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Abstract

The real-time urban traffic control algorithm CRONOS has been evaluated on an intersection by comparison of two reference control strategies, a local one and a centralized one. Recurrent traffic situations, from peak hour traffic to low traffic, have been studied, and the impact on the traffic from a fluidity point of view has been investigated using various criteria. The average behavior of CRONOS has also been analyzed by crossing the traffic signal colors with traffic variables. Several of the criteria are innovative, thanks to the real-time, accurate video-based traffic data collected.

The results show high benefits of CRONOS on the total delay compared to the two reference control strategies, and benefits are also obtained on the total number of stops and percentage of stops, especially in comparison with the local strategy. All traffic situations (peak to low traffic) are concerned by these results. The analysis of the average behavior of CRONOS shows a higher average number of cycles per hour, more global green duration per hour at the center of the intersection, to the detriment of the entries. Moreover, CRONOS switches more often from amber to red when no vehicles are present on the link in percentage of cycles or in number of cycles per hour; it switches more often from green to amber when vehicles are present on the link in percentage of cycles per hour.

Keywords: Signalized intersection; Real-time control strategy; On-field assessments; Impact on fluidity traffic criteria; Control strategy behavior

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1 Introduction

Urban traffic control (UTC) by traffic signals is a major element of safety for vehicles and pedestrians when crossing an intersection. Traffic signals share the time between the different flows, that are considered to be antagonistic, and eliminate the most serious conflicts. This was the first reason for installing signals on intersections in the early 1900s.

Nevertheless, in the face of the ever-growing amount of traffic in urban areas, traffic control by signals has become a significant traffic management tool in order to reduce the consequences of this increase: congestion, delay, stop, pollution, fuel consumption, noise, stress, discomfort.

From a methodological point of view, the first major problem when controlling signalized intersections is to face different conflictual objectives:

- First of all, looking for the best fluidity is sometimes incompatible with the best safety: controlling the traffic from a safety point of view implies constraints on the traffic signal color

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durations or correlations between traffic signals: these constraints imply limitations on traffic fluidity management.

- The different types of user (vehicle, pedestrian, emergency vehicle, bus, bicycle, etc.) frequently have competing interests in crossing an intersection.

- The management policy of a city, such as favoring a route, implies additional objectives.

These conflictual objectives require management choices, which will favor certain elements over others: flows, types of user, traffic consequences, parts of the urban network, for example.

In addition to these choices, the second major problem in urban traffic management is to reach the optimum, i.e. to carry out the objectives for the best. A number of problems appear: flexibility in the control method, the size of the controlled network, the CPU time required, the reliability of sensors, modeling and forecasting, etc.

Many UTC systems exist, all over the world, from the simplest fixed-time plan to the new generations which lead to greater flexibility of control.

This paper presents the UTC algorithm CRONOS (ContRol Of Networks by Optimization of Switchovers) (Boillot *et al.*, 1992a), (Boillot and Papageorgiou, 1992b). Two ideas have led to the development of this algorithm: using advanced sensors for real-time traffic measurements and focusing on its speed and flexibility.

After a review of the main adaptive UTC systems, the CRONOS algorithm is described in terms of its qualities and originalities. The second part of this paper describes the evaluation experiment performed during 8 months on an intersection in France in 1998/1999, by comparing CRONOS to two other control strategies. The experiment and the evaluation methodology are described. The results, which are given, concern the benefits of the algorithm for several traffic criteria and several traffic situations. Finally, original measured variables are analyzed in order better to understand the algorithm’s behavior despite its “black box” feature.

This paper follows a series of results on the environmental aspect published in (Midenet *et al.*, 2004).

2 Adaptive UTC systems

In the last 20 years, new generations of traffic control systems have appeared. In the literature, they are generally described as being “adaptive” or “real-time”, as opposed to the usual time plans. Literally, an adaptive system indicates a not-fixed time system. Following this definition, the usual time-plan based traffic control systems generally have an element of flexibility, but, different flexibility types, listed below, are concerned.

The time-plan based systems integrate two different types of adaptivity: the vehicle actuation functions, which adapt traffic signal color duration, and the macro-control functions, which switch from one plan to another according to the traffic demand. The vehicle actuation functions adapt the system to the local and random traffic variations at very short term, whereas the macro-control functions give flexibility to the control system for the daily variations of the recurrent traffic situations.

These adaptive time plans are certainly the most widely used control systems in the world. When the plan is well adjusted to the recurrent traffic situations and the sensors are working correctly, these methods show good performances in a wide range of situations. Nevertheless, a higher level of adaptivity can be obtained if the method can be freed from the constraints of the time plan.

