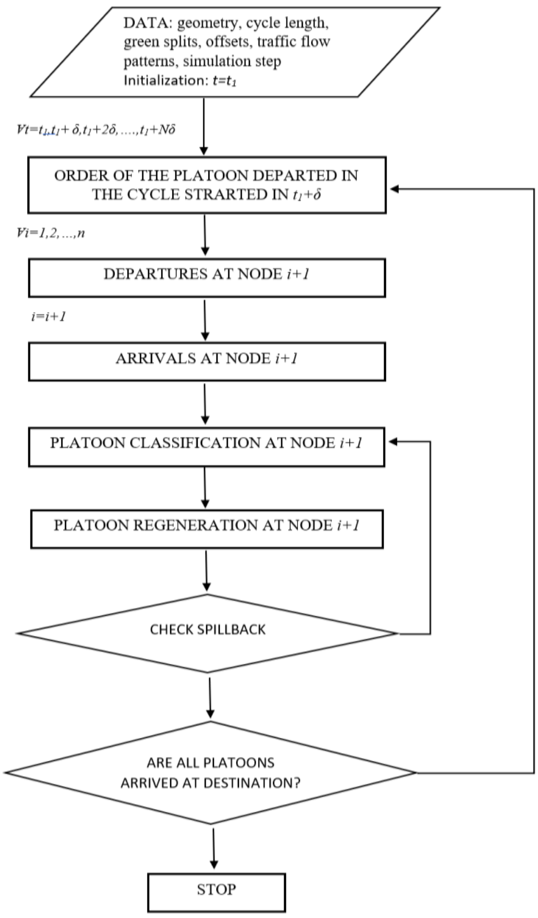


Figure 17 - Platoons simulation model in condition of over-saturation

4.1.5 Bus priority simulation model

The model described in the previous sections simulates the progression of car traffic as platoons, while for the simulation of public transport the bus movements and bus stops are modelled individually [57].

Given the transit data as routes, stops, number of passengers, timetable, the model computes bus departure time, bus arrival times at stops and predicts arrival times at the next node independently from traffic model, as buses are assumed running on reserved lanes and the interactions with car traffic occur only at nodes. Then the priority action of controller is simulated. To do it, the following priority acknowledgement rules are evaluated:

- FIFO rule: priority is assigned to the first bus request it;
- Number of passengers on board: priority is assigned to the bus with the highest number of passengers;
- Schedule adherence: priority is assigned to the bus with highest delay with respect to its schedule.

After selecting the priority rule, the priority action module chooses the most suitable action between the green extension, the green anticipation or no priority, depending on the predicted arrival time of the bus at the node. In particular, if the start time of the priority request and the corresponding end time (i.e. when the bus has crossed the intersection) is into the green phase, then it is not necessary to implement any priority action. Instead if the beginning of the priority is in the green phase and the end in the red phase, it is necessary to extend the duration of the green to allow the bus to complete the maneuver to cross the intersection. Finally, if the time interval for the priority occurs during the red time, it is then necessary to end this phase or to anticipate the green time.

Then the model, in this phase, computes bus delay at node *i+1* and alters the timing of the signal. The related information is sent to the platoon classification module, in order to update the platoon classification module. Figure 18 depicts the flow chart of the whole process for bus priority acknowledgment rule and simulation.

The movement of the buses along the artery is simulated based on the following hypotheses [54]:

- Buses are generated at the entry node into the artery depending on the frequency of the line, assuming a random distribution of the arrival moment with respect to the mean value and an initial offset with respect to the beginning of the simulation;
- Buses departing in the same cycle are advanced along the downstream arch as a single platoon;
- The law of the platoon's motion, similar to that of the cars, is assimilated to a uniform motion, which also includes the acceleration and deceleration phase;
- Time to stop at the bus stop (depending on the number of passengers boarding and alighting) and the delay at traffic light (including start and time lost) are added to the travel time defined by the law of motion;
- The number of passengers originating or destined for each stop is extracted from a normal distribution with mean and standard deviation defined by the user;
- The number of passengers boarded by each transit vehicle takes into account the number of passengers waiting and the number of seats available on the vehicle;

- The possibility of a vehicle of stopping at the platform and opening the doors depends on the length of the vehicle possibly already in the queue, the length of the platform and the length of the vehicle in question;
- The possibility of a vehicle not to stop at a bus stop or to overcome one or more fixed vehicles depends on the geometric configuration of the road and can be established by the user;
- The expectation of a public transport vehicle for a semi-formalized approach depends on the priority rules established for the intersection in question and on the previous sequence of bus arrivals, which may affect the application in the cycle in question.

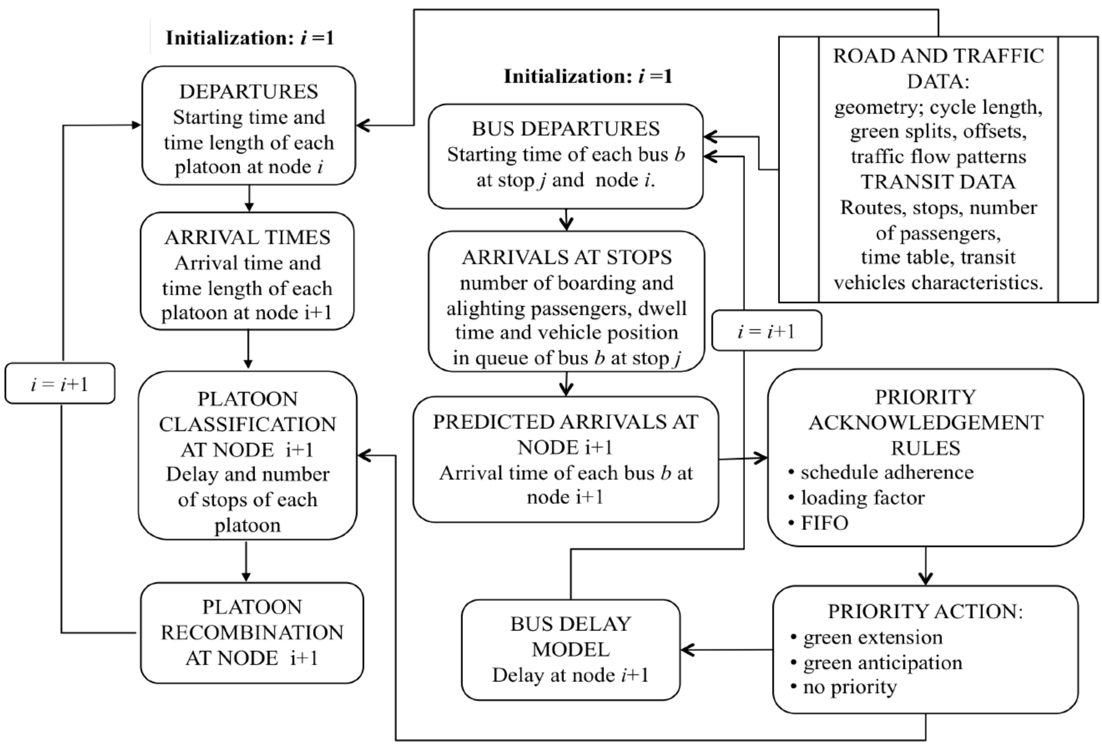


Figure 18 - Traffic and bus priority simulation model

4.1.6 Optimization algorithm

The problem of minimizing the delay function is non-convex and must therefore be solved using meta-heuristic algorithms. In this model an algorithm has been adopted that combines a research of the global optimum through a genetic algorithm and a local adjustment procedure around the tentative solution point.

4.1.6.1 Objective function

Typically, the traffic lights are designed to minimize the total delay of all vehicles at an intersection. However, minimizing vehicle delay may not be optimal when considering the passenger load of transit vehicles. For this reason, considering the total delay per person instead of the total delay per vehicle is more appropriate. Taking into account this assumption, the objective function (or fitness function), to be optimized, is defined as a linear combination of the total delays of the artery, considering the person delay of both private and public traffic:

$$f = \left(1 - w_p\right)\left[(1 - w_t)\sum_{i=1}^{n} w_i D_i^{(1)} + w_1\,(1 - w_1)\sum_{i=1}^{n} w_i D_i^{(2)} + w_t \sum_{i=1}^{n} w_i D_{h_i}^{(t)}\right] + w_p\left[w_1 \sum_{b=1}^{B}\sum_{i=1}^{n} w_i D_{b_i}^{(p_1)} + (1 - w_1)\sum_{b=1}^{B}\sum_{i=1}^{n} w_i D_{b_i}^{(2)}\right]$$

where:

- $D_i^{(1)}$ total car passenger delay at node i in direction 1
- $D_i^{(2)}$ total car passenger delay at node i in direction 2
- $D_i^{(t)}$ total car passenger delay at node i of queue h in lateral approach t
- $D_b^{(p)}$ total delay of passengers in bus b
- w_1 weight of delay in direction 1

- w_t weight of delay at lateral approach t
- w_i weight of delay at junction i
- w_b weight of delay for transit passengers

4.1.6.2 Genetic algorithm

The first step of the algorithm is to generate the initial population of candidate solutions, each of them is characterized by a specific genetic coding (genoma) whose elements are the cycle length, the green split in each of the 2 directions and the offset of each signal. Each solution is represented by:

$$\left\{C_1, \dots, C_{n,} g_1^{(1)}, \dots, g_n^{(1)}, g_1^{(2)}, \dots, g_n^{(2)}, \theta_1, \dots, \theta_n\right\}$$

where:

- C_i is the cycle of node i
- g_i is the green slip of node i in direction d
- θ_i is the offset of node i

The quality of the initial population affects the algorithm convergence significantly and the criteria for generating it are partly random and partly follow some good engineering design criteria. More specifically, the special designed solutions considered are:

- the actual signal settings;
- a maximal green bandwidth solution corresponding to the maximal of the actual cycle lengths of the artery and the actual green splits;
- a good practice solution obtained by applying the following simple rules, that are:
  - cycle length equal either to the minimum cycle or the optimum value for isolated junctions following Webster's assumptions on probabilistic arrivals:

$$C = max\{C_{Web,i}\} \quad or \quad C = max\{C_{min,i}\}$$

where:

$$C_{Web,i} = \frac{1{,}5\, L_i + 5}{1 - \sum_h^m (1 - y^*_{h,i})} \quad or \quad C_{min,i} = \frac{L_i}{1 - \sum_h^m (1 - y^*_{h,i})}$$

- green splits according to the either equisaturation criterion or a priority criterion that assigns all the available green to the artery:

$$\lambda_{k,i} = \frac{y^*_{h,i}}{\sum_h^m y^*_{h,i}} \quad \text{or} \quad \lambda_{h,i} = y^*_{h,i}\,,\ \lambda_{k,i} = 1 - \sum_h^m \lambda_{h,i}$$

where:

- $y^*_{h,i}$ saturation degree at node i for the critical lane group of stage h
- $\lambda_{h,i}$ green split for the critical lane group of stage h
- L_i lost time at node i

- offset set according to the maximum bandwidth criterion.

In the successive step a second-generation population of solutions is generated from those selected through a combination of genetic operators: crossover (also called recombination), and mutation.

The aim of crossover is to generate a couple of children for each couple of parents, choosing randomly (0.5 probability) which child receives each of the chromosomes of the first parent and assigning each chromosome of the second parent consequently. The probability of each individual to be selected d for the reproduction is proportional to their fitness value. Better individuals have so a higher probability to transmit their genetic inheritance. Moreover, in order to improve the algorithm flexibility, the crossover operator is applied only to a given rate of the whole population called crossover rate.

The mutation consists in the random modification of one or more genes of each individual of the population. These modifications are used to expand the search space for solutions even in areas far from the points where the population is concentrated. To avoid a deadlock into a local minimum, the frequency with which a mutation must take place is regulated by a specific probability, which varies between a minimum value (p_{minmut}) and a maximum value (p_{maxmut}) and proportional to the number of stall iterations (when the best physical form is not updated).

During the creation phase of a new population, the genetic algorithm transfers to the next generation the genome of the best solution found up to that moment (cloning). In particular, in the model this process was extended by cloning the whole set of the best solutions found up to that moment.

4.1.6.3 Hill-Climbing algorithm

The hill-climbing algorithm performs a local refining procedure near the solution point previously identified by the genetic algorithm. The algorithm attempts to increase first and then decrease the project variables and if improvements are recorded for at least one of them, it is performed again for all the sizes otherwise, the algorithm ends.

4.2 Software architecture

The software was created with two development environments:

- Microsoft Visual Studio 2005
- MATLAB 7.5 R2007b

The interface for data inputting is structured in tabs, in compliance with the latest specifications released by Microsoft.

A diagram of the division in modules of the software is represented by the following figure:

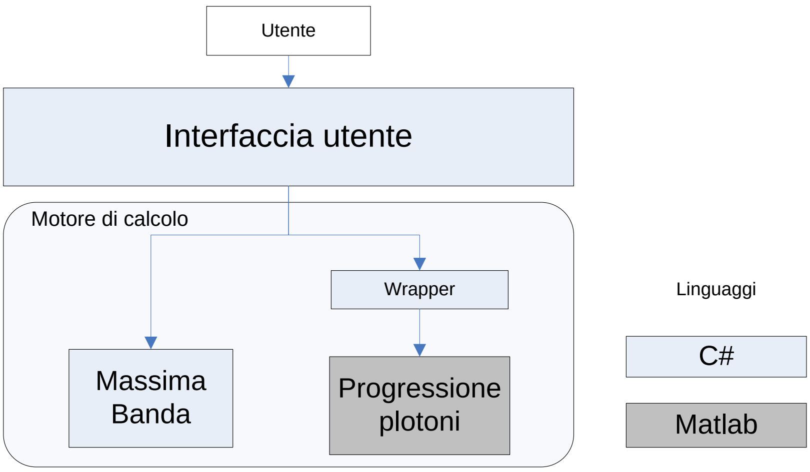


Figure 19 - Diagram of the modular software division

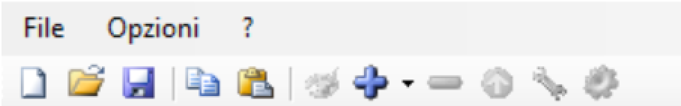
4.2.1 Menu

The main menus are two:

- *File*: Allows creation, opening and saving of projects;
- *Options*: Allows you to set default options.

All other features are accessible through the toolbar at the top of the application window.

The features are:



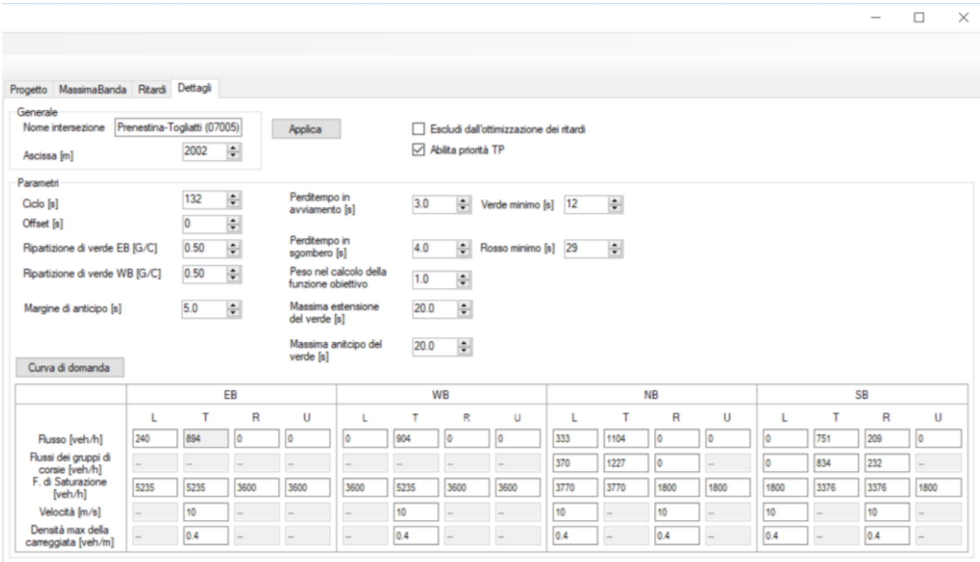
- Creation of a new project
- Opening a saved project
- Saving the current project
- Copy intersection
- Paste intersection
- Plot of the solution
- Import of the solution
- Adding a new intersection
- Cancellation of a new intersection
- Display of default options

From the main screen the following tabs are accessible:

- *Project*: where it is possible to insert some general parameters of the basic project like the name or the artery orientation (NB-SB or EB-WB);
- *Details*: with which it is possible to view the configuration parameters of the intersection;
- *Delays*: which allows calculation of the current configuration delay and the traffic light optimization according to the minimum delay criterion;
- *Maximum Bandwidth*: which allows the calculation of the maximum bandwidth of the current state and the traffic light optimization according to the maximum bandwidth criterion.

4.2.2 Details tab

Selecting an intersection, in the tab called *Details* it is possible to insert the input data related to the traffic and the traffic light of that specific intersection, necessary for the calculation of the delay.



The parameters of traffic light are:

- *Cycle* of intersection (in seconds);
- *Offset* (in seconds) referred to the crossing maneuver of the artery in direction east or north (according to the EB or NB orientation);
- *Green ratio* of both directions (two decimal places are possible);
- *Start-up lost time* (in seconds): is the time lost at the beginning of the green for the flows, directed along the artery, that must start moving from a standstill;
- *Clearance lost time* (in seconds): is the yellow time at the end of green and represents the time necessary to clear the intersection by the last vehicle that transits in the green, before to pass to the next phase in conflict with the previous one;

- *Minimum red/green time* (in seconds): represent the design constraints of the intersection that is taken into account during the optimization phase;
- *Margin of anticipation* (in seconds): in case of priority, represents the duration of green before the arrival of the vehicles with priority;
- *Maximum green extension* (in seconds): maximum possible extension of the green to give priority to public transport;
- *Maximum green anticipation* (in seconds): maximum possible anticipation of the green to give priority to public transport.

The input of traffic data has been set to allow the user to follow the usual practice, provided by the most popular software, such as Synchro and the High Capacity Capacity Manual (2000).

In particular, the maneuvers are organized by direction in the cardinal points:

- EB: eastbound approach
- WB: westbound approach
- NB: northbound approach
- SB: southbound approach

For each approach are then reported the different maneuvers:

- L: turn left
- T: through
- R: turn right
- U: U-turn

	EB				WB				NB				SB			
	L	T	R	U	L	T	R	U	L	T	R	U	L	T	R	U
Flusso [veh/h]	0	986	91	0	149	1289	0	31	0	0	0	0	63	169	50	0
Flussi dei gruppi di corsie [veh/h]	--	--	--	--	--	--	--	--	0	0	0	--	69	188	56	--
F. di Saturazione [veh/h]	3600	5060	5060	3600	5094	5094	3600	5094	1800	1800	1800	1800	2466	2466	2466	1800
Velocità [m/s]	--	13	--	--	--	13	--	--	13	--	13	--	13	--	13	--
Densità max della carreggiata [veh/m]	--	0.4	--	--	--	0.4	--	--	0.4	--	0.4	--	0.4	--	0.4	--

The following input parameters are entered in the table of flow data:

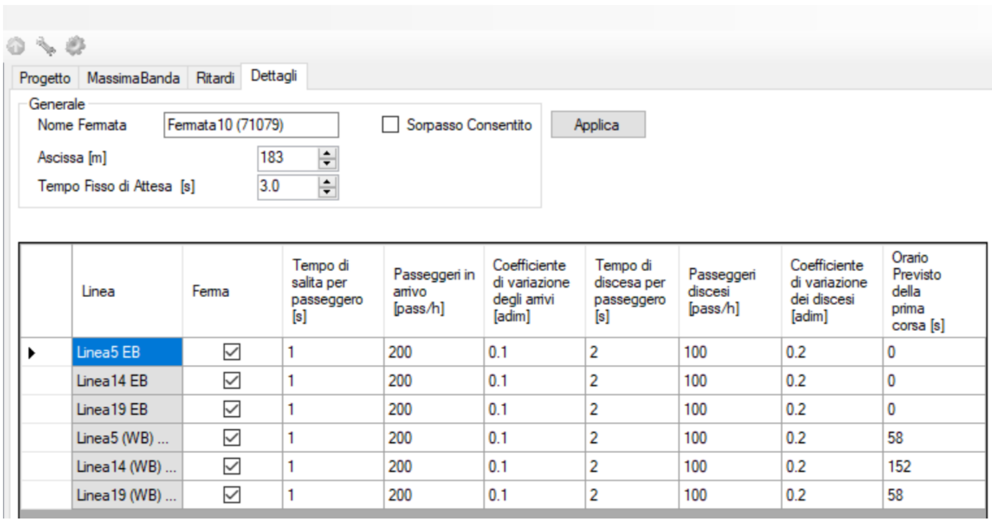
- *Flow for each maneuver (veh/h):* this value is used by the program to determine the incoming, outgoing and crossing flows of the artery from the transversal roads and the flow at the first approach in the incoming direction. The value of crossing flow of intermediate intersections are not necessary because they are determined by the simulation program;
- *Flow of lane group (veh/h):* this value represents the number of equivalent vehicles in each lane group and is used by the program to determine the disposal time of each platoon. The determination of lane groups and the calculation of equivalent vehicles can be carried out using the methods provided for in the traffic engineering manuals, for example the Highway Capacity Manual (2000);
- *Saturation flow (veh/h):* the value of the saturation flow must refer to each of the lane groups in fact, the saturation flow is the inverse of the service time of the queue. The calculation of the saturation flow can be made, starting from an ideal value, multiplying by the adjustment coefficients that take into account the different possible disturbance factors (for example, the HCM (2000) provides worksheets for the computation of adjustment factor for the width of lanes, the share of heavy vehicles, the longitudinal slope, the number of parking maneuvers, the presence of bus lines, the conflicts in the

left turns with the opposite vehicular flows and in the right turns with the crossing crosswalks);

- *Maximum density of the lane (veh/m):* the value of the total density of the lane leaving the intersection, in correspondence with the crossing maneuvers of the artery approaches. The density is therefore referred to the set of lanes of the part of the artery downstream of the intersection and serves the algorithm to calculate the length of the queue;
- *Speed (m/s):* the value of the speed in correspondence with the crossing maneuvers of the artery approaches.

4.2.3 Bus stop

Selecting a bus stop, in the tab called *Details* it is possible to view its configuration parameters.



In the section called *General,* the parameters relating to the bus stop to be defined are:

- *Name of bus stop;*
- *Abscissa (in meters):* position along the artery where the bus stop is located;
- *Fixed time of waiting (in seconds):* fixed time lost from the bus in case of stop;
- *Overtaking allowed:* indicates if the platform allows or not overtaking between buses.

In the table below, other parameters related to each individual line can be entered:

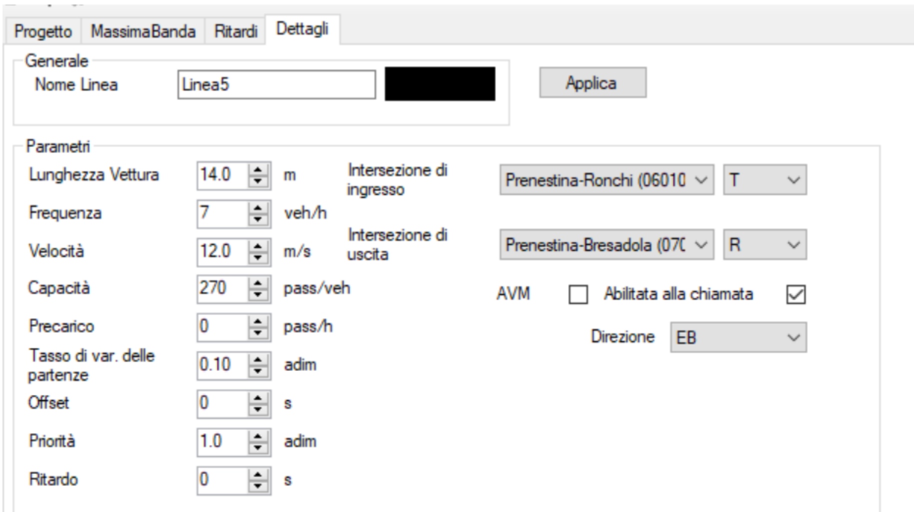
- *Line:* name and direction of the line;
- *Stop:* must be ticked if the line stops at this bus stop for passenger boarding/alighting;
- *Boarding time (in seconds)* for passenger;
- *Arrival rate (pass/h):* passenger per hour arriving at the bus stop and want to use the line;
- *Rate of the arrivals variation:* variance of arrival rate of passengers, expressed as a rate (Variance = Rate*Arrival Rate);
- *Alighting time (in seconds)* for passengers;
- *Alighting rate:* passenger per hour alighting at the bus stop
- *Rate of the alighting variation.:* variance of alighting rate of passengers, expressed as a rate (Variance = Rate*Alighting Rate);
- *Expected time (in seconds):* expected time of arrival at the bus stop relative to the time of entry on the artery of the bus.

4.2.4 Bus Line

Selecting a bus line, in the tab called *Details* it is possible to view its configuration parameters.

The information to be entered concerning the bus line are:

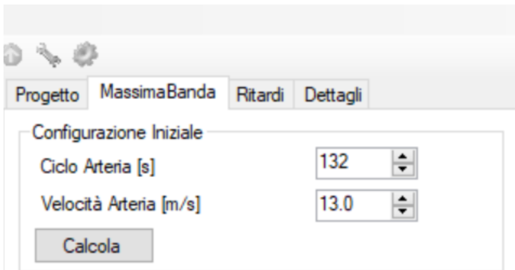
- *Name of the line;*
- *Color:* used in the visualization of the simulation;
- *Bus length (in meters);*
- *Frequency (bus/h):* frequency of departures;
- *Speed (m/s);*
- *Capacity (pass);*
- *Preload (pass):* number of passengers already on board at the entrance to the artery;
- *Variance departure:* The buses enter the artery one every 1 / F second with a variance equal to that fixed by the user;
- *Offset (in seconds):* bus offset for artery entry. The first vehicle has the mean value for the time of entry equal to Offset + 1 / F artery;
- *Priority:* priority associated with the bus when priority is assigned;
- *Call enabled:* If this option is activated, the vehicle is enabled to call the priority;
- *AVM:* Indicates whether the vehicle is equipped with the AVL system;
- *Direction:* direction of progression of the bus line along the artery;
- *Entry intersection:* intersection and maneuver to enter the artery;
- *Exit intersection:* intersection and maneuver to exit the artery.



4.2.5 Maximum bandwidth – Optimization

Selecting the tab called Maximum bandwidth, the computation of the maximal bandwidth of the initial configuration can be performed, entering the data about:

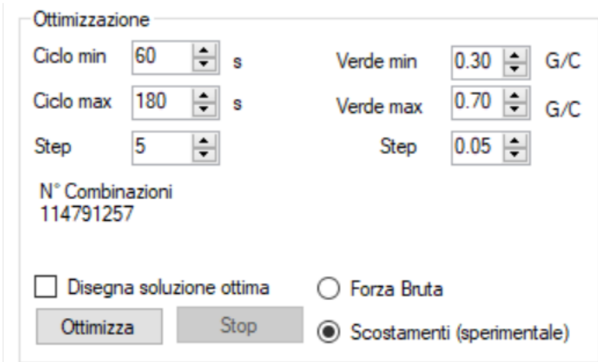
- Cycle of the artery (in seconds);
- Speed of the artery (in m/s).



The search for optimal maximum bandwidth is performed by a brute force algorithm. To set the size of the search space, the following constraints are defined:

- *Minimum Cycle (Min Cycle):* not necessarily coinciding with the minimum cycle value to guarantee the capacity conditions; the user may want a longer cycle under modest congestion conditions, or it may take a longer cycle short if, under over-saturation conditions, the minimum cycle was considered too high;

- *Maximum Cycle (Max Cycle):* maximum admissible value for the traffic light cycle, keeping in mind that low values cause a greater incidence of time loss and therefore reduce the capacity and high values increase the time proportionally to the red time and can therefore increase the delays to the approaches excessively;
- *Step* or search accuracy of the cycle;
- *Minimum green ratio:* expresses the capacity condition along the artery;
- *Maximum green ratio:* expresses the capacity condition for the transversal approaches to the artery;
- *Step* or search precision of the green ratio.



4.2.6 Delay – Optimization

Selecting the tab called Delay, it is possible to define a set of parameters for the application of public transport priority strategies, according to which it is decided to which bus to assign priorities

The global configuration is defined by:

- *Speed of recovery:* speed that network users are willing to add to their free speed to reach the vehicles that precede them;
- *Weight of FIFO rule:* weight assigned to the first vehicle that requires priority;
- *Weight of delay in timetable:* factor for every minute of delay on the timetable;
- *Cycle of recovery:* cycles for which it is not possible to assign the priority after having already assigned it;
- *Weight of priority of the line:* factor of the priority of the line;
- *Weight of passengers:* factor for each passenger on board.

The search for the best solution for optimization according to the minimum delay criterion is based on a genetic algorithm and a hill-climbing algorithm. To define the set of admissible solutions, the constraints must be defined:

- *Minimum Cycle (Min Cycle):* not necessarily coinciding with the minimum cycle value to guarantee the capacity conditions; the user may want a longer cycle under modest congestion conditions, or it may take a longer cycle short if, under over-saturation conditions, the minimum cycle was considered too high;
- *Maximum Cycle (Max Cycle):* maximum admissible value for the traffic light cycle, keeping in mind that low values cause a greater

incidence of time loss and therefore reduce the capacity and high values increase the time proportionally to the red time and can therefore increase the delays to the approaches excessively;

- *Step* or search accuracy of the cycle;
- *Minimum green ratio:* expresses the capacity condition along the artery;
- *Maximum green ratio:* expresses the capacity condition for the transversal approach to the artery;
- *Step* or search precision of the green ratio.

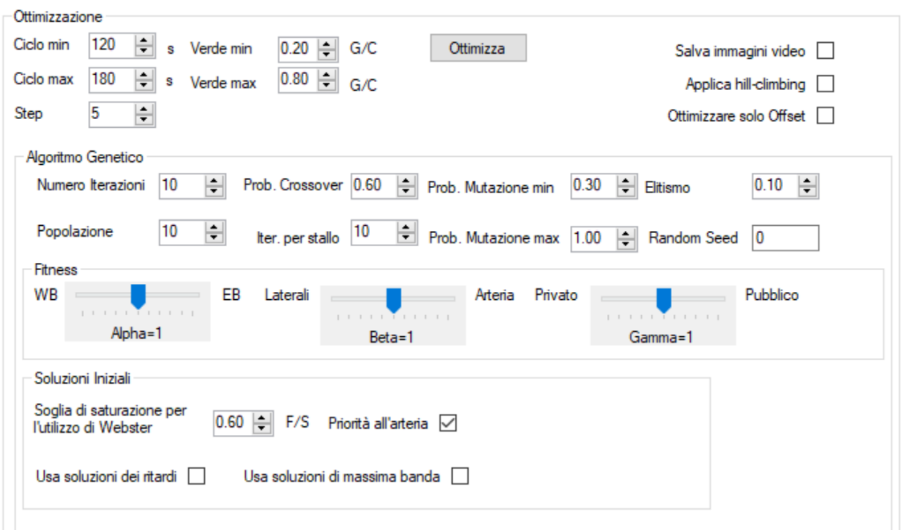
Beyond the space of the solutions also the parameters of the genetic algorithm can be defined and characterized by:

- Number of iterations of the algorithm;
- Population or number of individuals for each iteration;
- Probability of cross-over;
- Probability of minimum mutation;
- Probability of maximum mutation;
- Iterations for the detection of the stall;
- Elitism;
- Seed for generating random numbers;
- Weight to facilitate synchronization in one or the other direction;
- Weight to facilitate synchronization for the artery or for transverse approaches;
- Weight to facilitate synchronization for public transport or private transport.

The tab of optimization parameters of the genetic algorithm also allows the configuration of the initial population generation.

It is possible to set up different solutions:

1. Current solution: the algorithm takes the initial solution for generating individuals. In the initial population one of the individuals will always be the current configuration;
2. Good practice solution: obtained by applying the traffic light planning rules previously reported. The user can set the saturation degree threshold beyond which to adopt the minimum cycle instead of the optimal cycle of Webster and, in the case of a cycle greater than the minimum, choose whether to assign priority to the artery or to divide according to the criterion of equisaturation;
3. Solution of the current maximum bandwidth;
4. Solution of the current delays.

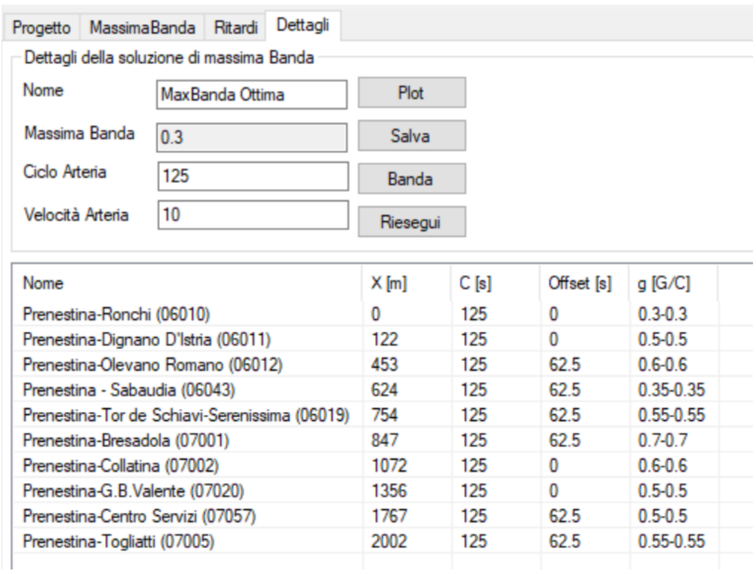


4.2.7 Output

At the end of the optimization procedures it is possible to display the results in numerical form and to export these outputs in aggregate or disaggregated form and in CSV format.

In the optimization according to the maximum bandwidth criterion are displayed:

- maximum bandwidth;
- synchronization cycle;
- synchronization speed;
- details of cycle, offset and green ratio of each intersection.

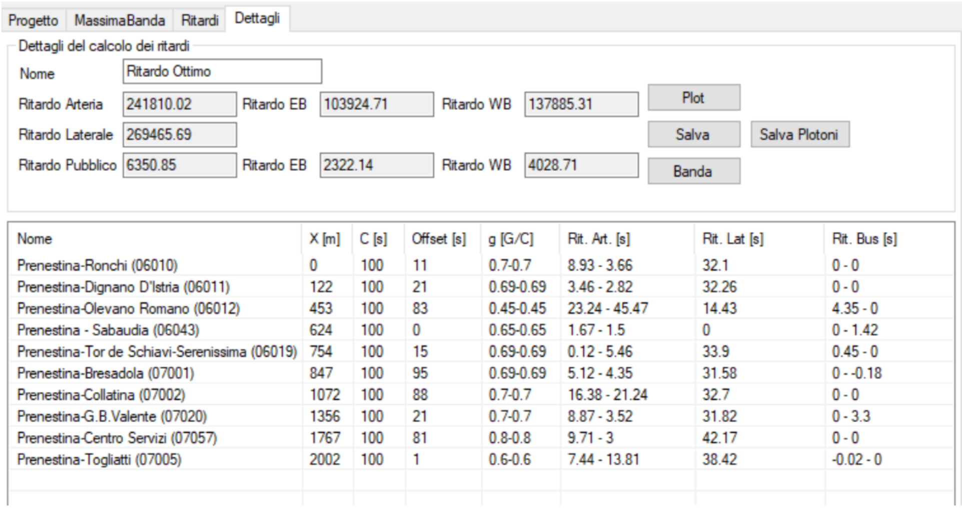


Nome	X [m]	C [s]	Offset [s]	g [G/C]
Prenestina-Ronchi (06010)	0	125	0	0.3-0.3
Prenestina-Dignano D'Istria (06011)	122	125	0	0.5-0.5
Prenestina-Olevano Romano (06012)	453	125	62.5	0.6-0.6
Prenestina - Sabaudia (06043)	624	125	62.5	0.35-0.35
Prenestina-Tor de Schiavi-Serenissima (06019)	754	125	62.5	0.55-0.55
Prenestina-Bresadola (07001)	847	125	62.5	0.7-0.7
Prenestina-Collatina (07002)	1072	125	0	0.6-0.6
Prenestina-G.B.Valente (07020)	1356	125	0	0.5-0.5
Prenestina-Centro Servizi (07057)	1767	125	62.5	0.5-0.5
Prenestina-Togliatti (07005)	2002	125	62.5	0.55-0.55

Similarly, the results of the optimization can also be viewed according to the minimum delay criterion. In this case the numeric outputs are:

- delay for vehicles;
- delay for public transport;
- delay for transversal approaches;

- cycle detail, offset, green ratio and average delays for each intersection.



Progetto | MassimaBanda | Ritardi | Dettagli

Dettagli del calcolo dei ritardi

Nome: Ritardo Ottimo

Ritardo Arteria: 241810.02 — Ritardo EB: 103924.71 — Ritardo WB: 137885.31 — Plot

Ritardo Laterale: 269465.69 — Salva — Salva Plotoni

Ritardo Pubblico: 6350.85 — Ritardo EB: 2322.14 — Ritardo WB: 4028.71 — Banda

Nome	X [m]	C [s]	Offset [s]	g [G/C]	Rit. Art. [s]	Rit. Lat [s]	Rit. Bus [s]
Prenestina-Ronchi (06010)	0	100	11	0.7-0.7	8.93 - 3.66	32.1	0 - 0
Prenestina-Dignano D'Istria (06011)	122	100	21	0.69-0.69	3.46 - 2.82	32.26	0 - 0
Prenestina-Olevano Romano (06012)	453	100	83	0.45-0.45	23.24 - 45.47	14.43	4.35 - 0
Prenestina - Sabaudia (06043)	624	100	0	0.65-0.65	1.67 - 1.5	0	0 - 1.42
Prenestina-Tor de Schiavi-Serenissima (06019)	754	100	15	0.69-0.69	0.12 - 5.46	33.9	0.45 - 0
Prenestina-Bresadola (07001)	847	100	95	0.69-0.69	5.12 - 4.35	31.58	0 - -0.18
Prenestina-Collatina (07002)	1072	100	88	0.7-0.7	16.38 - 21.24	32.7	0 - 0
Prenestina-G.B.Valente (07020)	1356	100	21	0.7-0.7	8.87 - 3.52	31.82	0 - 3.3
Prenestina-Centro Servizi (07057)	1767	100	81	0.8-0.8	9.71 - 3	42.17	0 - 0
Prenestina-Togliatti (07005)	2002	100	1	0.6-0.6	7.44 - 13.81	38.42	-0.02 - 0

For each solution it is possible to visualize a graphic output realized with MATLAB.

For maximum bandwidth, the effective red in each intersection and the progressions of the green bandwidth in the two directions are displayed in the space-time plane.

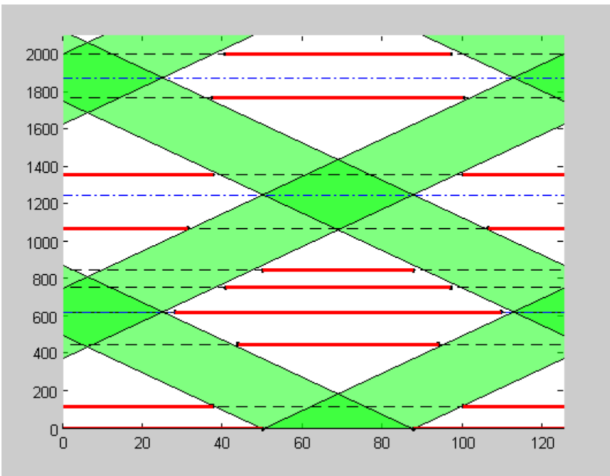


Figure 20 - Diagram of the effective red and the green bandwidth in the space-time plane

For minimum delay solutions, in two graphs produced automatically by the program the progression of the platoons and the bus trajectories, are displayed in each of the two directions of the artery.

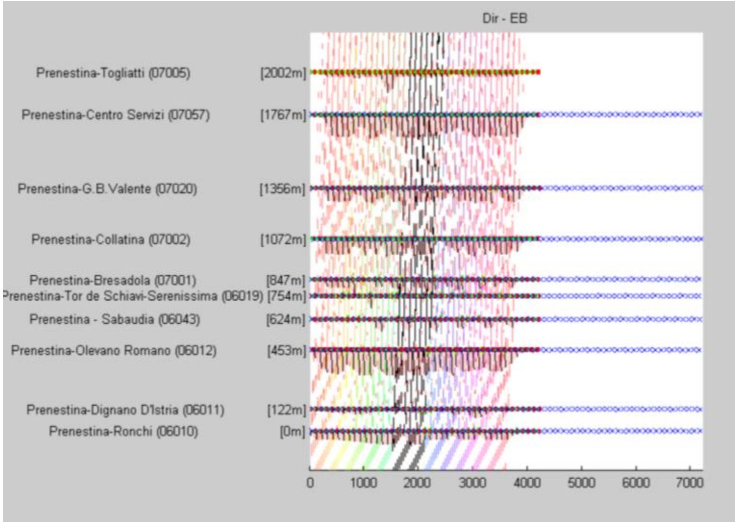


Figure 21- Representation of platoon progression of vehicles in the space-time plane

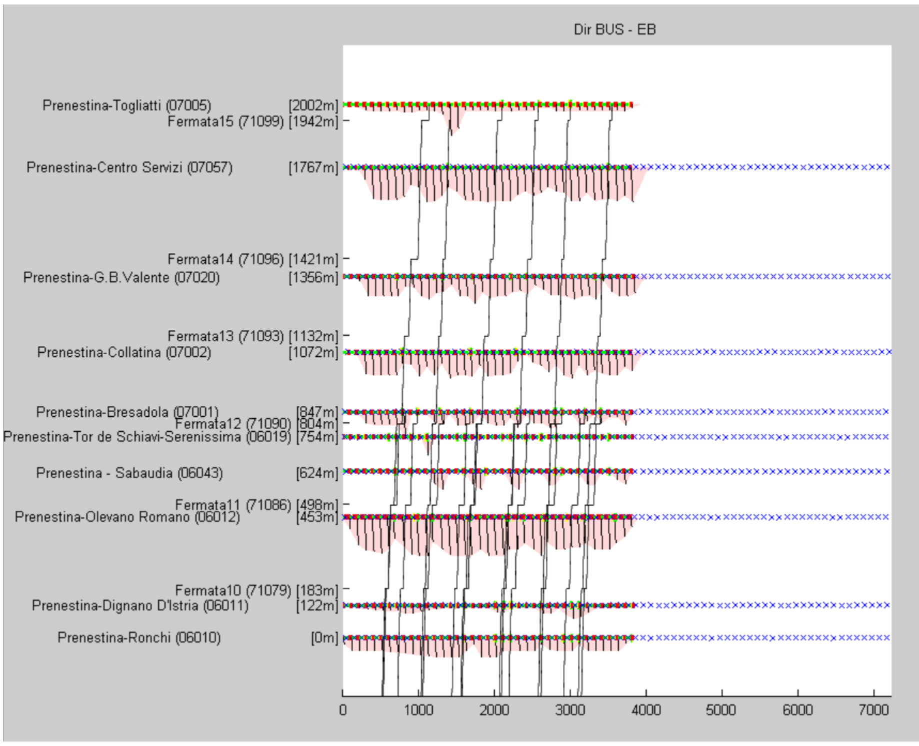


Figure 22 - Representation of buses trajectories in the space-time plane

4.3 Study network

The study corridor is via Prenestina, from the intersection of via Palmiro Togliatti to Piazza Maggiore, it is situated in the East area of Rome, in the district V and extends for a length of about 5 kilometers (Figure 23).