The first system to have followed this trend is the English system SCOOT (Hunt *et al.*, 1981). This control method produces a time plan incrementally. The Australian system SCATS (Lowrie, 1982) builds a time plan piece by piece. These systems are very close to a classical time plan, but they lead to a new type of flexibility, which follows changes in traffic not only throughout the day but also over a period of months. More such systems have recently appeared: CARS in Spain (Barcelo *et al.*, 1991) and MOTION in Germany (Bielefeldt *et al.*, 1994).

Other systems break further away from the notion of time plan and cycle duration: OPAC in the USA (Gartner, 1982), PRODYN in France (Henry *et al.*, 1983) and UTOPIA in Italy (Donati *et al.*, 1984). These systems minimize a traffic criterion using an optimization method to determine the green and red stage durations by time steps of 4 or 5 seconds. The cycle duration is not constrained and varies from one cycle to the next. These systems initially determine the different stages of the intersection and use minimum and maximum green durations. Thanks to their small time step and the use of magnetic-loop based sensors, these systems take into account the traffic flow variations at a scale of a few seconds and more globally (at the level of the intersection) than the vehicle actuation functions.

This new generation of systems does not need to re-actualize the control system after a few years as in the case of time plans. In other words, at constant infrastructure these methods do not age (this is also the case of the systems like SCOOT). Another advantage is their greater flexibility for finding the green and red durations according to the traffic situations, especially for those which have a wide possible cycle spectrum at each cycle.

Several experimental studies have shown benefits obtained by these UTC systems on the delay and the journey time compared to actualized time plans, although this result depends on the intersection characteristics and the traffic situations.

The main drawback of such systems is that they need numerous and reliable magnetic-loop based sensors. These sensors are placed at precise points and the traffic scene needs to be reconstructed. Furthermore, they are not able to optimize several intersections in the same optimization process, because the optimization methods behave exponentially with the number of intersections. This difficulty leads to a sub-optimality feature for a controlled network of several intersections.

In order to offset these drawbacks, the CRONOS algorithm was developed in the nineties. Two objectives were there at the very beginning: the first one was to build a non-exponential and fast optimization method providing the traffic signal states for the next second in less than one second. The stake is to react as fast as possible to the traffic variations. This method will not look at all solutions but will use a heuristic providing a good local minimum. The second objective was to use image-processing based traffic measurements, like queue length on link (Aubert *et al.*, 1996) and vehicle spatial occupancy inside the intersection. Video sensors provide precise and accurate road occupancy measurements and should improve intersection control performances.

3 The CRONOS algorithm

A zone of several adjacent intersections is considered in the following.

3.1 General structure and components

The general structure of the CRONOS algorithm is represented in Figure 1: one-second traffic measurements feed a forecasting and a modeling module. The forecasting module predicts, for a given time horizon, the future vehicle arrivals on each link entering the zone. This prediction is based on a rolling average of the arrivals in the past; it is used by the modeling module which calculates the value of a chosen traffic criterion for a given sequence of traffic signal states (colors) over the time horizon. These states are provided by an optimization module, which looks for the best sequence which minimizes the traffic criterion. When this sequence is found, the corresponding traffic signal states are applied on the intersection for the next time step, and the whole process is activated again one time step later.

“Place Fig. 1. about here”

The optimized traffic criterion is the total delay on the zone over the time horizon. The links entering the zone or connecting two intersections of the zone are considered in the delay. The criterion C is written as the sum of two terms:

$$C = \sum_{s=1,H} \left(\sum_{j=1,N} l_{s,j} + \sum_{k=1,N^{\text{int}}} l_{s,k}^{\text{int}} \right) \qquad (1)$$

where $l_{s,j}$ is the queue length at the time step s of the horizon H on the link j, $l_{s,k}^{\text{int}}$ is the number of stopped vehicles at the time step s in the storing inner area k of an intersection. The total number of links in the zone is N. The total number of storing areas inside the intersections is N^{int}. $l_{s,j}$ is based on the queue evolution equation at each time step s according to the calculated vehicle arrivals and departures during s ($a_{s,j}$ and $d_{s,j}$ respectively) for the considered link j.

$$l_{s+1,j} = l_{s,j} + a_{s,j} - d_{s,j} \qquad (2)$$

A same equation is obtained for $l_{s,k}^{\text{int}}$. The $d_{s,j}$ variables depend on the controlled variables which are the switchovers from red to green and green to amber (or red for pedestrian signals[1]) of every traffic signal group. One group is defined as the set of traffic signals which controls the same traffic flow. At the initial time step s = 1, the queues and the storing areas inside the intersections are measured directly by the video sensors.