Via Prenestina is developed with separate carriageways of 2/3 lanes for direction and is characterized by the presence of the exclusive bus lane for both directions, on which pass the tram lines 5,14,19. The number of stops present along the artery, served by these lines is 16 per direction.

The artery consists of several intersections of which 19 are signalized with traffic light systems centralized with UTOPIA-OMNIA system. The following table shows the street names of the intersections with the traffic light installation number (the value between parentheses) and the progressive distances:

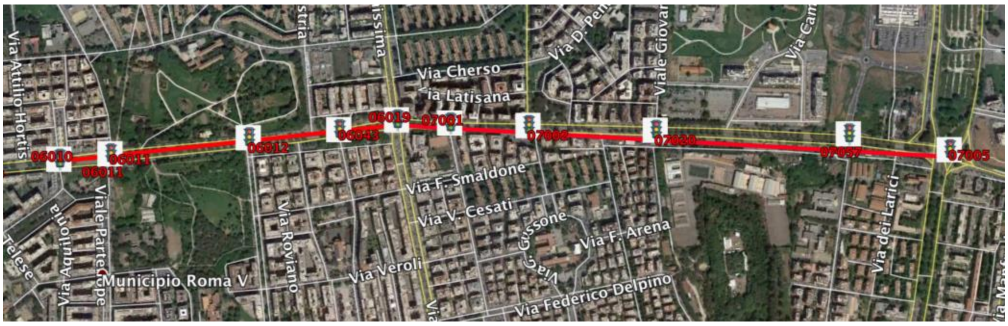
N	INTERSECTION	PROGRESSIVE DISTANCE [m]
1	Via Prenestina - Via Palmiro Togliatti (07005)	0
2	Via Prenestina - Centro Servizi (07057)	235
3	Via Prenestina - Via G.B.Valente (07020)	646
4	Via Prenestina - Via Collatina (07002)	930
5	Via Prenestina - Via Bresadola (07001)	1128
6	Via Prenestina - Tor de Schiavi (06019)	1248
7	Via Prenestina – Via Sabaudia (06043)	1378
8	Via Prenestina - Via Olevano Romano (06012)	1549
9	Via Prenestina - Via Dignano D'Istria (06011)	1880
10	Via Prenestina - Via Ronchi (06010)	2002
11	Via Prenestina - Largo Telese (06009)	2203
12	Via Prenestina - Largo Preneste (06008)	2619
13	Via Prenestina - Via di Portonaccio (06007)	2724
14	Via Prenestina - Via Giovenale (06024)	3036
15	Via Prenestina - Via Fieramosca (06006)	3719
16	P.le Prenestino - C.ne Casilina (06005)	3770
17	Via Prenestina - Deposito ATAC (06057)	3900
18	Via Prenestina - P.le Labicano (09004)	4669
19	Piazza di Porta Maggiore (01117)	5100

Table 1 – Intersections under study and progressive distances

Figure 23 – The study corridor: Via Prenestina

Because of its length, to avoid an ineffective synchronization and a dispersion of the flow along excessively long links, the artery has been divided into 3 blocks:

- **BLOCK 1**



1) Via Prenestina – Via Palmiro Togliatti
2) Via Prenestina-Centro Servizi
3) Via Prenestina-Via G.B.Valente
4) Via Prenestina-Via Collatina
5) Via Prenestina-Via Bresadola
6) Via Prenestina-Tor de Schiavi
7) Via Prenestina – Via Sabaudia
8) Via Prenestina-Via Olevano Romano
9) Via Prenestina-Via Dignano D'Istria
10) Via Prenestina-Via Ronchi

- **BLOCK 2**

11) Via Prenestina - Largo Telese
12) Via Prenestina - Largo Preneste
13) Via Prenestina - Via di Portonaccio

- **BLOCK 3**

14) Via Prenestina-Via Giovenale
15) Via Prenestina-Via Fieramosca
16) P.le Prenestino-C.ne Casilina
17) Via Prenestina-Dep. ATAC
18) Via Prenestina-P.le Labicano
19) Piazza di Porta Maggiore

4.4 Methodology

4.4.1 Data collection

For each signalized intersection, the traffic counts were made available by the ATAC. The data are referred to the year 2016. The surveys were done in three different time slots of the day: morning peak-hour (7: 30-9: 30), lunchtime (12: 30-14: 30) and evening rush hour (17: 30-19: 30). Data was collected for each vehicle category and for each allowed maneuver. Not all the intersections were monitored and for those missing, a balance of flows was performed. The timing diagrams of the current state of all the traffic lights of the analyzed network have always been provided by ATAC. In addition, from the website of ATAC, the information on the route and the frequency of tram lines 5,14,19 have been acquired. All these data were subsequently analyzed and used as input for the SINTAC software.

4.4.2 Inputting

For synchronizing and optimizing the artery, the block configuration was maintained on SINTAC. At the beginning, the succession of intersections and stops of each block was reproduced and subsequently all the necessary input data, previously illustrated in section 4.3, were inserted.

4.4.2.1 Flow

From the surveys it was possible to obtain the total vehicles that move in the network during three different periods of the day, in order to obtain the hourly flows, the total value has been divided by the total number of survey hours (that is 6). This calculation was made for each movement allowed for each approach of each intersection.

Below, the input flow for each junction is reported:

- **BLOCK 1**

		FLOW FOR MANEUVER [veh/h]			
N	**INTERSECTION**	**EB**	**WB**	**NB**	**SB**
1	Via Prenestina-Via Palmiro Togliatti	1134	904	1437	960
2	Via Prenestina-Centro Servizi	1311	1446	0	139
3	Via Prenestina-Via G.B.Valente	1297	1585	0	371
4	Via Prenestina-Via Collatina	1262	1474	325	434
5	Via Prenestina-Via Bresadola	1406	1143	252	0
6	Via Prenestina-Tor de Schiavi	1104	1275	1084	1017
7	Via Prenestina – Via Sabaudia	1105	1329	0	0
8	Via Prenestina-Via Olevano Romano	1207	1329	258	0
9	Via Prenestina-Via Dignano D'Istria	1080	1481	497	0
10	Via Prenestina-Via Ronchi	1077	1469	0	282

Table 2 - Flows of block 1

- **BLOCK 2**

N	INTERSECTION	FLOW FOR MANEUVER [veh/h]			
		EB	WB	NB	SB
11	Via Prenestina-Largo Telese	1433	1096	486	246
12	Via Prenestina-Largo Preneste	1311	1324	604	1107
13	Via Prenestina-Via di Portonaccio	1381	1650	12	0

Table 3 - Flows of block 2

- **BLOCK 3**

N	INTERSECTION	FLOW FOR MANEUVER [veh/h]			
		EB	WB	NB	SB
14	Via Prenestina-Via Giovenale	1188	1324	0	0
15	Via Prenestina-Via Fieramosca	1188	1210	0	693
16	P.le Prenestino-C.ne Casilina	962	1166	412	0
17	Via Prenestina-Dep. ATAC	962	1191	0	0
18	Via Prenestina-P.le Labicano	0	1191	1634	0
19	Piazza di Porta Maggiore	604	0	0	2370

Table 4 - Flows of block 3

4.4.2.2 Saturation flow

The calculation of the saturation flow is made applying the Highway Capacity Manual (2000) procedure. In the HCM, the saturation flow is calculated for each lane group from an ideal value then multiplied by some adjustment coefficients (Figure 24) that consider the different possible disturbance factors. The equation is:

$$S = S_o \cdot N \cdot f_w \cdot f_{HV} \cdot f_g \cdot f_p \cdot f_{bb} \cdot f_a \cdot f_{LU} \cdot f_{LT} \cdot f_{RT} \cdot f_{Lpb} \cdot f_{Rpb}$$

where:

- S = saturation flow rate for subject lane group, expressed as a total for all lanes in lane group (veh/h);
- S_o = base saturation flow rate per lane sets equal to 1900 (pc/h/ln);
- N = number of lanes in lane group;
- f_w = adjustment factor for lane width;
- f_{HV} = adjustment factor for heavy vehicles in traffic stream;
- f_g = adjustment factor for approach grade;
- f_p = adjustment factor for existence of a parking lane and parking activity adjacent to lane group;
- f_{bb} = adjustment factor for blocking effect of local buses that stop within intersection area;
- f_a = adjustment factor for area type;
- f_{LU} = adjustment factor for lane utilization;
- f_{LT} = adjustment factor for left turns in lane group;
- f_{RT} = adjustment factor for right turns in lane group;
- f_{Lpb} = pedestrian adjustment factor for left-turn movements;
- f_{Rpb} = pedestrian-bicycle adjustment factor for right-turn movements.

The worksheet (Figure 25) provides by the manual is used to compute the saturation flow for all the intersection and then the obtained data are inserted in SINTAC.

In the appendix of this thesis it is possible to find the saturation flow worksheets of each intersection.

4.4.2.3 Other traffic data

The other traffic data to be entered are the speed, that is set equal to 13 m/s for the entire network and the maximum density for lane equal to 0,4 veh/m.

EXHIBIT 16-7. ADJUSTMENT FACTORS FOR SATURATION FLOW RATE

Factor	Formula	Definition of Variables	Notes
Lane Width	$f_w = 1 + \frac{(W - 3.6)}{9}$	W = lane width (m)	W ≥ 2.4 if W > 4.8, a two-lane analysis may be considered
Heavy Vehicles	$f_{HV} = \frac{100}{100 + \%HV(E_T - 1)}$	% HV = % heavy vehicles for lane group volume	
Grade	$f_g = 1 - \frac{\%G}{200}$	% G = % grade on a lane group approach	$-6 \le \%G \le +10$
Parking	$f_p = \frac{N - 0.1 - \frac{18N_m}{3600}}{N}$	N = number of lanes in lane group N_m = number of parking maneuvers/h	$0 \le N_m \le 180$, $f_p \ge 0.050$ $f_p = 1.000$ for no parking
Bus Blockage	$f_{bb} = \frac{N - \frac{14.4N_B}{3600}}{N}$	N_B = number of buses stopping/h	$0 \le N_B \le 250$, $f_{bb} \ge 0.55$
Type of Area	$f_a = 0.900$ in CBD $f_a = 1.000$ in all other areas		
Lane Utilization	$f_{LU} = v_g/(v_{g1}N)$	v_g = unadjusted demand flow rate for the lane group, veh/h v_{g1} = unadjusted demand flow rate on the single lane in the lane group with the highest volume, and N = number of lanes in the lane group	
Left Turns	Protected Phasing: Exclusive lane: $f_{LT} = 0.95$ Shared lane: $f_{LT} = \frac{1}{1 + 0.05P_{LT}}$	P_{LT} = proportion of LT in lane group	See Exhibit C16-1 Appendix C, for non-protected phasing alternatives
Right Turns	Exclusive lane: $f_{RT} = 0.85$ Shared lane: $f_{RT} = 1 - (0.15)P_{RT}$ Single lane: $f_{RT} = 0.9 - (0.135)P_{RT}$	P_{RT} = proportion of RT in lane group	
Pedestrian/ Bicycle Blockage	LT Adjustment: $f_{Lpb} = 1.0 - P_{LT}(1 - A_{pbT})(1 - P_{LTA})$ RT Adjustment: $f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1 - P_{RTA})$	P_{LT} = proportion of LT in lane group A_{pbT} = permitted phase adjustment P_{LTA} = proportion of LT protected green over total LT green P_{RT} = proportion of RT in lane group P_{RTA} = proportion of RT protected green over total RT green	Refer to Appendix D for step-by-step procedure

Note:
See Chapter 10, Exhibit 10-9 for default values of base saturation flow rates and variables used to derive adjustment factors.
1. The table contains formulas for all adjustment factors. However, for situations in which permitted phasing is involved, either by itself, or in combination with protected phasing, separate tables are provided, as indicated in this exhibit.

Figure 24 - Saturation flow adjustment factors

Saturation Flow Rate (see Exhibit 16-7 to determine adjustment factors)												
Lane group												
Base saturation flow, s_o (pc/h/ln)												
Number of lanes, N												
Lane width adjustment factor, f_w												
Heavy vehicle adjustment factor, f_{HV}												
% Grade adjustment factor, f_g												
Parking adjustment factor, f_p												
Bus blockage adjustment factor, f_{bb}												
Area type adjustment factor, f_a												
Lane utilization adjustment factor, f_{LU}												
Left-turn adjustment factor, f_{LT}												
Right-turn adjustment factor, f_{RT}												
Left-turn ped/bike adjustment factor, f_{Lpb}												
Right-turn ped/bike adjustment factor, f_{Rpb}												
Saturation flow, s (veh/h) $s = s_o\, N\, f_w\, f_{HV}\, f_g\, f_p\, f_{bb}\, f_{LU}\, f_a\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb}$												

Figure 25 - Example of saturation flow worksheet

4.4.2.4 Traffic light parameters

The parameters of the traffic lights were obtained from the timing diagrams. The cycle (C), the green ratio (G/C) and the offset of the current situation for all the intersections are:

- **BLOCK 1**

	Cycle	G/C (EB)	G/C (WB)	Offset
Via Prenestina-Via Palmiro Togliatti	160	0.59	0.59	0
Via Prenestina-Centro Servizi	132	0.52	0.52	0
Via Prenestina-Via G.B.Valente	132	0.65	0.4	0
Via Prenestina-Via Collatina	132	0.37	0.52	0
Via Prenestina-Via Bresadola	132	0.67	0.67	0
Via Prenestina-Tor de Schiavi	132	0.35	0.35	0
Via Prenestina – Via Sabaudia	132	0.67	0.67	0
Via Prenestina-Via Olevano Romano	132	0.6	0.6	0
Via Prenestina-Via Dignano D'Istria	132	0.61	0.61	0
Via Prenestina-Via Ronchi	132	0.36	0.65	0

Table 5 - Traffic light parameters of current situation of BLOCK 1

- **BLOCK 2**

	Cycle	G/C (EB)	G/C (WB)	Offset
Via Prenestina-Largo Telese	108	0.56	0.56	0
Via Prenestina-Largo Preneste	138	0.46	0.36	0
Via Prenestina-Via di Portonaccio	138	0.36	0.36	0

Table 6 - Traffic light parameters of current situation of BLOCK 2

- **BLOCK 3**

	Cycle	G/C (EB)	G/C (WB)	Offset
Via Prenestina-Via Giovenale	108	0.61	0.61	0
Via Prenestina-Via Fieramosca	120	0.5	0.5	0
P.le Prenestino-C.ne Casilina	120	0.37	0.83	0
Via Prenestina-Dep. ATAC	90	0.73	0.73	0
Via Prenestina-P.le Labicano	122	0.5	0.5	0
Piazza di Porta Maggiore	153	0.29	0.01	0

Table 7 - Traffic light parameters of current situation of BLOCK 3

Start-up and clearance lost time have been set to 3s and 4s respectively.

4.4.2.5 Bus line parameters

The parameters to be entered for the bus line are the length of tram, the capacity and the speed set equal to 33m, 270 pass/veh and 13m/s respectively. The tram frequency is 7 veh/h for line 5 and 14 and 5 veh/h for line 19.

4.4.3 Preliminary analysis with HCM method

The High Capacity Manual 2000 contains a chapter (chapter 16) for estimating the capacity, the level of service and other performance measures for signalized intersections. The methodology suggested by this manual is used to perform a preliminary analysis of the current performance of the intersections under study.

4.4.3.1 Capacity and Degree of Saturation

The capacity of a given lane group is defined as the maximum hourly flow of vehicles that can be discharged through the intersection from the lane group in question. The formula, proposed by HCM, for calculating capacity c is:

$$c_i = s_i \frac{g_i}{C}$$

where:

- c_i = capacity of lane group i (veh/h)
- $\frac{g_i}{C}$ = effective green ratio for lane group i
- s_i= saturation flow rate for lane group i (veh/h)

Knowing the capacity, it is possible to calculate the degree of saturation (or volume-to-capacity) of a lane group, that is the ratio between flow rate and capacity (v/c). This measure is used as a reference to assess the current operational state of the intersections. The degree of saturation of each approach for each junction, are shown below:

- **BLOCK 1**

	v/c			
	EB	WB	NB	SB
Via Prenestina-Via Palmiro Togliatti	0.52	0.35	0.88	0.57
Via Prenestina-Centro Servizi	0.78	0.68	-	0.23
Via Prenestina-Via G.B.Valente	0.60	0.99	-	0.68
Via Prenestina-Via Collatina	0.85	0.67	0.19	0.25
Via Prenestina-Via Bresadola	0.75	0.59	0.25	-
Via Prenestina-Tor de Schiavi	0.79	0.91	0.52	0.39
Via Prenestina – Via Sabaudia	0.57	0.43	-	-
Via Prenestina-Via Olevano Romano	0.59	0.79	0.19	-
Via Prenestina-Via Dignano D'Istria	0.78	0.53	0.66	-
Via Prenestina-Via Ronchi	0.39	0.53	-	0.43

Table 8 - Degree of Saturation of BLOCK 1

- **BLOCK 2**

	v/c			
	EB	WB	NB	SB
Via Prenestina-Largo Telese	0.65	0.72	0.32	0.36
Via Prenestina-Largo Preneste	0.70	0.90	0.50	0.43
Via Prenestina-Via di Portonaccio	0.79	0.91	0.01	-

Table 9 - Degree of Saturation of BLOCK 2

- **BLOCK 3**

	v/c			
	EB	WB	NB	SB
Via Prenestina-Via Giovenale	0.69	0.78	-	-
Via Prenestina-Via Fieramosca	0.83	0.54	-	0.49
P.le Prenestino-C.ne Casilina	0.99	0.50	0.44	-
Via Prenestina-Dep. ATAC	0.47	0.44	-	-
Via Prenestina-P.le Labicano	-	0.39	0.49	-
Piazza di Porta Maggiore	0.70	-	-	0.58

Table 10 - Degree of Saturation of BLOCK 3

A v/c ratio less than 0.85 generally indicates that adequate capacity is available and vehicles are not expected to experience significant queues and delays. As the v/c ratio approaches 1.0, traffic flow may become unstable, and delay and queuing conditions may occur. Once the demand exceeds the capacity (a v/c ratio greater than 1.0), traffic flow is unstable and excessive delay and queuing is expected. The results show that most of the intersections are operating under capacity (<1.0). Movements that require more attention are the westbound for Via G.B Valente, Via Tor de Schiavi, Largo Preneste, Via di Portonaccio and the eastbound for Circonvallazione Casilina.

4.4.3.2 Control Delay and Level of Service

The HCM 2000 contains, also, a methodology for the computation of the average delay suffered by each vehicle for each approach and for the intersection as a whole and provides the criteria for determining the corresponding Level of Service. To calculate the control delay per vehicle for each lane group, the following formula is proposed by HCM:

$$d = PF \cdot 0{,}5C \cdot \frac{\left(1+\frac{g}{C}\right)^2}{1-\min(1,X)\cdot\frac{g}{C}} + \frac{T}{4}\left[(X-1)+\sqrt{(X-1)^2+\frac{8kx}{cT}}\right]$$

where:

- d control delay per vehicle [s/veh];
- PF is the adjustment factor of progression;
- C is the traffic-light cycle;
- g effective green time for lane group [s];
- X degree of saturation for lane group;
- T period of observation [h];
- c lane group capacity [veh/h];
- k calibration factor.