The value of the rolling time horizon depends on the spatial extent of the zone. It is typically around one minute for one controlled intersection. The time-step value depends on the complexity of each controlled intersection and their number. It must be superior to the maximum computational time for solving the optimization process.

The optimization module is a heuristic method based on a modified version of the Box algorithm (Kuester and Mize, 1973). Not all the solutions have been investigated, only a very few. The principle of the method is as follows: in the first step, the criterion value is calculated for a set of initial solutions (a solution is the set of values for the controlled variables over the time horizon). The second step is an iterative process up to convergence and consists, at each iteration, in looking for the worst solution and modifying it. Two types of modification are used: the first one tries to

[1] According to the French norm, the pedestrian traffic signals have no amber stage.

move the worst solution away from the centroid of the other solutions. The second one tries to bring the worst solution closer to the centroid. The effect of these successive iterations is to lead all solutions towards a region of the solution space. The convergence is reached when all solutions are very close to each other.

The traffic measurements are obtained by automatic image-processing of video cameras. These one-second measurements are the queue length at the stop line for each link, the traffic flow at the entries or the exits of the intersection, the spatial occupancy inside the intersection for pre-defined spatial areas. These areas represent storing zones behind a traffic signal or for left-turning vehicles.

Concerning the CRONOS initialization, a set of parameters is defined for each controlled zone. The data types are few and can be classified into three categories: infrastructure data (list of intersections, list of links, link length, list of traffic signal groups), traffic data (saturation flow, free flow) and traffic signal data (safety constraints defined below).

3.2 Qualities and originalities

Compared to the other real-time UTC, the CRONOS qualities can be summarized into three points.

Its optimization method offers good properties: its speed in finding a good local minimum and its polynomial complexity as the number of intersections increases. A useful innovation arises from these properties: the possibility to control a zone made up of several intersections in the same optimization process. The advantage is to be totally consistent with its decisions. The vehicle arrivals on each link are modeled according to the decision of the upstream intersection at the same time step and do not need to be predicted from the previous optimization step of this intersection.

The second quality concerns the modeling module: the traffic model is designed to take full advantage of the image-processing based measurement richness. For that purpose, the storing areas inside the intersection and the spatial extension of the queue (for representing a congested link and for taking into account the arrival time of a vehicle in a queue) are modeled.

The last main quality of this algorithm concerns its flexibility properties in the choice of traffic signal states. This leads to a control process with variable cycle duration from one cycle to the next and no predefined stage: no cycle duration or stages are defined in advance. The intersection is described as a set of safety constraints on the traffic signal groups. These constraints deal with the duration of each traffic signal state (minimum/maximum green, etc.) and with the correlation between two traffic signal states (conflicting green, etc.). Any solution of the traffic signal states which verifies the safety constraints is a possible solution. Thanks to this kind of intersection description, the strategy can choose from among a wide range of traffic signal states, which gives maximum flexibility. The real-time UTC systems generally have variable cycles but they are always based on a pre-defined set of stages. This specific property is particularly useful for a complex intersection where the conflicts matrix presents independent antagonistic blocks. This innovation can be viewed as a re-definition of an intersection not in terms of stages but simply with safety constraints. The safety and the management aspects become separated because the safety has been explicitly defined and the management does not include additional implicit constraints.

Several simulation trials were performed between 1991 and 1996 and showed that CRONOS was able to control different types of complex intersections and a zone of several intersections. Given the promising results, it was decided to undertake a real-life evaluation of the CRONOS performances.

An eight-month experiment was undertaken on a single intersection and consisted in evaluating CRONOS in comparison with two other strategies taken as reference. A complete control chain was built to control the traffic signal groups every second (Boillot *et al.*, 1997). This experiment and the results are described below.

Although the experiment concerned a single intersection, it should be noted that CRONOS is designed to control zones of several intersections in the same optimization (one CRONOS for the entire zone).

4 Real-life experiment

4.1 The experimental site

The experimental site is an isolated intersection (Figure 2) near the INRETS Institute in the Val de Marne department, a suburb of Paris. This intersection is the crossing of two double-lane roads. The first is a main road connecting Paris to a motorway towards the south of France, the traffic is heavy, with typically 1000 veh/hour in each direction during peak hours and 500 veh/hour during the fluid periods. A secondary road connects suburban cities with lighter traffic: 400 veh/hour and 300 veh/hour for the peak and the fluid hours respectively.