Then the average delay for each intersection approach was obtained from a weighted average of the control delay of lane group weighted by the adjusted flows in the lane groups:

$$d_A = \frac{\sum d_i v_i}{\sum v_i}$$

where:

- d_A delay for approach A [s/veh];
- d_i delay for lane group i (on approach A) [s/veh];
- v_i adjusted flow for lane group i [veh/h];

Aggregating these values, the average delay for intersection was provided:

$$d_I = \frac{\sum d_A v_A}{\sum v_A}$$

where:

- d_I delay per vehicle for intersection [s/veh];
- d_A delay for approach A [s/veh];
- v_A adjusted flow for approach A [veh/h];

The following tables show the results obtained:

- **BLOCK 1**

	Delay by approach [s/veh]				Intersection delay [s/veh]
	EB	WB	NB	SB	
Via Prenestina-Via Palmiro Togliatti	18	15	57	41	35
Via Prenestina-Centro Servizi	38	28		25	33
Via Prenestina-Via G.B.Valente	13	65		43	42
Via Prenestina-Via Collatina	47	23	22	23	32
Via Prenestina-Via Bresadola	11	9	38		13
Via Prenestina-Tor de Schiavi	35	42	16	15	30
Via Prenestina – Via Sabaudia	9	8			8
Via Prenestina-Via Olevano Romano	15	8	30		13
Via Prenestina-Via Dignano D'Istria	4	12	41		13
Via Prenestina-Via Ronchi	45	10		39	26

Table 11 – Control Delay with HCM method of BLOCK 1

- **BLOCK 2**

	Delay by approach [s/veh]				Intersection delay [s/veh]
	EB	**WB**	**NB**	**SB**	
Via Prenestina-Largo Telese	18	19	24	25	20
Via Prenestina-Largo Preneste	20	40	18	17	25
Via Prenestina-Via di Portonaccio	25	31	12		28

Table 12 – Control Delay with HCM method of BLOCK 2

- **BLOCK 3**

	Delay by approach [s/veh]				Intersection delay [s/veh]
	EB	**WB**	**NB**	**SB**	
Via Prenestina-Via Giovenale	14	17			16
Via Prenestina-Via Fieramosca	12	19		25	17
P.le Prenestino-C.ne Casilina	66	6	27		32
Via Prenestina-Dep. ATAC	4	4			4
Via Prenestina-P.le Labicano		16	21		20
Piazza di Porta Maggiore	52			14	22

Table 13 – Control Delay with HCM method of BLOCK 3

The LOS is directly related to the average control delay per vehicle and can be used as an index to evaluate the performance of a signalized intersection. For its calculation the following criteria, present in the HCM, were used as reference:

Level of Service	Control Delay per Vehicle (s/veh)
A	≤ 10
B	> 10 - 20
C	>20 - 35
D	>35 - 55
E	>55 - 80
F	>80

Figure 26 - Level of Service

	LOS
Via Prenestina-Via Palmiro Togliatti	C
Via Prenestina-Centro Servizi	C
Via Prenestina-Via G.B.Valente	D
Via Prenestina-Via Collatina	C
Via Prenestina-Via Bresadola	B
Via Prenestina-Tor de Schiavi	C
Via Prenestina – Via Sabaudia	A
Via Prenestina-Via Olevano Romano	B
Via Prenestina-Via Dignano D'Istria	B
Via Prenestina-Via Ronchi	C

Table 14 - Level of Service BLOCK 1

	LOS
Via Prenestina-Largo Telese	C
Via Prenestina-Largo Preneste	C
Via Prenestina-Via di Portonaccio	C

Table 15 -- Level of Service BLOCK 2

	LOS
Via Prenestina-Via Giovenale	B
Via Prenestina-Via Fieramosca	B
P.le Prenestino-C.ne Casilina	C
Via Prenestina-Dep. ATAC	A
Via Prenestina-P.le Labicano	B
Piazza di Porta Maggiore	C

Table 16 - Level of Service BLOCK 3

4.4.4 Computation of current delay with SINTAC

Once a preliminary analysis has been performed and all the necessary data have been entered in SINTAC, the delays of the current situation are calculated with the software. The following tables show the results of delays for private vehicles and public transport:

	Total Artery Delay [s]	Total Lateral Delay [s]	Total Tram Delay [s]
BLOCK 1	563390	232790	371745
BLOCK 2	199343	66497	176715
BLOCK 3	200185	108994	365940
TOT	962918	407320	914400

Table 17 - Total delay of current situation

- **BLOCK 1**

	Delay EB [s]	Delay WB [s]	Delay Lateral [s]	Delay Tram EB [s]	Delay Tram WB [s]
Prenestina-Togliatti	25	20	44	1	0
Prenestina-Centro Servizi	47	30	21	4	1
Prenestina-G.B.Valente	7	71	34	0	4
Prenestina-Collatina	37	18	25	31	0
Prenestina-Bresadola	1	6	37	1	2
Prenestina-Tor de Schiavi	48	45	13	16	0
Prenestina - Sabaudia	4	0	0	2	2
Prenestina-Olevano Romano	7	13	30	3	10
Prenestina-Dignano D'Istria	0	12	33	0	6
Prenestina-Ronchi	35	8	35	0	0

Table 18 - Intersection delay of current situation of BLOCK 1

- **BLOCK 2**

	Delay EB [s]	Delay WB [s]	Delay Lateral [s]	Delay Tram EB [s]	Delay Tram WB [s]
Prenestina-Largo Telese	21	19	23	1	0
Prenestina-Largo Preneste	1	42	20	0	23
Prenestina-Portonaccio	37	25	11	13	3

Table 19 - Intersection delay of current situation of BLOCK 2

- **BLOCK 3**

	Delay EB [s]	Delay WB [s]	Delay Lateral [s]	Delay Tram EB [s]	Delay Tram WB [s]
Prenestina-Giovenale	18	17	0	0	37
Prenestina-Fieramosca	8	19	22	3	2
P.le Prenestino-C.ne Casilina	57	3	51	17	1
Prenestina-Dep. ATAC	11	8	0	0	2
Prenestina-P.le Labicano	0	22	24	9	7
Piazza di Porta Maggiore	45	0	11	0	2

Table 20 - Intersection delay of current situation of BLOCK 3

Knowing the delay at each approach of each intersection, it is possible to calculate with the same aggregation procedure carried out following the HCM method, the average delay for each intersection from the results obtained by SINTAC:

		Intersection delay [s/veh]
1	Prenestina-Togliatti	34
2	Prenestina-Centro Servizi	37
3	Prenestina-G.B.Valente	41
4	Prenestina-Collatina	27
5	Prenestina-Bresadola	7
6	Prenestina-Tor de Schiavi	30
7	Prenestina - Sabaudia	2
8	Prenestina-Olevano Romano	12
9	Prenestina-Dignano D'Istria	11
10	Prenestina-Ronchi	21
11	Prenestina-Largo Telese	21
12	Prenestina-Largo Preneste	21
13	Prenestina-Portonaccio	31
14	Prenestina-Giovenale	17
15	Prenestina-Fieramosca	16
16	P.le Prenestino-C.ne Casilina	32
17	Prenestina-Dep. ATAC	9
18	Prenestina-P.le Labicano	23
19	Piazza di Porta Maggiore	18

Table 21 – Intersection delay of current situation

4.5 Optimization

The results of the previous chapter showed a high value of the total delay for the artery and the lateral approaches that led to considering the need to search for new optimal solutions. For this reason, the parameters of traffic lights have been optimized with SINTAC. As previously described, the algorithm behind the software is characterized by several parameters that have been calibrated by performing various tests and finally a number of iterations equal to 20 and an initial population of 50 individuals have been chosen. Moreover, the best solution, in terms of total delay, has been obtained using as the initial solution for optimizing the current maximum bandwidth.

The following tables show the optimal traffic lights parameters obtained with SINTAC for the three blocks:

- **BLOCK 1**

	Cycle	G/C (EB)	G/C (WB)	Offset
Via Prenestina-Via Palmiro Togliatti	100	0.6	0.6	1
Via Prenestina-Centro Servizi	100	0.8	0.8	83
Via Prenestina-Via G.B.Valente	100	0.7	0.7	21
Via Prenestina-Via Collatina	100	0.7	0.7	41
Via Prenestina-Via Bresadola	100	0.69	0.69	85
Via Prenestina-Tor de Schiavi	100	0.69	0.69	15
Via Prenestina – Via Sabaudia	100	0.65	0.65	28
Via Prenestina-Via Olevano Romano	100	0.72	0.72	88
Via Prenestina-Via Dignano D'Istria	100	0.69	0.69	0
Via Prenestina-Via Ronchi	100	0.7	0.7	62

Table 22 - Optimal traffic light parameters of BLOCK 1

- **BLOCK 2**

	Cycle	G/C (EB)	G/C (WB)	Offset
Via Prenestina-Largo Telese	120	0.72	0.72	6
Via Prenestina-Largo Preneste	120	0.63	0.63	1
Via Prenestina-Via di Portonaccio	120	0.71	0.71	0

Table 23 - Optimal traffic light parameters of BLOCK 2

- **BLOCK 3**

	Cycle	G/C (EB)	G/C (WB)	Offset
Via Prenestina-Via Giovenale	105	0.61	0.61	0
Via Prenestina-Via Fieramosca	105	0.56	0.56	0
P.le Prenestino-C.ne Casilina	105	0.71	0.71	0
Via Prenestina-Dep. ATAC	105	0.65	0.65	95
Via Prenestina-P.le Labicano	105	0.5	0.5	77
Piazza di Porta Maggiore	105	0.29	0.2	16

Table 24 - Optimal traffic light parameters of BLOCK 3

The delays generated by the optimization with SINTAC are:

	Total Artery Delay [s]	Total Lateral Delay [s]	Total Tram Delay [s]
BLOCK 1	266733	261500	49140
BLOCK 2	67124	107772	22995
BLOCK 3	98114	92616	85320
TOT	431971	461888	157455

Table 25 - Total delay optimized situation

- **BLOCK 1**

	Delay EB [s]	Delay WB [s]	Delay Lateral [s]	Delay Tram EB [s]	Delay Tram WB [s]
Prenestina-Togliatti	2	15	33	0	0
Prenestina-Centro Servizi	9	4	42	0	0
Prenestina-G.B.Valente	6	6	32	0	0
Prenestina-Collatina	24	3	33	0	2
Prenestina-Bresadola	20	13	31	1	0
Prenestina-Tor de Schiavi	2	12	34	1	2
Prenestina - Sabaudia	5	9	0	1	0
Prenestina-Olevano Romano	3	25	33	3	0
Prenestina-Dignano D'Istria	13	8	33	0	0
Prenestina-Ronchi	9	19	32	0	0

Table 26 - Intersection delay of optimized situation of BLOCK 1

- ***BLOCK 2***

	Delay EB [s]	Delay WB [s]	Delay Lateral [s]	Delay Tram EB [s]	Delay Tram WB [s]
Prenestina-Largo Telese	9	11	40	0	0
Prenestina-Largo Preneste	6	10	32	1	2
Prenestina-Portonaccio	9	6	34	0	2

Table 27 - Intersection delay of optimized situation of BLOCK 2

- **BLOCK 3**

	Delay EB [s]	Delay WB [s]	Delay Lateral [s]	Delay Tram EB [s]	Delay Tram WB [s]
Prenestina-Giovenale	3	17	0	0	10
Prenestina-Fieramosca	4	9	24	1	3
P.le Prenestino-C.ne Casilina	1	5	35	0	1
Prenestina-Dep. ATAC	8	10	0	0	0
Prenestina-P.le Labicano	0	14	22	0	1
Piazza di Porta Maggiore	34	0	9	0	1

Table 28 - Intersection delay of optimized situation of BLOCK 3

4.6 Comparison of scenarios

To evaluate the benefits, in terms of delays, obtained from the optimization of traffic signal parameters, the results of the two scenarios are compared. The tables present the total delay of each block for the corridor of Via Prenestina, for the lateral approaches and for the entire network (sum of artery and lateral). Finally, the last table shows the total delay for public transport.

	Total Artery Delay [s]		
	CURRENT SCENARIO	*OPTIMIZED SCENARIO*	*Variation*
BLOCK 1	563307.63	266733.37	***-53%***
BLOCK 2	199342.64	67123.82	***-66%***
BLOCK 3	199602.53	98113.83	***-51%***
TOT	962252.80	431971.02	***-55%***

Table 29 - Comparison of total artery delay in the current and optimized situation

	Total Lateral Delay [s]		
	CURRENT SCENARIO	*OPTIMIZED SCENARIO*	*Variation*
BLOCK 1	232790.17	261500.4	***12%***
BLOCK 2	66497.26	107771.78	***62%***
BLOCK 3	108994.41	92616.05	***-15%***
TOT	407319.58	461888.23	***13%***

Table 30 - Comparison of total lateral delay in the current and optimized situation

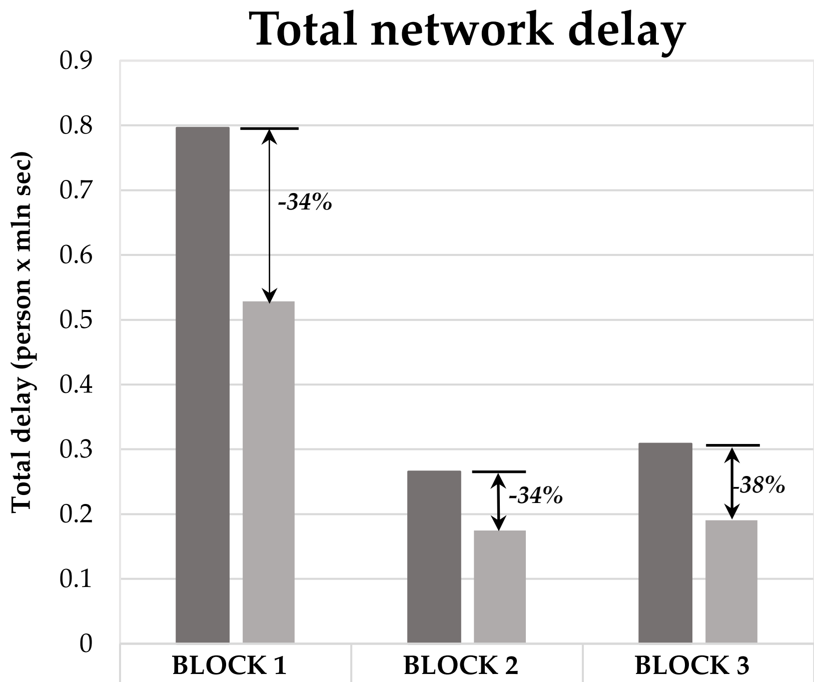
	Total Network Delay [s]		
	CURRENT SCENARIO	*OPTIMIZED SCENARIO*	*Variation*
BLOCK 1	796097.8	528233.77	***-34%***
BLOCK 2	265839.9	174895.6	***-34%***
BLOCK 3	308596.94	190729.88	***-38%***
TOT	1369572.38	893859.25	***-35%***

Table 31 - Comparison of total network delay in the current and optimized situation

	Total Tram Delay [s]		
	CURRENT SCENARIO	*OPTIMIZED SCENARIO*	*Variation*
BLOCK 1	371745	49140	**-87%**
BLOCK 2	176715	22995	**-87%**
BLOCK 3	365940	85320	**-77%**
TOT	914400	157455	**-83%**

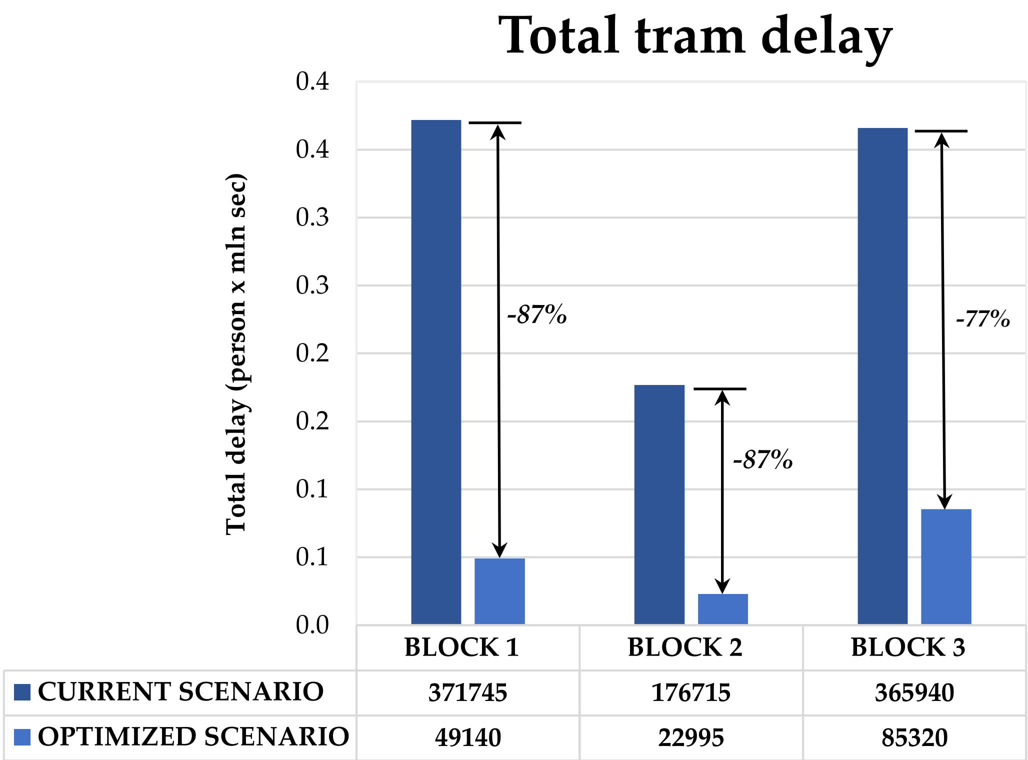
Table 32 - Comparison of total tram delay for the current and optimized situation

The graph below shows the total network delays of vehicles and the total delays of public transport for each block, for the current scenario and in the situation with signal parameters optimized by SINTAC:



	BLOCK 1	**BLOCK 2**	**BLOCK 3**
CURRENT SCENARIO	**796097.8**	**265839.9**	**308596.94**
OPTIMIZED SCENARIO	**528233.77**	**174895.6**	**190729.88**

Graph 1 - Comparison of total network delay in the current and optimized situation



Graph 2 - Comparison of total bus delay in the current and optimized situation

The comparison shows that the performance improvements achieved, for the general traffic that travels along the artery, are about 55% in reduction of delays, while the lateral approaches show a worsening, except for block 3. This result is consistent with the model structure since the optimization of signal parameters has been set giving priority to the artery. Considering the entire network, a possible implementation of this optimal solution found with SINTAC would result in a reduction of delays of 35%.

Analyzing the impacts on public transport, the results show a significant decrease in delays of 83%.

Optimizing the traffic light parameters by giving priority to public transport brings benefits not only to buses but also to the general traffic.

5. MICROSCOPIC TRAFFIC SIMULATION

In order to evaluate a traffic system management strategy before implementing it, traffic simulation can be a suitable tool. Microscopic simulation allows to compare and analyze different scenarios in a controlled setting without disrupting traffic conditions on the road. Various road traffic simulators are available and, in this thesis, SUMO simulator has been selected to test the impacts of implementing the new optimal signals regulation.

5.1 SUMO simulator

"Simulation of Urban Mobility" (SUMO) is an open source, highly portable, traffic simulation package which is developed since the year 2000 by the Institute of Transportation Research at the German Aerospace Centre. SUMO is designed to handle large road networks and allows modelling of intermodal traffic systems including road vehicles, public transport and pedestrians. The core of the simulation software is written in C++, but additional software libraries are available (i.e. Python and Java code). SUMO is purely microscopic in nature: each vehicle is modelled explicitly, has its own route, and moves individually through the given network. The simulation is space-continuous and time-discrete with a default duration of each time step of one second. Included with SUMO is a wealth of supporting tools:

- SUMO: command line simulation.
- SUMO-GUI: simulation with a graphical user interface.
- NETCONVERT: network importer and generator.
- NETEDIT: a graphical network editor

- NETGENERATE: abstract network generator.
- OD2TRIPS: converter from O/D matrices to trips.
- JTRROUTER: routes generated based on turning ratios at intersections.
- DUAROUTER: routes generator based on a dynamic user assignment.
- DFROUTER: route generator with use of detector data.
- POLYCONVERT: to import points of interest and polygons from different formats and translates them into a description that may be visualized by SUMO-GUI.

The accuracy of the traffic flow simulation model is closely related to the accuracy in reproducing the actual driving behavior. SUMO consists of submodels that allow replicating the real movements of vehicles in the network. The following subsections describe the car-following, lane-changing and intersection models embedded in the microsimulator.

5.1.1 Car-following model

The car-following model is used to describe the behavior of a following vehicle with respect to the preceding vehicle in the same lane. Car-following forms one of the main processes in microscopic simulation, characterizing the longitudinal interaction of vehicles on the road. Three main classes based on different logic, can be defined:

- Stimulus-response models: in which acceleration (or deceleration) is considered as the response to a stimulus that can be the speed of the follower vehicle, the difference in speed between follower and leader and the space race.

- Safety-distance models: based on the assumption that the follower always keeps a safe distance to the vehicle in front.
- Psycho-physical models: which considering the driver's perception basing on some thresholds for, e.g., the minimum speed difference between follower and leader perceived by the follower.

SUMO includes several vehicle-following models, which are explained below.

5.1.1.1 Krauss Model

The default car-following model of SUMO is the Krauss model [59]. In traffic simulation each vehicle can have two different motion states: free motion and interacting motion. In free motion, no leading vehicle limits the speed of the following vehicle. Therefore, its speed is bounded to its maximum (depending of the speed limit):

$$v \leq v_{max}$$

If two vehicles interact, they both intend avoiding a collision with each other. At every time step the speed of the following vehicle is adapted to the speed of the leading vehicle in order to achieve a collision-free system behavior. For this reason, the model assumes that drivers choose a speed that is not higher than a convenient safe velocity:

$$v \leq v_{safe}$$

The safe speed is computed, every time step, using the following equation:

$$v_{safe}(t) = v_l(t) + \frac{g(t) - v_l(t)\tau}{\frac{\bar{v}}{b(\bar{v})} + \tau}$$

t: time step
$v_l(t)$: velocity of the leading vehicle in time *t*
$g(t)$: gap between vehicle and leading vehicle *i* in time *t*
τ: driver's reaction time $\bar{v}$: average velocity of the leader and the follower $\bar{v} = \frac{v_l+v_f}{2}$
b: deceleration function

In real life, the acceleration of a vehicle depends on its performances and other factors, like air resistance and others. To prevent that vehicles in the simulation are driving faster than is possible, the desired speed v_{des} is calculated.

The desired speed of each vehicle v_{des} is the minimum value between the safe speed v_{safe}, the current speed plus the maximum acceleration and the maximum speed:

$$v_{des}(t) = \min[\, v_{safe}(t), v(t) + a, v_{max}]$$

Due to the imperfection of the human drivers, a random error is subtracted from the desired speed v_{des}:

$$v(t) = \max[0, rand[v_{des}(t) - \epsilon a, v_{des}(t)]]$$

5.1.1.2 Wiedemann Model

Wiedemann's model [60] is a psycho-physical vehicle following model and it is known for its extensive use in VISSIM microsimulation software. This model assumes that a driver will perform an action (acceleration/deceleration) when a threshold, expressed as a function of speed difference and spacing, is reached.

When the distance between two vehicles is large, the following driver is not influenced by the lead vehicle's acceleration and tries to move at desired speed. At a certain distance, SDV, the following driver perceives that he is approaching to a slower leading vehicle and when this perceptual threshold is crossed (point A), it starts to decelerate until the leader's speed.

Since driver is not able to control his speed sufficiently well enough, he will decelerate below lead vehicle's speed, increasing the spacing until the acceleration perceptual threshold (OPDV) is reached (point B). Now the driver will again accelerate to match the leader's speed and the process continues.

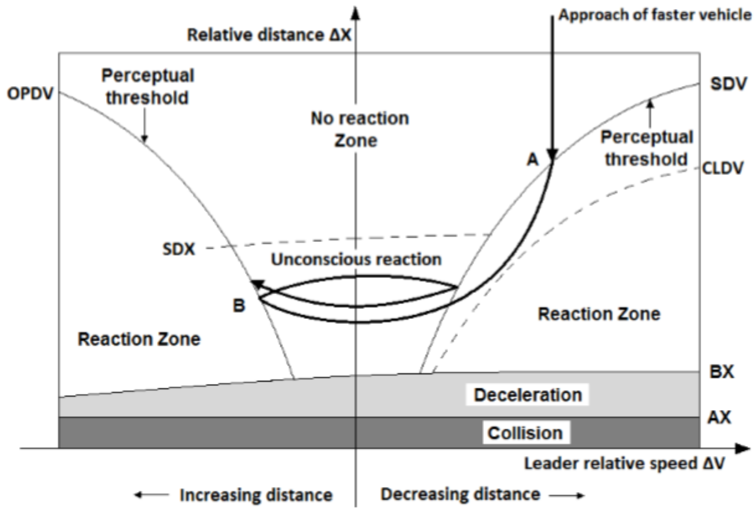


Figure 27 - Wiedemann Car-following logic

5.1.1.3 Intelligent Driver Model (IDM)

The intelligent driver model (IDM) proposed by Treiber et al. (2000) [61] is an accident free model that describes the dynamics of a vehicle through the following equations:

$$\dot{x} = \frac{dx}{dt} = v$$

$$\dot{v} = \frac{dv}{dt} = a\left[\left(1 - \left(\frac{v}{v_{des}}\right)^{\delta} - (\frac{s^*(v, \Delta v)}{s})^2\right)\right]$$

with $s^*(v, \Delta v) = s_0 + vT + \frac{v\,\Delta v}{2\sqrt{a\,b}}$

v: current speed

s: current gap to the leading vehicle

v_{des}: desired speed

s*: desired gap

s_0: minimum desired net distance (relevant for low velocities only)

T: safe time headway

a: maximum acceleration

δ: acceleration exponent characterizing how the acceleration decreases with velocity, set to 4 (δ=1 corresponds to a linear decrease while δ→∞ denotes a constant acceleration).

b: comfortable deceleration

The acceleration combines two possible driving behaviors: free road behavior described by the first term and interaction behavior regulated by the second.

$$\dot{v}_{free} = a\left[1 - \left(\frac{v}{v_{des}}\right)^{\delta}\right]$$

$$\dot{v}_{brake} = a\left(\frac{s^*}{s}\right)^2$$

On a free road, the distance s to the leading vehicle is large and the vehicle's acceleration is approximately equal to a for low velocities and tends to zero when v approaches v_{des}. When vehicle approach each other's, in case of stationary traffic condition, it tends to keep a velocity-dependent distance vT, which corresponds to following the leading vehicle with a constant desired time gap T. While in case of non-stationary traffic, an 'intelligent' driving behavior is activated trying to limit braking deceleration to the comfortable deceleration b. In critical situations, however, the IDM deceleration becomes significantly higher, making this model collision free.

5.1.2 Lane-changing model

Another fundamental component of vehicle dynamics is the lane-changing behavior. This is needed to simulate lateral movements on multilane roads. Vehicles change their lane for multiple reasons, mandatory or discretionary and the lane-changing model in SUMO currently recognizes four motivations for the decision to change lane:

- Strategic (another lane must be used to continue the current route);
- Cooperative (the vehicle would like to clear the lane for another vehicle);
- Speed gain (the vehicle speed up its travel by changing to a faster lane);
- Keep right (the vehicle should keep the left lanes clear for faster vehicles).

Due to the different reasons for lane changes and the high number of traffic situations that need to be addressed, the SUMO lane-changing model is very complex and in continuous development. A recent improvement was the prevention of the deadlock, which occurs when two vehicles on adjacent lanes must move on the same lane occupied by another vehicle and they reach the end of a dead lane (Figure 28).In this case a deadlock occurs, creating an undesirable impediment to traffic flow, because both cannot be passed over and do not have the space to perform the movement maneuver on the other lane (vehicles in SUMO cannot go back). To prevent this situation special care should be taken: for example, the blocking follower slows down when approaching the dead-end to ensure that the blocking leader has enough space to complete its lane change or if the blocking follower is too fast the blocking leader must slow down to leave enough space for the follower before the dead-end.

In case of a lane change across multiple lanes, an additional space is considered in front of the dead-end to complete the change of position.

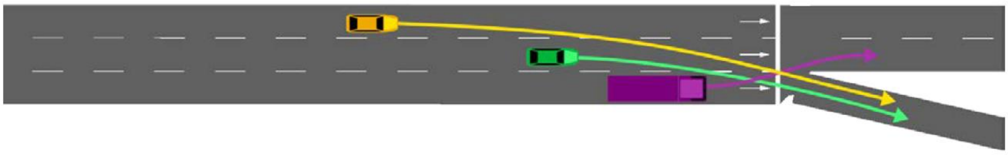


Figure 28 - Example of situations which may lead to a deadlock: the purple vehicle needs to change left and the green and yellow vehicles need to change right to continue with their route.

5.1.2.1 Strategic change

Strategic change is performed when a vehicle is on a dead lane and must change its lane to continue its route. The lane-changing model implemented in SUMO is based on maximizing the drivable distance without changing lanes and minimizing the number of necessary lane changes. For this reason, at each simulation step a sequence of computations are performed:

- The sequence of lanes, called *bestLanes*, that can be followed without lane changing up to a maximum distance.
- The occupation of these *bestLanes* in terms of traffic density.
- The *bestLaneOffset* that indicates the lanes strategically advisable (*bestLaneOffset*=0 strategically advisable, *bestLaneOffset*=-1 lane change need, *bestLaneOffset*=-2 strategically unadvisable).

The urgency of a lane change is evaluated in the model based on the following factors:

- Remaining distance to the dead-end.
- The presumed speed while approaching the dead-end lane (*lookAheadSpeed*).
- The occupation of the ultimate and the intermediate target lane.

Another important aspect is the speed adjustment to allow the successful execution of the desired lane change maneuver, in fact, whenever a desired lane change cannot be executed due to blocking vehicles, a vehicle adjusts its speed to allow the lane change to succeed in later steps.

5.1.2.2 Cooperative change

The cooperative lane changing is carried out with the sole purpose of helping another vehicle to change lanes towards its lane. In SUMO a vehicle may only change its lane if there is enough physical space on the target lane and if it does not get too close to the leader and the immediate follower on the target lane. If either of these conditions is not met, the vehicle is said to have a blocking leader or a blocking follower. In the model vehicles are always informed by other vehicles about being a blocking follower and they show a cooperative behavior, for example adjusting the velocity and allowing the lane changing maneuver.

5.1.2.3 Tactical change

The tactical lane change is performed when a vehicle overtakes a slow leader, respecting the obligation to use only the overtaking lane (left lane for right-handed driving) to perform this maneuver. The choice of moving to another lane is balanced with the speed gain obtained. Each vehicle has a variable *SpeedGainProbability* that indicates the favorable direction of change through a sign and the expected benefit through a number, if this exceeds a threshold value, a modification of the lane is attempted. A new addition to the lane-changing model is the ability to overcome the leader by changing two lanes, as shown in the picture.

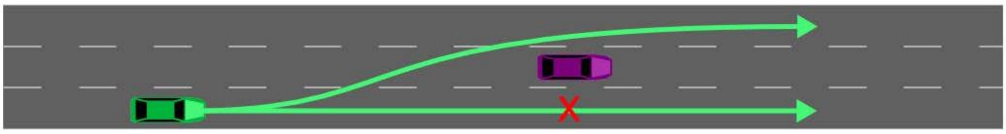


Figure 29 - Example of tactical lane change: the green vehicle is faster than the purple one and to prevent slow down it change to the left to overtake its leader

5.1.2.4 Regulatory change

In the model, the regulation lane change defines the driver's behavior to keep the right and clear the left lane (defined as a lane of traffic rules) as soon as possible, if not used for overtaking maneuvers. This is regulated by the variable *KeepRightProbabilty* that activates a change to the right lane when a threshold value is exceeded.

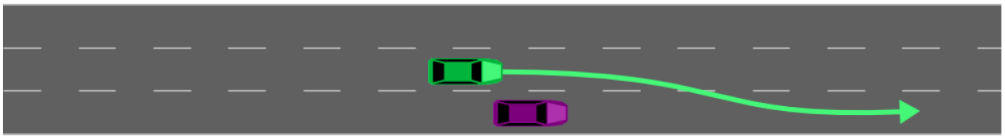


Figure 30 - Example of regulatory lane change: after the green vehicle complete the overtaking maneuver, it returns on the right lane

5.1.2.5 Teleporting

Currently, when a deadlock occurs the lane-changing model solves this problem in a non-standard and fictitious way by teleporting the vehicles after a defined time interval has elapsed. A teleported vehicle is removed from the network and moved along its route with the average speed of the edge it was removed from. The vehicle is reinserted into the network if there is enough place to be placed on a lane which allows to continue its drive. Consequently a vehicle may teleport multiple times within one simulation.

5.1.3 Intersection model

The behavior of vehicles, when approaching and crossing an intersection, is of immense importance in microscopic traffic simulation. Here the vehicles need to avoid collision with any vehicle that crosses their path. This requires the management of different types of intersections that are found in reality as priority intersections, right-first-left rules and traffic lights. In the intersection model built into SUMO, when a vehicle approaching an intersection, the software computes how long it will occupy the junction and check all approaching vehicles in all foe links of its entry link. If the requested time slot is separated from all approaching foe time slots by a suitable safety gap (depending on the speed difference between the vehicle and its approaching foes) the vehicle can pass the entry link and thus enter the intersection. In the model, moreover, a vehicle informs the entry links to the next few intersections on its current path about its approach and this allows the other vehicles to adjust their speed. During the evolution of SUMO the model has experienced a growing increase in complexity and in the current versions, a concept of "impatience" is implemented that allows vehicles that were waiting over a given threshold to enter the junction even if it means that vehicles with priority have to slow down a bit.

5.2 Implementation of the network in SUMO

The process followed to replicate the analyzed network on SUMO involves the subsequent steps: at first the map was imported into the simulator, then the traffic demand was created and finally, to run the simulation, the configuration file was generated. In order to reproduce different scenarios, two different networks were created: one representing the current situation and the other the optimized one.

5.2.1 Network building

The network file is required in the XML format and contains information on how junctions (nodes) are connected with roads (edges consisting of one or more lanes), how lanes are connected at junctions, what are the top speeds and shapes of lanes and also information about traffic light logic.

Two main tools exist to generate such network:

- NETGENERATE to create an abstract road map
- NETCONVERT to convert network from a different source into the SUMO-format.

The source used for extracting data was Open Street Map (OSM) (Figure 31). This website allows to download and save street data on OSM file format, selecting a rectangular area from the map or specifying a bounding box with geographic coordinates.

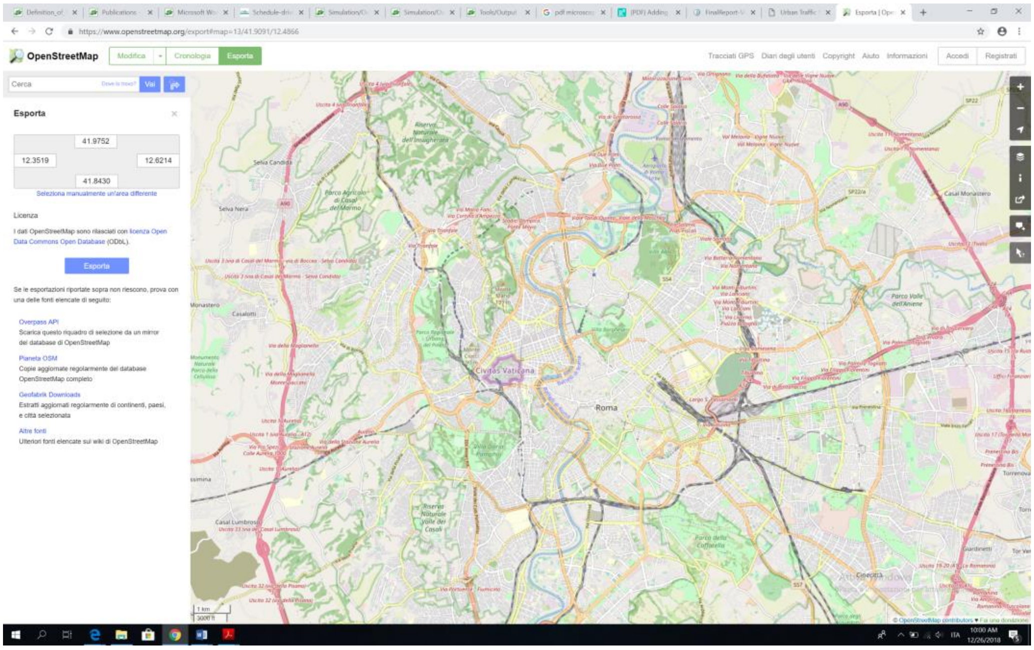


Figure 31 - Browser interface for the OpenStreetMap web page

Then using **<u>NETCONVERT</u>** tool, the OSM files can be transformed into road network structure file that SUMO can read. The following call to **NETCONVERT** is used (implemented) to convert the OSM file "map.osm.xml" into "map.net.xml":

```
netconvert --osm-files map.osm.xml -o map.net.xml
```

Some sample codes of the map.net.xml file are as follows:

- edge is a connection between two nodes ("junctions") and includes the definitions of lanes it consists of:

```
<edge id="<ID>" from="<FROM_NODE_ID>" to="<TO_NODE_ID>"
priority="<PRIORITY>">
        <lane id="<ID>_0" index="0" speed="<SPEED>" length="<LENGTH>"
            shape="0.00,495.05,248.50,495.05"/>
       <lane id="<ID>_1" index="1" speed="<SPEED>" length="<LENGTH>"
            shape="0.00,498.35,2.00,248.50,498.35,3.00"/>
 </edge>
```

- junction represents the area where different streams cross, including the right-of-way rules vehicles have to follow when crossing the intersection:

```
<junction id="<ID>" type="<JUNCTION_TYPE>" x="<X-POSITION>" y="<Y-POSITION>" incLanes="<INCOMING_LANES>" intLanes="<INTERNAL_LANES>"/>
 </junction>
```

- traffic light program defines the phases of a traffic light:

```
<tlLogic id="<ID>" type="<ALGORITHM_ID>" programID="<PROGRAM_ID>"
   offset="<TIME_OFFSET>">
    <phase duration="<DURATION#1>" state="<STATE#1>"/>
    <phase duration="<DURATION#1>" state="<STATE#1>"/>
</tlLogic>
```

5.2.1.1 Traffic lights setting

Normally, NETCONVERT generates traffic lights and programs for junctions during the computation of the networks, adding them in the map.net.xml file. The XML definition of a traffic controller includes the ID of traffic light, the type (static, actuated or delay-based), the id of the traffic light program, the initial time offset of the program and some attributes which describe the phase, like the duration and the state:

```
<tlLogic id="0" programID="my_program" offset="0" type="static">
  <phase duration="31" state="GGggrrrrGGggrrrr"/>
  <phase duration="5"  state="yyggrrrryyggrrrr"/>
  <phase duration="6"  state="rrGGrrrrrrGGrrrr"/>
  <phase duration="5"  state="rryyrrrrrryyrrrr"/>
</tlLogic>
```

The programs imported by NETCONVERT, however, differ from those set in reality and the NETEDIT tool is used to manage and modify the duration of the semaphores. NETEDIT is a visual network editor that includes a GUI, making the edition quite user-friendly. The Figure 32 shows an example of traffic light visualization on NETEDIT.

To replicate the scenarios to be simulated, all TLS programs have been modified for each intersection: in one file the durations of the traffic lights have been set for the current situation and in the other the traffic lights have been edited for the optimized scenario.

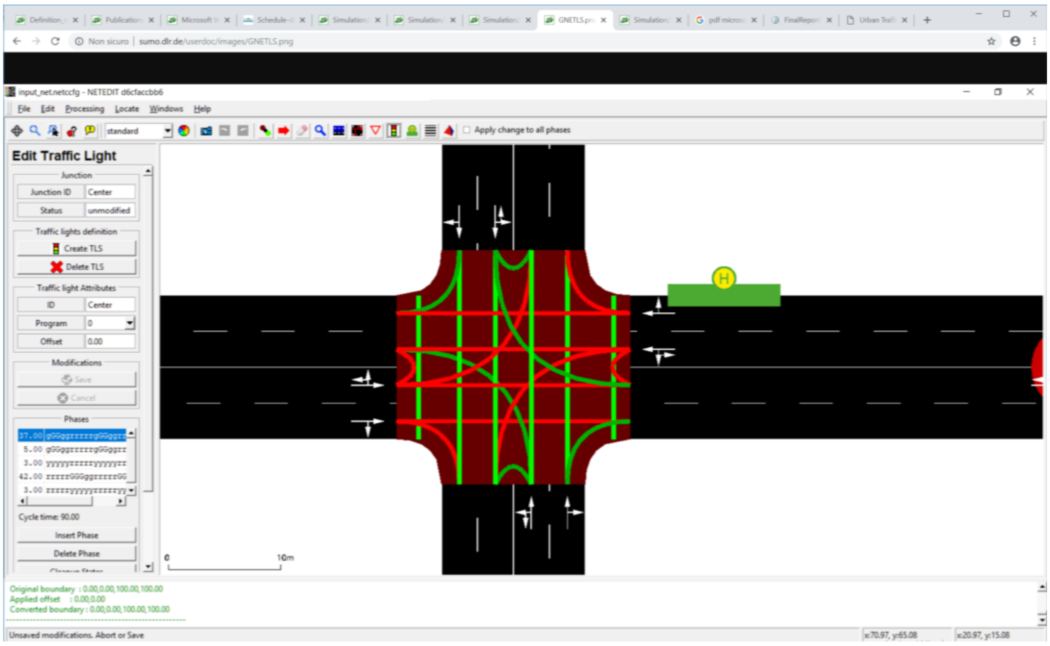


Figure 32 - Example of traffic light on NETEDIT

5.2.1.2 Detectors

Detectors in SUMO are additionals and they save information about vehicle that passed over a certain position on the lane. In the simulation Lanearea Detectos (E2) are used, which capture traffic on an area along a lane or lanes. A Detectors file, describing where detectors are located in the network, has been created and added to the configuration file. The file format is as follows:

```
<additional>
  <e2Detector id="<ID>" length="<DETECTOR_LENGTH>"  lane="<LANE_ID>"
     pos="<START_POSITION_ON_FIRST_LANE>"
freq="<AGGREGATION_TIME>" file="<OUTPUT_FILE>"
</additional>
```

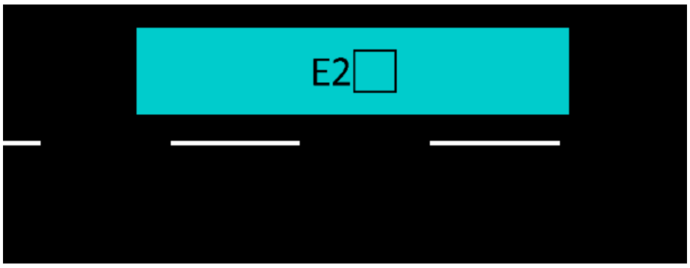


Figure 33 - e2Detector

5.2.2 Demand modelling

After having generated a network, a traffic demand file is needed. It includes the route, defined by edges and the physical property of vehicles such as type of vehicle, acceleration, deceleration, length and maximum speed. Two separate files were inserted for private vehicles and public transport.

5.2.2.1 Generation of vehicle flows

The measured traffic flows at the intersections were used for the generation of vehicles and their routes. The map.rou.xml file was manually written and it is structured as a series of xml tags as shown below:

```
<routes>
   <vType id="type1" length="4" maxSpeed="13" carFollowModel="Krauss"
     accel="2.6" decel="4.5" sigma="0.5"/>
   <route id="route0" edges=" id_beginning id_middle id_end"/>
    ….
   <flow id="0" type="type1" route="route0" begin="0" end="5400" number="23"
     departLane="free" departPos="free"/>
    ….
</routes>
```

These tags define the basic properties of vehicles, including also additional parameters related to car-following, lane-changing and intersection model, determine the route as a collection of successive edges and distribute each path to a flow. The definition of flows allows to assign each route to a specific quantity of vehicles indicated with the attribute "number", which has the same parameters and which will be generated periodically during the interval specified between the "begin" and "end" attributes.

5.2.2.2 Additional file for public transport

To introduce public transport in the network, an additional file, named bus.stop.xml, is written. The file specifies the bus stops location (name of lane, begin and end position on the lane) , the attributes of bus characteristics and the paths of each line. In addition, vehicles must be informed that they must stop at a bus stop, so a list of stop places is also included in the route definition. Each stop place is described by two attributes, "bus_stop" and "duration" where "bus_stop" is the name of the bus stop the vehicle shall halt at and "duration" is the time the vehicle shall wait at the bus stop in seconds.

```xml
<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="http://sumo.dlr.de/xsd/additional_file.xsd">
   <busStop id="busstop1" lane="2/1to1/1_0" startPos="20" endPos="40"
lines="5,14,19"/>
   <busStop id="busstop2" lane="1/2to0/2_0" startPos="20" endPos="40"
lines="5,14,19"/>
   <busStop id="busstop3" lane="0/1to0/0_0" startPos="20" endPos="40"
lines="5,14,19"/>
   <busStop id="busstop4" lane="1/0to2/0_0" startPos="20" endPos="40"
lines="5,14,19"/>

<vType id="tram" accel="2" decel="1.5" sigma="0.1" length="33" maxSpeed="13"
     vClass="tram" personCapacity="270"/>

   <vehicle id="0" type="tram" depart="0" color="1,1,0">
      <route edges=" id_beginning id_middle id_end"/>
      <stop busStop="busstop1" duration="30"/>
      <stop busStop="busstop2" duration="30"/>
      <stop busStop="busstop3" duration="30"/>
      <stop busStop="busstop4" duration="30"/>
   </vehicle>
</additional>
```

5.2.3 Simulation outputs

SUMO allows to generate a large number of different measures, reported in specific files in XML-format by default. Some of the available outputs are:

- Queue output: lane-based calculation of the actual queue in front of a junction;
- Trip information output: aggregated information about each vehicle's journey (i.e. departure time, arrival time, duration, route length);
- Emission output: emission values of all vehicles for every simulation step;

- Simulation state statistics output: information about the current state of the simulation (i.e. number of vehicles that are loaded, inserted, running, waiting to be inserted, have reached their destination and how long they needed to finish the route);

Per default, all are disabled, and have to be triggered individually by adding the text below in the SUMO configuration file:

```
<output>
    <queue-output value="queue.out.xml"/>
   <tripinfo-output value="tripinfo.out.xml"/>
   <emission-output value="emission.out.xml"/>
   <summary-output value="summary.out.xml"/>
</output>
```

5.2.4 Configuration and execution of simulation

The last step is to run the simulation, defining the configuration file map.sumo.cfg. Within the file are specified the various input files, described in the previous paragraphs and the time period when the simulation will begin and end, according to the following structure:

```
<configuration>
    <input>
      <net-file value="map.net.xml"/>
      <route-files value="map.rou.xml"/>
     <additional-files value="bus.stop.xml,detectors.xml"/>
    </input>
    <time>
     <begin value="0"/>
     <end value="10000"/>
    </time>
</configuration>
```

It is executable in two different ways:

- using the command line directly through the following call:

```
sumo-gui  map.sumo.cfg
```

- running the configuration file with SUMO-GUI for a graphic representation of the simulation. (Figure 34)

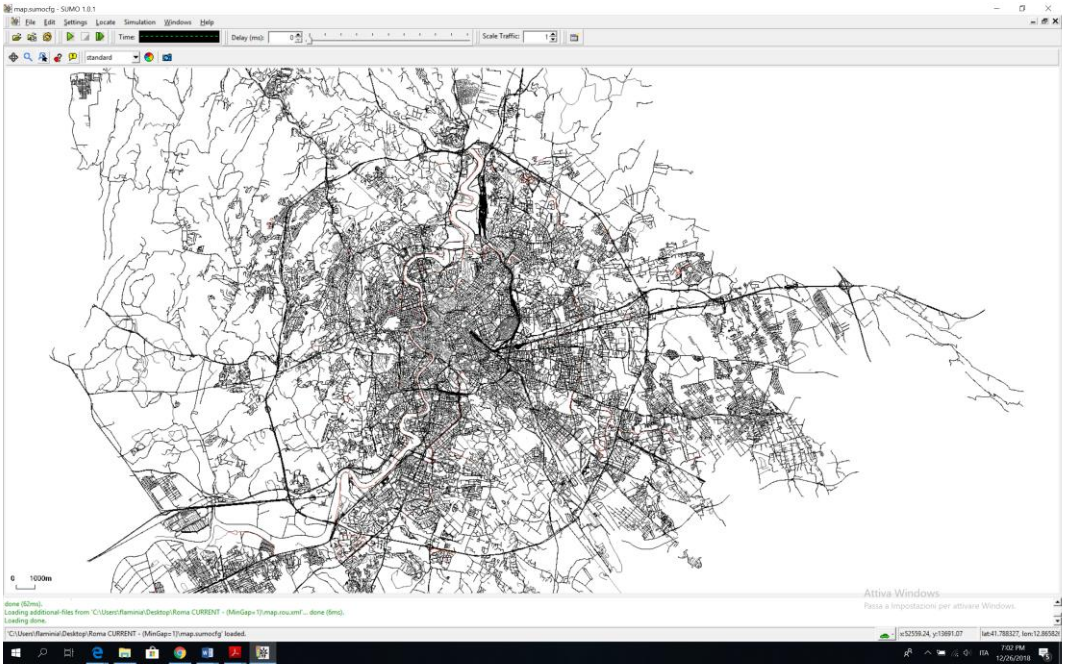


Figure 34 – Execution of simulation on SUMO-GUI

5.3 Simulation results

Once the configuration file was created, the model was executed for the two scenarios to be simulated: the first representing the current situation and the second one representing the scenario optimized with SINTAC. Using the detectors installed along the network, at each approach of each intersection, a vast amount of measures has been generated. The attributes considered in order to perform a comparison between the two scenarios are:

- *meanTimeLoss* that is the average time loss (in seconds) per vehicle in the corresponding detection interval
- *nVehSeen* that is the number of vehicle that was on the detector in the corresponding detection interval

These attributes allow computing the delay of vehicles at each intersection, the total delay along the artery separately for vehicles and transit and also the delay for the lateral approaches and the entire network. The results are reported in the following tables:

	CURRENT SCENARIO	***OPTIMIZED SCENARIO***	
	Intersection Delay [s]		***Variation***
Via Prenestina-Via Palmiro Togliatti	40	24	***-40%***
Via Prenestina-Centro Servizi	25	11	***-57%***
Via Prenestina-Via G.B.Valente	34	15	***-57%***
Via Prenestina-Via Collatina	25	25	***0%***
Via Prenestina-Via Bresadola	9	4	***-58%***
Via Prenestina-Tor de Schiavi	40	22	***-44%***
Via Prenestina – Via Sabaudia	6	1	***-83%***
Via Prenestina-Via Olevano Romano	14	11	***-19%***
Via Prenestina-Via Dignano D'Istria	9	9	***-5%***
Via Prenestina-Via Ronchi	13	7	***-45%***

Table 33 – Intersection delay for the two scenarios

	CURRENT SCENARIO	*OPTIMIZED SCENARIO*	
	Intersection Delay [s]		***Variation***
Via Prenestina-Largo Telese	15	10	***-32%***
Via Prenestina-Largo Preneste	31	32	***2%***
Via Prenestina-Via di Portonaccio	17	4	***-75%***
Via Prenestina-Via Giovenale	12	8	***-33%***
Via Prenestina-Via Fieramosca	21	15	***-31%***
P.le Prenestino-C.ne Casilina	7	5	***-30%***
Via Prenestina-Dep. ATAC	5	9	***75%***
Via Prenestina-P.le Labicano	25	12	***-54%***
Piazza di Porta Maggiore	18	17	***-5%***

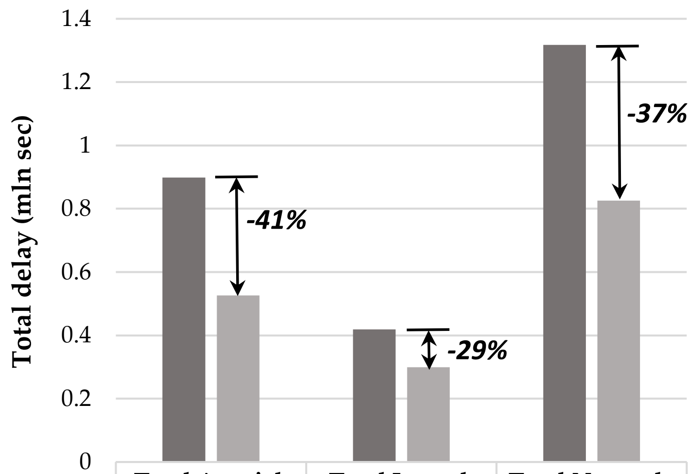
Table 33 – Comparison of intersection delay for the two scenarios

CURRENT SCENARIO	*OPTIMIZED SCENARIO*	*Variation*
Total Artery Delay [s]		
898644	526061	***-41%***
Total Lateral Delay [s]		
419004	299584	***-29%***
Total Network Delay [s]		
1317647	825645	***-37%***

Table 34 - Comparison of total private vehicle delay for the two scenarios

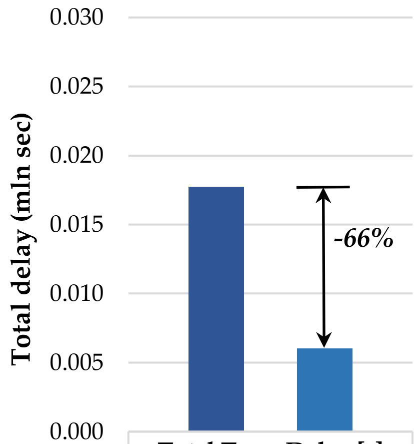
CURRENT SCENARIO	*OPTIMIZED SCENARIO*	*Variation*
Total Tram Delay [s]		
17749	10930	***-66%***

Table 35 - Comparison of total tram delay for the two scenarios



	Total Arterial Delay	Total Lateral Delay	Total Network Delay
CURRENT SCENARIO	898644	419004	1317647
OPTIMIZED SCENARIO	526061	299584	825645

Graph 3 - Comparison Total delay for the two scenarios



	Total Tram Delay [s]
CURRENT SCENARIO	17749
OPTIMIZED SCENARIO	6020

Graph 4 - Total tram delay for the two scenarios

Results from Tables 32 and 33 show that the implementation of the solution found with SINTAC may minimize the delay in most of the intersections. In particular, it emerges that the most complex nodes of the network such as Palmiro Togliatti, Tor de Schiavi, Largo Preneste, Portonaccio, Labicano and Porta Maggiore, can benefit from a significant reduction of delay.

For the entire corridor of Via Prenestina, the total benefit is to 41%, while for the side streets of 29%. Therefore, the improvement in delay reduction for the entire network may be of 37%. Considering public transport, the benefits achieved from the optimal solution proposed are 66%.

The results of the simulation validate the effectiveness of the signal synchronization respects to the existing situation with uncoordinated intersections.

6. CURRENT STATE EVALUATION

The delay is the most important measure of effectiveness at a signalized intersection because it refers to the amount of lost travel time, fuel consumption and discomfort for the drivers. In this study, the delay was chosen a reference indicator to compare the performance of 19 signalized intersections under different scenarios. The accurate prediction of delay is, therefore, very important, but its precise estimation is difficult due to random traffic flows and other uncontrollable factors. In the previous chapters, the delays related to the current traffic conditions of the study network has been calculated with different models. This chapter compares these results, evaluating the intersection delays calculated with the HCM methodology and SINTAC. Evaluation is performed with reference to the current state.

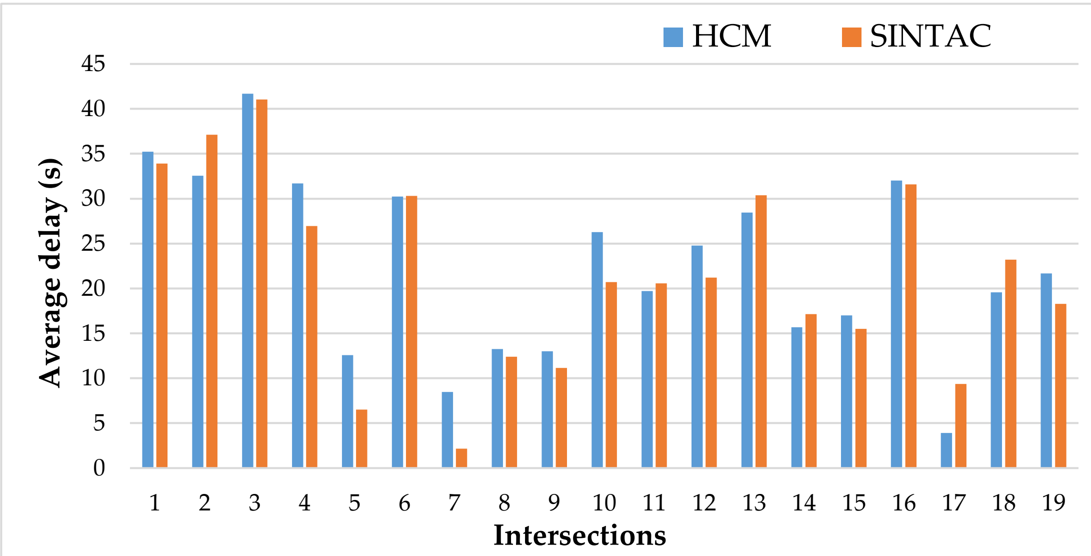
The following table reports the delays obtained by the two different models:

		Total intersection flow (veh/h)	*Intersection delay [s]*		*Difference percentage SINTAC-HCM*
			HCM	**SINTAC**	
1	Togliatti	4435	35	34	-4%
2	Centro Servizi	2896	33	37	14%
3	G.B.Valente	3253	42	41	-2%
4	Collatina	3495	32	27	-15%
5	Bresadola	2801	13	6	-48%
6	Tor de Schiavi	4480	30	30	0%
7	Sabaudia	2434	8	2	-74%
8	Olevano Romano	2794	13	12	-6%
9	Dignano D'Istria	3058	13	11	-14%
10	Ronchi	2828	26	21	-21%

Table 36 - Intersection delays of current state obtained from two different models

		Total intersection flow (veh/h)	*Intersection delay [s]*		*Difference percentage SINTAC-HCM*
			HCM	**SINTAC**	
11	Largo Telese	3261	20	21	*4%*
12	Largo Preneste	4346	25	21	*-14%*
13	Portonaccio	3031	28	30	*7%*
14	Giovenale	2512	16	17	*9%*
15	Fieramosca	3091	17	15	*-9%*
16	C.ne Casilina	2541	32	32	*-1%*
17	Dep. ATAC	2153	4	9	*139%*
18	P.le Labicano	2825	20	23	*18%*
19	Porta Maggiore	2974	22	18	*-16%*

Table 36 - Intersection delays of current state obtained from two different models



Graph 5 – Comparison delays of the three models

From the graph it is possible to observe that the most critical intersections, with the highest delays, are the first four together with the node 6,13 and 16. The intersections 2 and 3 are located between two complex nodes which intersect two important streets, respectively Via Togliatti and Via Collatina characterized by high flows that feed the artery.

Also the nodes 6, 13 and 16 are crucial points of the network where other important roads converge.

For a clearer view of the configuration of the intersections and the allowed maneuvers, in the appendix the images of each junction are reported.

7. VALIDATION OF SUMO MODEL

To achieve adequate reliability of the simulation model results and to test its accuracy in replicating the traffic system, its validation is performed. The process consists of comparing the traffic data collected from the field and the traffic data generated by the model. In particular, the exiting flow from each intersection is used as the validation measure.

The observed and simulated data are reported below on the scatter plot and the R-squared is determined:

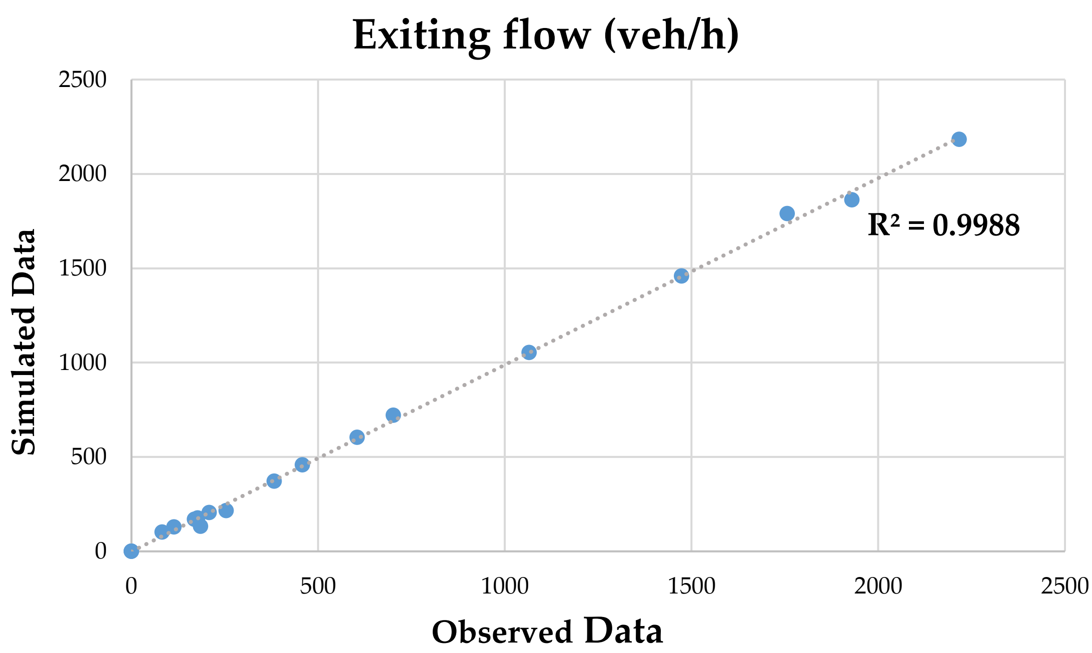


Figure 35 - Comparison of observed and simulated exiting flow

The value of the correlation coefficient (R^2) close to 1 indicates that the simulation model almost perfectly fits the data. To better quantify the relationship between the models, other measures of goodness-of-fit are used: the root-mean-square error (*RMSE*), the root-mean-square percent error (*RMSPE*), the mean error (*ME*), the mean percent error (MPE), the mean absolute error (*MAE*) and the mean percent absolute error (*MAPE*). These measures are calculated as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(X_n^{sim} - X_n^{obs})^2} \qquad RMSPE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{X_n^{sim} - X_n^{obs}}{X_n^{obs}}\right)^2}$$

$$ME = \frac{1}{N}\sum_{n=1}^{N}(X_n^{sim} - X_n^{obs}) \qquad MPE = \frac{100}{N}\sum_{n=1}^{N}\left(\frac{X_n^{sim} - X_n^{obs}}{X_n^{obs}}\right)$$

$$MAE = \frac{1}{N}\sum_{n=1}^{N}(|X_n^{sim} - X_n^{obs}|) \qquad MAPE = \frac{100}{N}\sum_{n=1}^{N}\left(\frac{|X_n^{sim} - X_n^{obs}|}{X_n^{obs}}\right)$$

The values are reported in the following table:

RMSE	*RMSPE*	*ME*	*MPE*	*MAE*	*MAPE*
26	10%	-4	-1%	17	5%

Table 37 - Goodness-of-fit measures of model validation

The obtained results validate the good ability of the model in replicating reality.

7.1 Model comparison

After validating the model, in this section it is shown a comparison between the intersection delays of the current state obtained by the simulation and those computed by SINTAC:

		Total intersection flow (veh/h)	*Intersection delay [s]*		*Difference percentage SINTAC-SUMO*
			SINTAC	SUMO	
1	Togliatti	4434.6	34	40	*-15%*
2	Centro Servizi	2896	37	25	*46%*
3	G.B.Valente	3253	41	34	*20%*
4	Collatina	3495	27	25	*9%*
5	Bresadola	2801	6	9	*-31%*
6	Tor de Schiavi	4480	30	40	*-24%*
7	Sabaudia	2434	2	6	*-64%*
8	Olevano Romano	2794	12	14	*-13%*
9	Dignano D'Istria	3058	11	9	*24%*
10	Ronchi	2828	21	13	*57%*
11	Largo Telese	3261	21	15	*39%*
12	Largo Preneste	4346	21	31	*-54%*
13	Portonaccio	3031	30	17	*83%*
14	Giovenale	2512	17	12	*41%*
15	Fieramosca	3091	15	21	*-27%*
16	C.ne Casilina	2541	32	7	*328%*
17	Dep. ATAC	2153	9	5	*87%*
18	P.le Labicano	2825	23	25	*-7%*
19	Porta Maggiore	2974	18	18	*3%*
					27%

Table 38 – Comparison SINTAC and SUMO model

Calculating the difference percentage between the two models and then the mean of the values, in order to have a comparison parameter, it emerges that SINTAC overestimates the delay of 27% compared to SUMO.

This result can be motivated by the different structure of the model in calculating delays:

- SINTAC computes the delay simulating the vehicles as a platoon and classifying it in different typologies;
- SUMO reports the delay as the time lost due to driving below the maximum possible speed and includes delays resulting from conditions such as congestion and car following. In this microsimulator there are no factors that take into account platoon progression.

As the last comparison, the total delay for the corridor, the lateral approaches and the entire network computed with SINTAC and SUMO, is reported:

CURRENT SCENARIO

SINTAC	SUMO	*Variation*
Total Arterial Delay [s]		
962253	1032759	**7%**
Total Lateral Delay [s]		
407320	397971	**-2%**
Total Network Delay [s]		
1369572	1430730	**4%**

Table 39 – Comparison of results SINTAC-SUMO

8. CONCLUSIONS AND FUTURE WORKS

In this study, a project has been presented aimed to improve the traffic performances of Via Prenestina in Rome, an urban corridor hosting a tramway on a separate lane and composed of 19 signalized intersections. The methodology applied to signal control design consists in optimizing and synchronizing the timing of signals at successive intersections along the artery and implementing transit signal priority with the aim to reduce the overall person delay, both for the passengers of tram and cars. The optimization of signal parameters was performed using SINTAC software, which applies a platoon-based model to simulate the vehicles and buses movement and calculate the delay. The results show a reduction of delay of 55% for the artery and of 35% for the entire network (artery and lateral approach). The benefit for the public transport is 83%.

The effectiveness of the solution was subsequently validated with the microscopic traffic simulator SUMO. A comparative analysis between the scenario with the current signals plan and that with the optimized traffic signals parameters was performed. The results confirm the positive impacts that the implementation of this synchronized traffic signals system with transit priority could have. The reduction of delay for the main corridor of Via Prenestina is of 49%, for the entire network of 40%, and for public transport of 32%.

The study demonstrates that the application of priority strategies for transit vehicles in signal optimization brings benefit, not only to public transport, but also to general traffic. The reduction of delays leads to improve the overall mobility of the study network.

This leads to a more reliable and attractive public transport and to less discomfort for private cars, reducing travel times as well as emissions and fuel consumptions.

Future research possibilities proposed include:

- the integration of ITS technologies such as GPS based Automatic Vehicle Location (AVL) and some advanced transportation software to obtain more accurate information with which to model and provide bus priority;
- a more detailed analysis of traffic flows also in the area adjacent to the study corridor to assess the possible installation of informative panels, as a support to traffic management, in order to divert the flows on alternative routes.

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10. APPENDIX

10.1 Saturation flow worksheets

- INTERSECTION 1: *Via Prenestina – Via Palmiro Togliatti*

Saturation Flow Rate											
	WB			EB			SB		NB		
Lane group		←		↗	→			↙↓	↰	↑	
Base saturation flow, s_0 [pc/h/ln]		1900		1900	1900			1900	1900	1900	
Number of lanes, N		3		1	2			3	2	2	
Lane width adjustment factor, f_W		0.967		0.967	0.967			0.967	1.044	1.044	
Heavy-vehicle adjustment factor, f_{HV}		1.000		1.000	1.000			1.000	1.000	1.000	
Grade adjustment factor, f_g		1.000		1.000	1.000			1.000	1.000	1.000	
Parking adjustment factor, f_p		1.000		1.000	1.000			1.000	1.000	1.000	
Bus blockage adjustment factor, f_{bb}		1.000		1.000	1.000			1.000	1.000	1.000	
Area type adjustment factor, f_a		1.000		1.000	1.000			1.000	1.000	1.000	
Lane utilization adjustment factor, f_{LU}		0.950		1.000	0.950			0.950	1.000	0.950	
Left-turn adjustment factor, f_{LT}		1.000		0.950	1.000			1.000	0.950	1.000	
Right-turn adjustment factor, f_{RT}		1.000		1.000	1.000			0.967	1.000	1.000	
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000		1.000	1.000			1.000	1.000	1.000	
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000		1.000	1.000			1.000	1.000	1.000	
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**5235**		**1745**	**3490**			**5064**	**3770**	**3770**	

- INTERSECTION 2: *Via Prenestina – Centro Servizi*

Saturation Flow Rate									
	WB			EB			SB		
Lane group		←		↗	→				↙
Base saturation flow, s_0 [pc/h/ln]		1900		1900	1900				1900
Number of lanes, N		3		1	2				1
Lane width adjustment factor, f_W		0.967		0.989	0.967				0.967
Heavy-vehicle adjustment factor, f_{HV}		0.980		0.990	0.980				0.990
Grade adjustment factor, f_g		1.000		1.000	1.000				1.000
Parking adjustment factor, f_p		1.000		1.000	1.000				1.000
Bus blockage adjustment factor, f_{bb}		1.000		1.000	1.000				1.000
Area type adjustment factor, f_a		1.000		1.000	1.000				1.000
Lane utilization adjustment factor, f_{LU}		0.950		1.000	0.950				1.000
Left-turn adjustment factor, f_{LT}		1.000		0.950	1.000				1.000
Right-turn adjustment factor, f_{RT}		1.000		1.000	1.000				0.850
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000		1.000	1.000				1.000
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000		1.000	1.000				1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**5132**		**1767**	**3421**				**1546**

- INTERSECTION 3: *Via Prenestina – Via G.B. Valente*

Saturation Flow Rate								
	WB		EB			SB		
Lane group								
Base saturation flow, s_0 [pc/h/ln]		1900	1900	1900		1900		1900
Number of lanes, N		3	1	2		1		2
Lane width adjustment factor, f_W		0.967	0.967	0.967		0.600		0.933
Heavy-vehicle adjustment factor, f_{HV}		0.980	0.990	0.980		0.990		0.990
Grade adjustment factor, f_g		1.000	1.000	1.000		1.000		1.000
Parking adjustment factor, f_p		1.000	1.000	1.000		1.000		1.000
Bus blockage adjustment factor, f_{bb}		1.000	1.000	1.000		1.000		1.000
Area type adjustment factor, f_a		1.000	1.000	1.000		1.000		1.000
Lane utilization adjustment factor, f_{LU}		0.950	1.000	0.950		1.000		1.000
Left-turn adjustment factor, f_{LT}		1.000	0.950	1.000		0.950		1.000
Right-turn adjustment factor, f_{RT}		0.975	1.000	1.000		1.000		0.850
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000	1.000	1.000		1.000		1.000
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000	1.000	1.000		1.000		1.000
Adjusted saturation flow, s [veh/h] **$s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$**		**5004**	**1728**	**3421**		**1072**		**2985**

- INTERSECTION 4: *Via Prenestina – Via Collatina*

Saturation Flow Rate										
	WB		EB		SB			NB		
Lane group										
Base saturation flow, s_0 [pc/h/ln]		1900		1900		1900			1900	
Number of lanes, N		3		3		2			2	
Lane width adjustment factor, f_W		0.967		0.967		1.267			1.267	
Heavy-vehicle adjustment factor, f_{HV}		0.980		0.980		0.990			0.990	
Grade adjustment factor, f_g		1.000		1.000		1.000			1.000	
Parking adjustment factor, f_p		1.000		1.000		1.000			1.000	
Bus blockage adjustment factor, f_{bb}		1.000		1.000		1.000			1.000	
Area type adjustment factor, f_a		1.000		1.000		1.000			1.000	
Lane utilization adjustment factor, f_{LU}		0.950		0.950		0.950			0.950	
Left-turn adjustment factor, f_{LT}		0.987		0.994		0.990			0.993	
Right-turn adjustment factor, f_{RT}		0.994		0.996		0.966			0.965	
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000		1.000		1.000			1.000	
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000		1.000		1.000			1.000	
Adjusted saturation flow, s [veh/h] **$s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$**		**5032**		**5081**		**4332**			**4339**	

• INTERSECTION 5: *Via Prenestina – Via Bresadola*

Saturation Flow Rate								
	WB		EB		SB		NB	
Lane group								
Base saturation flow, s_0 [pc/h/ln]		1900		1900		1900		1900
Number of lanes, N		3		3		2		2
Lane width adjustment factor, f_W		0.967		0.967		1.267		1.267
Heavy-vehicle adjustment factor, f_{HV}		0.980		0.980		0.990		0.990
Grade adjustment factor, f_g		1.000		1.000		1.000		1.000
Parking adjustment factor, f_p		1.000		1.000		1.000		1.000
Bus blockage adjustment factor, f_{bb}		1.000		1.000		1.000		1.000
Area type adjustment factor, f_a		1.000		1.000		1.000		1.000
Lane utilization adjustment factor, f_{LU}		0.950		0.950		0.950		0.950
Left-turn adjustment factor, f_{LT}		0.987		0.994		0.990		0.993
Right-turn adjustment factor, f_{RT}		0.994		0.996		0.966		0.965
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000		1.000		1.000		1.000
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000		1.000		1.000		1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**5032**		**5081**		**4332**		**4339**

• INTERSECTION 6: *Via Prenestina – Via Tor de Schiavi*

Saturation Flow Rate										
	WB			EB			SB		NB	
Lane group										
Base saturation flow, s_0 [pc/h/ln]		1900	1900		1900	1900	1900	1900	1900	1900
Number of lanes, N		2	1		2	1	1	2	2	1
Lane width adjustment factor, f_w		0.967	1.00		0.967	1	0.967	0.967	0.967	0.967
Heavy-vehicle adjustment factor, f_{HV}		0.980	0.990		0.980	0.962	0.980	0.990	0.990	0.971
Grade adjustment factor, f_g		1.000	1.00		1.000	1.00	1.00	1.000	1.000	1.00
Parking adjustment factor, f_p		1.000	1.00		1.000	1.00	1.00	1.000	1.000	1.00
Bus blockage adjustment factor, f_{bb}		1.000	1.00		1.000	1.00	1.00	1.000	1.000	1.00
Area type adjustment factor, f_a		1.000	1.00		1.000	1.00	1.00	1.000	1.000	1.00
Lane utilization adjustment factor, f_{LU}		0.950	1.00		0.950	1.00	1.00	0.950	0.950	1.00
Left-turn adjustment factor, f_{LT}		1.000	1.00		1.000	1.00	1.00	1.000	0.992	1.00
Right-turn adjustment factor, f_{RT}		1.000	0,85		1.000	0,85	1.00	0.970	1.000	0.85
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000	1.00		1.000	1.00	1.00	1.000	1.000	1.00
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000	1.00		1.000	1.00	1.00	1.000	1.000	1.00
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**3421**	**1881**		**3421**	**1827**	**1801**	**3352**	**3427**	**1516**

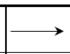
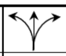
- INTERSECTION 7: *Via Prenestina – Via Sabaudia*

Saturation Flow Rate						
	WB			EB		
Lane group		←			→	
Base saturation flow, s_0 [pc/h/ln]		1900			1900	
Number of lanes, N		3			2	
Lane width adjustment factor, f_W		1.044			1.044	
Heavy-vehicle adjustment factor, f_{HV}		0.980			0.980	
Grade adjustment factor, f_g		1.000			1.000	
Parking adjustment factor, f_p		1.000			1.000	
Bus blockage adjustment factor, f_{bb}		1.000			1.000	
Area type adjustment factor, f_a		1.000			1.000	
Lane utilization adjustment factor, f_{LU}		0.950			0.950	
Left-turn adjustment factor, f_{LT}		1.000			1.000	
Right-turn adjustment factor, f_{RT}		1.000			1.000	
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000			1.000	
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000			1.000	
Adjusted saturation flow, s [veh/h] $s = s_0\, N\, f_W\, f_{HV}\, f_g\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb}$		**5545**			**3697**	

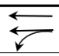
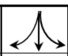
- INTERSECTION 8: *Via Prenestina – Via Olevano Romano*

Saturation Flow Rate									
	WB			EB			NB		
Lane group		←			→	↴	↰		↱
Base saturation flow, s_0 [pc/h/ln]		1900			1900	1900	1900		1900
Number of lanes, N		2			2	1	1		1
Lane width adjustment factor, f_w		0.967			0.967	0.967	1.378		1.378
Heavy-vehicle adjustment factor, f_{HV}		0.980			0.980	0.990	1.000		1.000
Grade adjustment factor, f_g		1.000			1.000	1.000	1.000		1.000
Parking adjustment factor, f_p		1.000			1.000	1.000	1.000		1.000
Bus blockage adjustment factor, f_{bb}		1.000			1.000	1.000	1.000		1.000
Area type adjustment factor, f_a		1.000			1.000	1.000	1.000		1.000
Lane utilization adjustment factor, f_{LU}		0.950			0.950	1.000	1.000		1.000
Left-turn adjustment factor, f_{LT}		1.000			1.000	1.000	0.950		1.000
Right-turn adjustment factor, f_{RT}		1.000			1.000	0.850	1.000		0.938
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000			1.000	1.000	1.000		1.000
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000			1.000	1.000	1.000		1.000
Adjusted saturation flow, s [veh/h] $s = s_0\, N\, f_w\, f_{HV}\, f_g\, f_p\, f_{bb}\, f_a\, f_{LU}\, f_{LT}\, f_{RT}\, f_{Lpb}\, f_{Rpb}$		**3421**			**3421**	**1546**	**2487**		**2456**

• INTERSECTION 9: *Via Prenestina – Via Dignano D'Istria*

Saturation Flow Rate			
	WB	EB	NB
Lane group			
Base saturation flow, s_0 [pc/h/ln]	1900	1900	1900
Number of lanes, N	3	3	1
Lane width adjustment factor, f_W	0.967	0.967	1.433
Heavy-vehicle adjustment factor, f_{HV}	1.000	1.000	1.000
Grade adjustment factor, f_g	1.000	1.000	1.000
Parking adjustment factor, f_p	1.000	1.000	1.000
Bus blockage adjustment factor, f_{bb}	1.000	1.000	1.000
Area type adjustment factor, f_a	1.000	1.000	1.000
Lane utilization adjustment factor, f_{LU}	0.950	0.950	0.950
Left-turn adjustment factor, f_{LT}	1.000	1.000	0.989
Right-turn adjustment factor, f_{RT}	1.000	1.000	0.962
Left-turn ped/bike adjustment factor, f_{Lpb}	1.000	1.000	1.000
Right-turn ped/bike adjustment factor, f_{Rpb}	1.000	1.000	
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**5235**	**5235**	**2460**

• INTERSECTION 10: *Via Prenestina – Via Ronchi*

Saturation Flow Rate			
	WB	EB	SB
Lane group			
Base saturation flow, s_0 [pc/h/ln]	1900	1900	1900
Number of lanes, N	3	3	1
Lane width adjustment factor, f_W	0.967	0.967	1.433
Heavy-vehicle adjustment factor, f_{HV}	0.980	0.980	0.990
Grade adjustment factor, f_g	1.000	1.000	1.000
Parking adjustment factor, f_p	1.000	1.000	1.000
Bus blockage adjustment factor, f_{bb}	1.000	1.000	1.000
Area type adjustment factor, f_a	1.000	1.000	1.000
Lane utilization adjustment factor, f_{LU}	0.950	0.950	0.950
Left-turn adjustment factor, f_{LT}	0.994	1.000	0.989
Right-turn adjustment factor, f_{RT}	1.000	0.987	0.973
Left-turn ped/bike adjustment factor, f_{Lpb}	1.000	1.000	1.000
Right-turn ped/bike adjustment factor, f_{Rpb}	1.000	1.000	1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**5101**	**5067**	**2466**

• INTERSECTION 11: *Via Prenestina – Largo Talese*

Saturation Flow Rate					
	WB	EB	SB	NB	
Lane group					
Base saturation flow, s_0 [pc/h/ln]	1900	1900	1900	1900	1900
Number of lanes, N	2	3	1	2	1
Lane width adjustment factor, f_W	1.044	0.967	1.156	1.156	1.156
Heavy-vehicle adjustment factor, f_{HV}	0.980	0.980	0.980	0.990	0.980
Grade adjustment factor, f_g	1.000	1.000	1.000	1.000	1.00
Parking adjustment factor, f_p	1.000	1.000	1.000	1.000	1.00
Bus blockage adjustment factor, f_{bb}	1.000	1.000	1.000	1.000	1.00
Area type adjustment factor, f_a	1.000	1.000	1.000	1.000	1.00
Lane utilization adjustment factor, f_{LU}	0.950	0.950	0.950	0.950	1.00
Left-turn adjustment factor, f_{LT}	1.000	1.000	0.992	0.970	1.00
Right-turn adjustment factor, f_{RT}	0.987	0.971	0.974	1.000	0.85
Left-turn ped/bike adjustment factor, f_{Lpb}	1.000	1.000	1.000	1.000	1.00
Right-turn ped/bike adjustment factor, f_{Rpb}	1.000	1.000	1.000	1.000	1.00
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**3649**	**4982**	**1976**	**4004**	**1830**

• INTERSECTION 12: *Via Prenestina – Largo Preneste*

Saturation Flow Rate					
	WB	EB	SB	NB	
Lane group					
Base saturation flow, s_0 [pc/h/ln]	1900	1900	1900	1900	1900
Number of lanes, N	3	3	3	1	2
Lane width adjustment factor, f_w	0.967	0.967	0.967	1.022	1.022
Heavy-vehicle adjustment factor, f_{HV}	1.000	1.000	1.000	1.000	1.000
Grade adjustment factor, f_g	1.000	1.000	1.000	1.000	1.000
Parking adjustment factor, f_p	1.000	1.000	1.000	1.000	1.000
Bus blockage adjustment factor, f_{bb}	1.000	1.000	1.000	1.000	1.000
Area type adjustment factor, f_a	1.000	1.000	1.000	1.000	1.000
Lane utilization adjustment factor, f_{LU}	0.950	0.950	0.950	1.000	1.000
Left-turn adjustment factor, f_{LT}	1.000	0.989	0.985	0.950	1.000
Right-turn adjustment factor, f_{RT}	1.000	0.994	0.968	1.000	0.973
Left-turn ped/bike adjustment factor, f_{Lpb}	1.000	1.000	1.000	1.000	1.000
Right-turn ped/bike adjustment factor, f_{Rpb}	1.000	1.000	1.000	1.000	1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**5235**	**5145**	**4991**	**1845**	**3779**

• INTERSECTION 13: *Via Prenestina – Via di Portonaccio*

Saturation Flow Rate									
	WB			EB			NB		
Lane group	↙	←			→	↘			↗
Base saturation flow, s_0 [pc/h/ln]	1900	1900			1900	1900			1900
Number of lanes, N	1	2			2	1			1
Lane width adjustment factor, f_w	0.967	0.967			0.967	0.967			1.378
Heavy-vehicle adjustment factor, f_{HV}	1.000	1.000			1.000	1.000			1.000
Grade adjustment factor, f_g	1.000	1.000			1.000	1.000			1.000
Parking adjustment factor, f_p	1.000	1.000			1.000	1.000			1.000
Bus blockage adjustment factor, f_{bb}	1.000	1.000			1.000	1.000			1.000
Area type adjustment factor, f_a	1.000	1.000			1.000	1.000			1.000
Lane utilization adjustment factor, f_{LU}	1.000	0.950			0.950	1.000			1.000
Left-turn adjustment factor, f_{LT}	0.950	1.000			1.000	1.000			1.000
Right-turn adjustment factor, f_{RT}	1.000	1.000			1.000	0.850			0.850
Left-turn ped/bike adjustment factor, f_{Lpb}	1.000	1.000			1.000	1.000			1.000
Right-turn ped/bike adjustment factor, f_{Rpb}	1.000	1.000			1.000	1.000			1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**1745**	**3490**			**3490**	**1561**			**2225**

• INTERSECTION 14: *Via Prenestina – Via Giovenale*

Saturation Flow Rate					
	WB		EB		
Lane group		↖ ⇇		→	
Base saturation flow, s_0 [pc/h/ln]		1900		1900	
Number of lanes, N		2		2	
Lane width adjustment factor, f_w		0.967		0.967	
Heavy-vehicle adjustment factor, f_{HV}		1.000		1.000	
Grade adjustment factor, f_g		1.000		1.000	
Parking adjustment factor, f_p		1.000		1.000	
Bus blockage adjustment factor, f_{bb}		1.000		1.000	
Area type adjustment factor, f_a		1.000		1.000	
Lane utilization adjustment factor, f_{LU}		0.950		0.950	
Left-turn adjustment factor, f_{LT}		1.000		1.000	
Right-turn adjustment factor, f_{RT}		0.987		1.000	
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000		1.000	
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000		1.000	
Adjusted saturation flow, s [veh/h] $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**3445**		**3490**	

• INTERSECTION 15: *Via Prenestina – Via Fieramosca*

Saturation Flow Rate								
	WB			EB			SB	
Lane group								
Base saturation flow, s_0 [pc/h/ln]	1900	1900		1900			1900	1900
Number of lanes, N	1	2		2			1	1
Lane width adjustment factor, f_W	1.044	1.044		1.000			1.156	1.156
Heavy-vehicle adjustment factor, f_{HV}	1.000	1.000		1.000			1.000	1.000
Grade adjustment factor, f_g	1.000	1.000		1.000			1.000	1.000
Parking adjustment factor, f_p	1.000	1.000		1.000			1.000	1.000
Bus blockage adjustment factor, f_{bb}	1.000	1.000		1.000			1.000	1.000
Area type adjustment factor, f_a	1.000	1.000		1.000			1.000	1.000
Lane utilization adjustment factor, f_{LU}	1.000	0.950		0.950			0,95	1.000
Left-turn adjustment factor, f_{LT}	0,95	1.000		1.000			1.000	1.000
Right-turn adjustment factor, f_{RT}	1.000	0.977		1.000			1.000	0,85
Left-turn ped/bike adjustment factor, f_{Lpb}	1.000	1.000		1.000			1.000	1.000
Right-turn ped/bike adjustment factor, f_R	1.000	1.000		1.000			1.000	1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**1984**	**3684**		**3610**			**2196**	**2196**

• INTERSECTION 16: *Via Prenestina – C.ne Casilina*

Saturation Flow Rate								
	WB			EB		NB		
Lane group								
Base saturation flow, s_0 [pc/h/ln]	1900			1900		1900		1900
Number of lanes, N	2			2		1		1
Lane width adjustment factor, f_W	0.967			0.967		1.044		1.044
Heavy-vehicle adjustment factor, f_{HV}	1.000			1.000		1.000		1.000
Grade adjustment factor, f_g	1.000			1.000		1.000		1.000
Parking adjustment factor, f_p	1.000			1.000		1.000		1.000
Bus blockage adjustment factor, f_{bb}	1.000			1.000		1.000		1.000
Area type adjustment factor, f_a	1.000			1.000		1.000		1.000
Lane utilization adjustment factor, f_{LU}	0.950			0.950		1.000		1.000
Left-turn adjustment factor, f_{LT}	0.977			1.000		0.950		1.000
Right-turn adjustment factor, f_{RT}	1.000			1.000		1.000		0.850
Left-turn ped/bike adjustment factor	1.000			1.000		1.000		1.000
Right-turn ped/bike adjustment fact	1.000			1.000		1.000		1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$	**3408**			**3490**		**1885**		**1687**

- INTERSECTION 17: *Via Prenestina – Deposito ATAC*

Saturation Flow Rate						
	WB			EB		
Lane group		←			→	
Base saturation flow, s_0 [pc/h/ln]		1900			1900	
Number of lanes, N		2			2	
Lane width adjustment factor, f_w		0.967			0.967	
Heavy-vehicle adjustment factor, f_{HV}		1.000			1.000	
Grade adjustment factor, f_g		1.000			1.000	
Parking adjustment factor, f_p		1.000			1.000	
Bus blockage adjustment factor, f_{bb}		1.000			1.000	
Area type adjustment factor, f_a		1.000			1.000	
Lane utilization adjustment factor, f_{LU}		0.950			0.950	
Left-turn adjustment factor, f_{LT}		1.000			1.000	
Right-turn adjustment factor, f_{RT}		1.000			1.000	
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000			1.000	
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000			1.000	
Adjusted saturation flow, s [veh/h] $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**3490**			**3490**	

- INTERSECTION 18: *Via Prenestina – P.le Labicano*

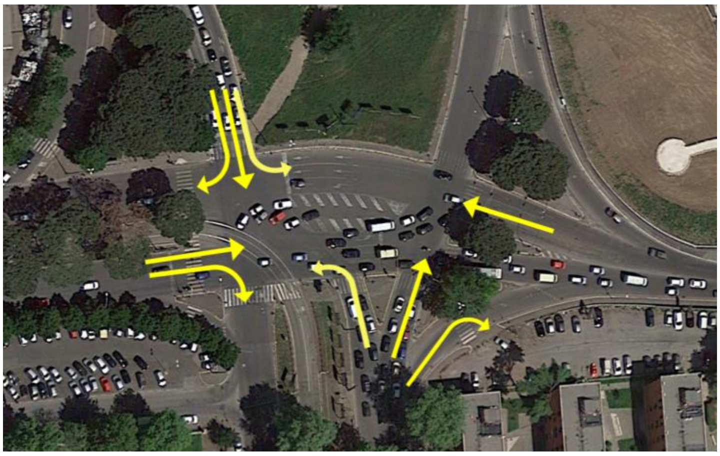
Saturation Flow Rate						
	WB			NB		
Lane group		←		↰		↱
Base saturation flow, s_0 [pc/h/ln]		1900		1900		1900
Number of lanes, N		3		5		3
Lane width adjustment factor, f_w		0.967		0.933		0.933
Heavy-vehicle adjustment factor, f_{HV}		1.000		1.000		1.000
Grade adjustment factor, f_g		1.000		1.000		1.000
Parking adjustment factor, f_p		1.000		1.000		1.000
Bus blockage adjustment factor, f_{bb}		1.000		1.000		1.000
Area type adjustment factor, f_a		1.000		1.000		1.000
Lane utilization adjustment factor, f_{LU}		0.950		1.000		1.000
Left-turn adjustment factor, f_{LT}		1.000		0.950		1.000
Right-turn adjustment factor, f_{RT}		1.000		1.000		0.850
Left-turn ped/bike adjustment factor, f_{Lpb}		1.000		1.000		1.000
Right-turn ped/bike adjustment factor, f_{Rpb}		1.000		1.000		1.000
Adjusted saturation flow, s [veh/h] $s = s_0 N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$		**5235**		**8423**		**4522**

- INTERSECTION 19: *Piazza di Porta Maggiore*

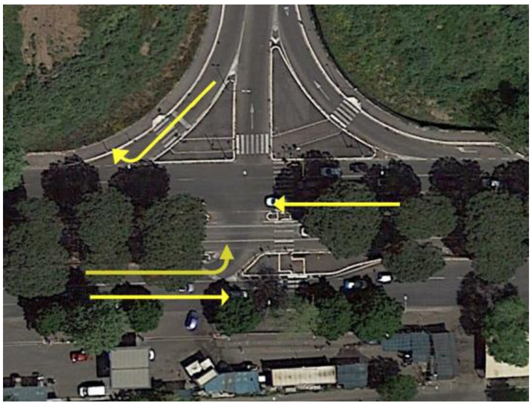
Saturation Flow Rate						
	EB			SB		
Lane group			↷		↓	↙
Base saturation flow, s_0 [pc/h/ln]			1900		1900	1900
Number of lanes, N			2		2	2
Lane width adjustment factor, f_W			1.044		1.044	1.044
Heavy-vehicle adjustment factor, f_{HV}			1.000		1.000	1.000
Grade adjustment factor, f_g			1.000		1.000	1.000
Parking adjustment factor, f_p			1.000		1.000	1.000
Bus blockage adjustment factor, f_{bb}			1.000		1.000	1.000
Area type adjustment factor, f_a			1.000		1.000	1.000
Lane utilization adjustment factor, f_{LU}			1.000		0.950	1.000
Left-turn adjustment factor, f_{LT}			1.000		1.000	1.000
Right-turn adjustment factor, f_{RT}			0,85		1.000	0.850
Left-turn ped/bike adjustment factor, f_{Lpb}			1.000		1.000	1.000
Right-turn ped/bike adjustment factor, f_{Rpb}			1.000		1.000	
Adjusted saturation flow, s [veh/h] $s = s_0 N f_W f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$			**3969**		**3770**	**3374**

10.2 Images of intersections

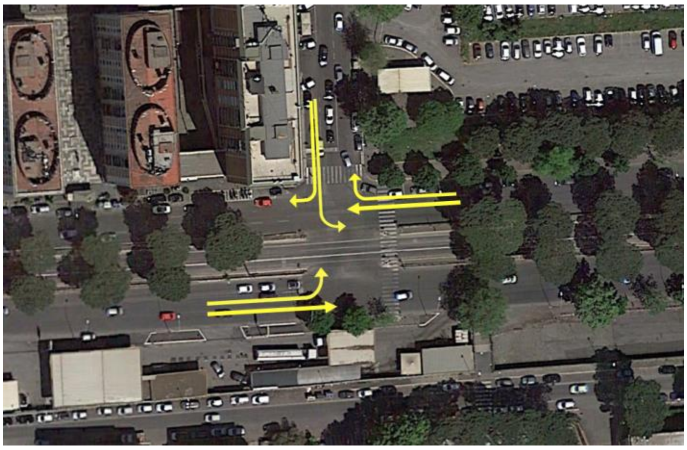
1) *Via Prenestina – Via Palmiro Togliatti*



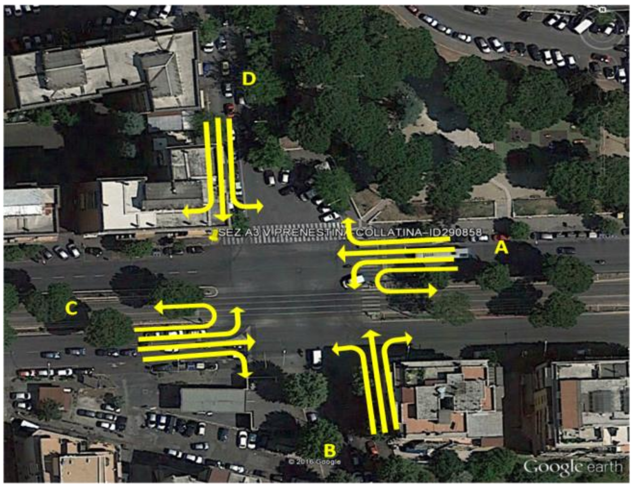
2) *Via Prenestina – Centro Servizi*



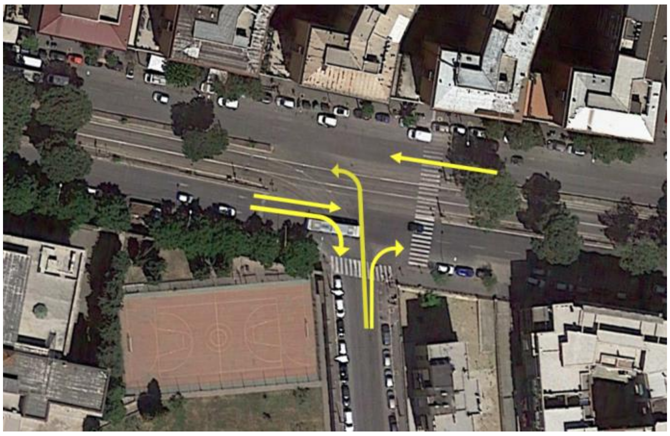
3) *Via Prenestina – Via G.B. Valente*



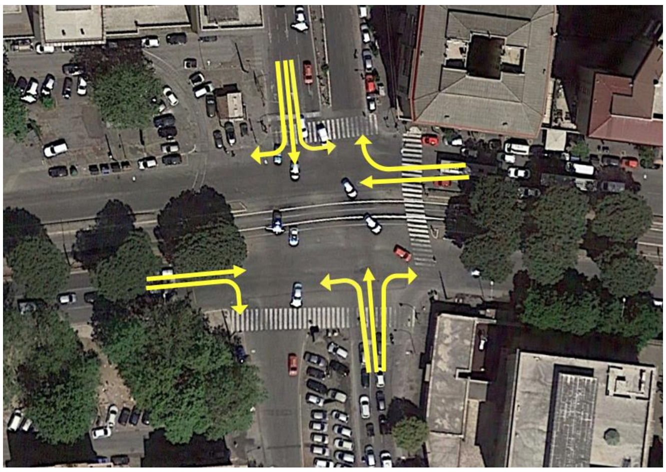
4) *Via Prenestina – Via Collatina*



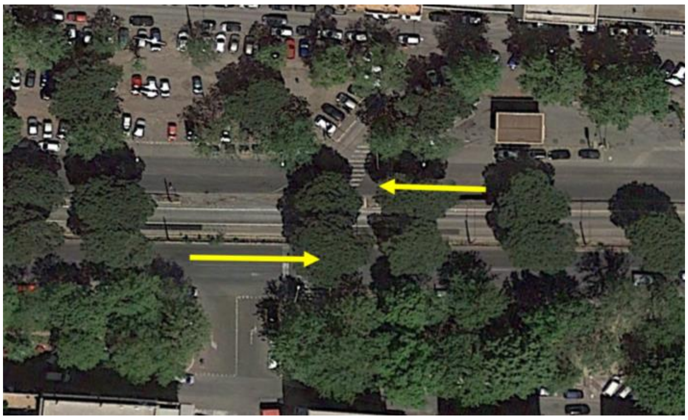
5) *Via Prenestina – Via Bresadola*



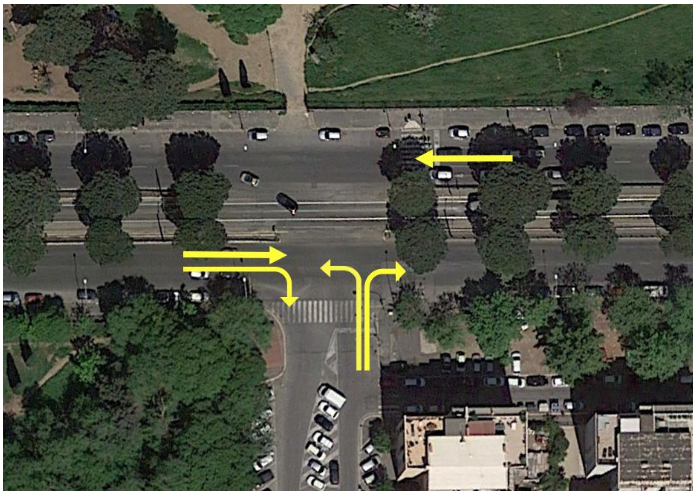
6) *Via Prenestina – Via Tor de Schiavi*



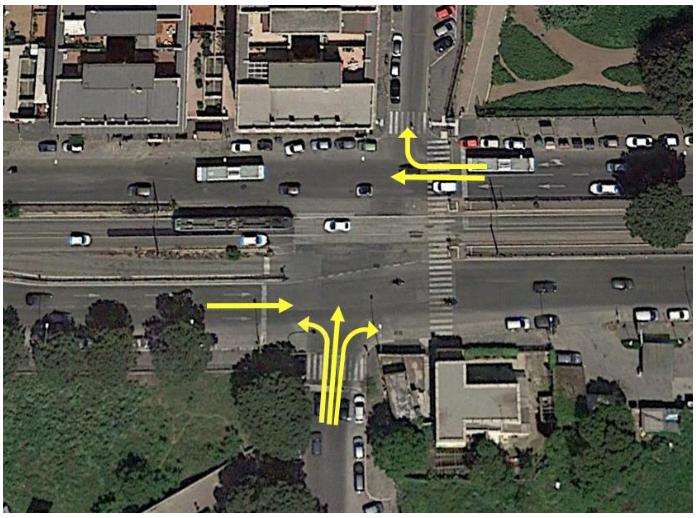
7) *Via Prenestina – Via Sabaudia*



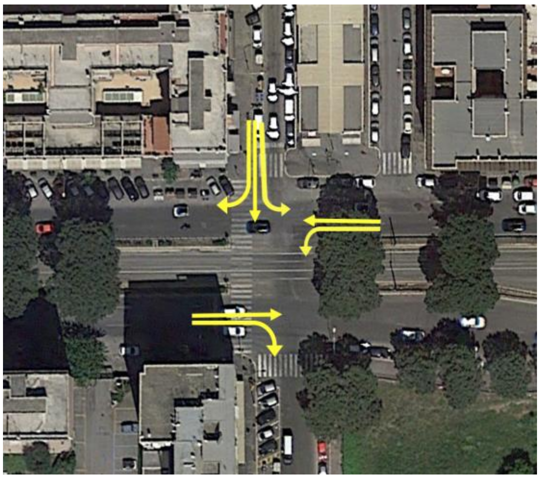
8) Via Prenestina – Via Olevano Romano



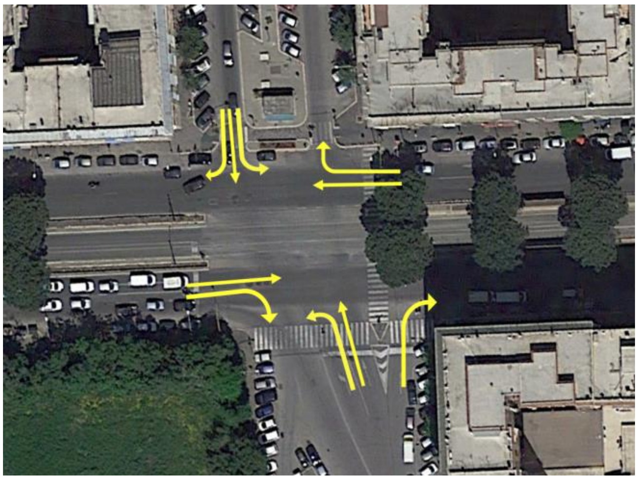
9) *Via Prenestina – Via Dignano D'Istria*



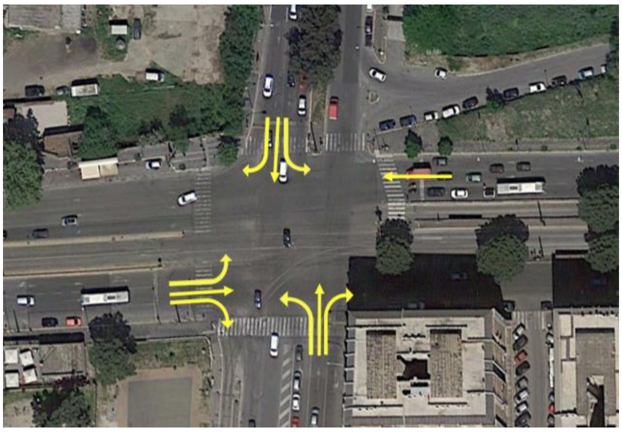
10) *Via Prenestina – Via Ronchi*



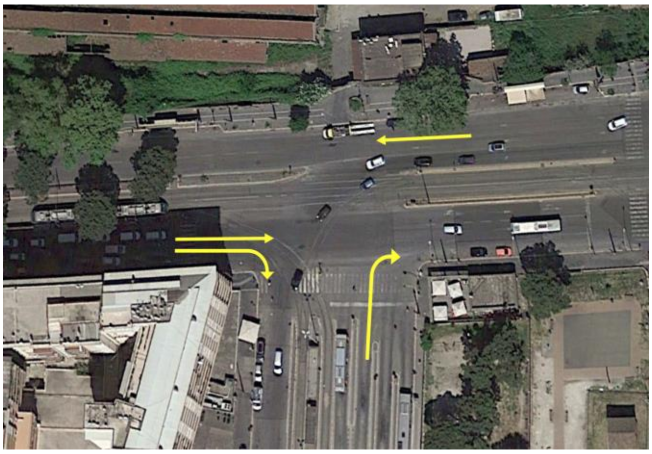
11) *Via Prenestina – Largo Talese*



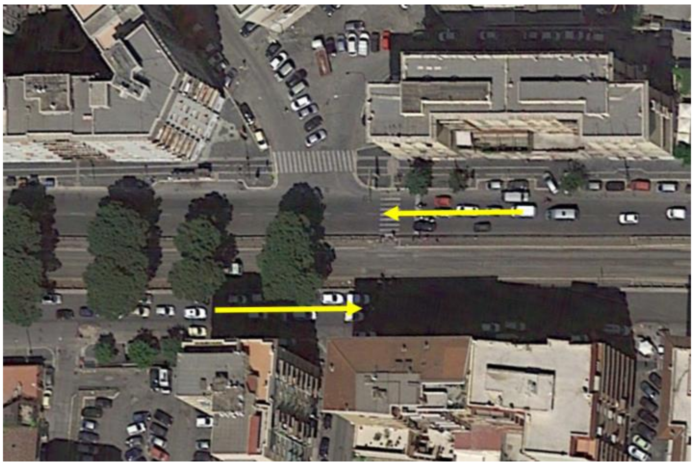
12) *Via Prenestina – Largo Preneste*



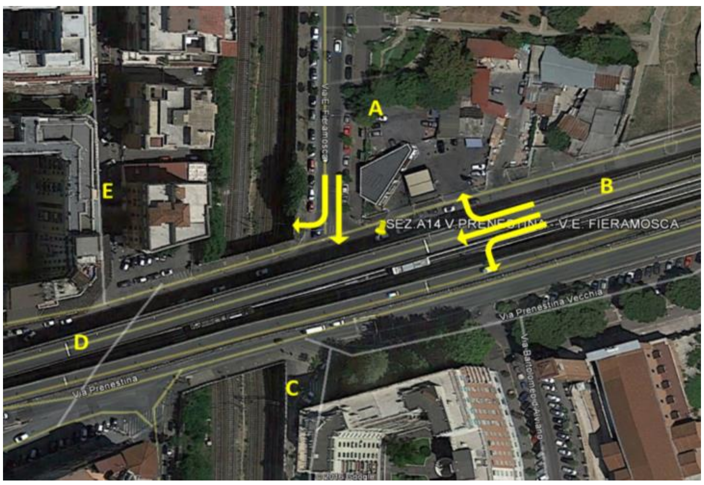
13) *Via Prenestina – Via di Portonaccio*



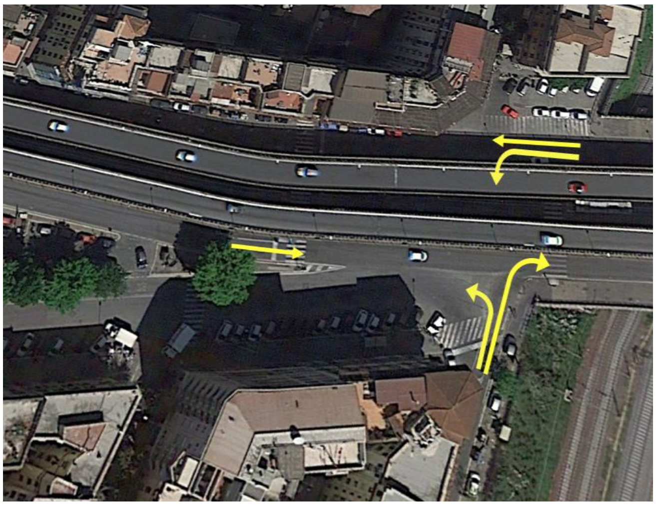
14) *Via Prenestina – Via Giovenale*



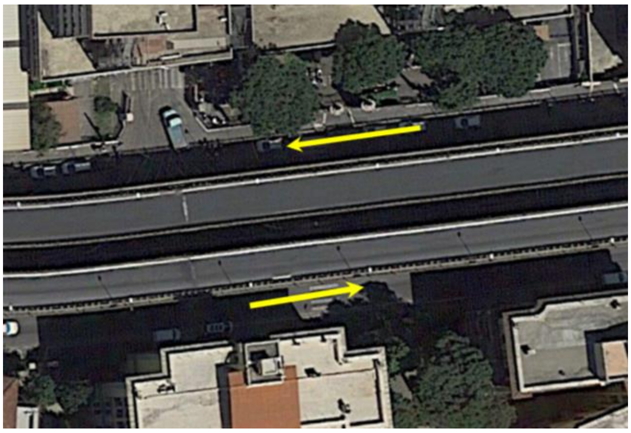
15) *Via Prenestina – Via Fieramosca*



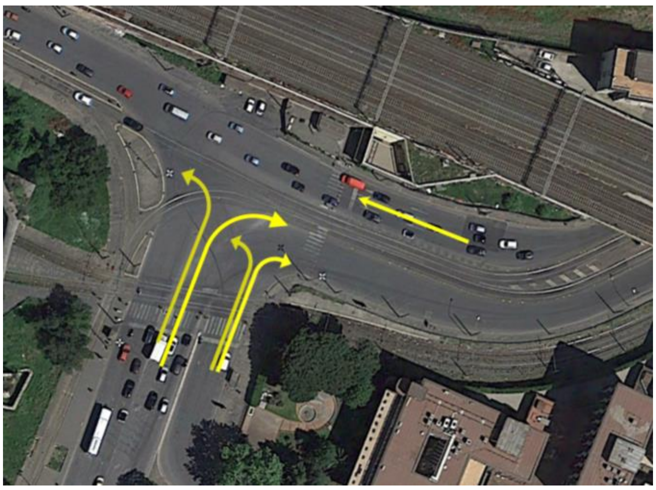
16) *Via Prenestina – C.ne Casilina*



17) *Via Prenestina – Deposito ATAC*



18) *Via Prenestina – P.le Labicano*



19) *Piazza di Porta Maggiore*