"Place Fig. 2 about here"

In terms of infrastructure, this intersection presents several characteristics: the right-turning vehicles do not enter the inner intersection due to dedicated links. Four traffic signal groups manage the traffic flow inside the intersection and control storing areas with a capacity of roughly 6 to 8 vehicles. Eight fixed cameras are installed to provide a complete spatial coverage of the inner intersection, the entries and the exits.

The images are automatically processed to extract one-second video-based traffic measurements. The image-processing system is described in (Blosseville *et al.*, 1989) and in (Aubert and Boillot, 1997). The measurements, used by the CRONOS strategy and the evaluation described here, are the spatial occupation rate and the number of stopped vehicles for a set of defined inner areas of the intersection, the queue length and a flow indicator in front of the stop line on each link. We speak about *flow indicator* rather than *flow measure* because of the non-optimal position of cameras that have been optimally positioned primarily for queue length or spatial occupancy.

More details on the experimental site can be found in (Midenet *et al.*, 2004).

4.2 The control chain

In order to make an experiment easier over several months, the intersection was connected to an INRETS laboratory which housed the control system and the evaluation system. A complete control chain, from the data recording to the traffic signals control, was built. It piloted the intersection controller in real-time and sent it the traffic signal commands every second. Its architecture is shown in Figure 3.

"Place Fig.3 about here"

This control chain is made up of elements located on the intersection and inside the laboratory. On the intersection there is the intersection controller, which receives the signal states (colors) from the control system to be applied each second on each set of traffic signals and switches the signal lamps; and there is a Safety and Transmission Module (STM) which allows communication between the intersection controller and the control system. The STM also verifies the safety constraints on the signal states before sending them to the controller. Inside the laboratory there is a communication component which coordinates the sending of commands; an image processing module which receives the images and elaborates video-based measurements; the control strategy which determines the next traffic signal states to be applied on the intersection; evaluation means such as video tapes and data recordings.

The chain functions as an exchange, every second, between the intersection controller and the control strategy system. At the beginning of a second, the video-based measurements are provided to the control strategy. The optimization algorithm looks for the next optimal switchovers which minimize the chosen traffic criterion. The traffic signal states, for the next second, are sent, via the Communication Module, to the STM which checks their coherence from a safety point of view. If no problem is detected, these commands are sent to the intersection controller. At the beginning of the next second, the controller applies the commands on the intersection. The current traffic signal states and the video images are sent continuously, every second, to the laboratory, even if the control strategy does not control the intersection. This functionality records these variables whatever the control strategy applied.

For strategy evaluation purposes, all data are recorded every second: video tape recordings for the images, the traffic signal states and the traffic measurements.

4.3 The Safety and Transmission Module

Ensuring total safety on the intersection is of prime necessity. It is essential that, every second, the traffic signal states verify every safety constraint defined for a given intersection: these constraints are, for example, the antagonisms, the minimum and maximum duration for each traffic signal color, the clearance time. These constraints concern vehicle traffic signals as well as pedestrian ones. Usually, some of these constraints are verified by the intersection controller itself, while the other constraints are implicitly included in each time plan built by the traffic engineers.

When a real-time UTC algorithm controls an intersection, unusual traffic signal states may be generated, so it is very important to establish explicitly, for each intersection, every constraint that must not be violated. This is what has been done for this experimental intersection. Here is an example among others of such a constraint: if the traffic signal S1 is green, then the traffic signal S2 must be green, except at the beginning of green of S1, where S2 can stay red during three seconds at most (see Figure 2). This constraint is due to the high vehicle speeds on the main road leading to a dangerous situation if the first traffic signal is set at green and the following one at red 30 meters along.

A safety module, incorporated in the STM, has been elaborated by INRETS in order to ensure safety on the intersection. Its aim is to filter the commands before sending them to the controller in order to verify all safety constraints on the traffic signals. It is important to point out that these defined constraints concern an intersection and not a specific control strategy. They are clearly identified for each intersection.

4.4 The experiment

The experiment was undertaken from July 1998 to February 1999. Three control strategies controlled the intersection alternately: CRONOS and two others (L-STRAT and C-STRAT) which are the usual control strategies for this intersection. They are called the reference strategies in the following.

L-STRAT (L for local) is a local control strategy: it is a time plan with vehicle actuation functionalities built for this intersection by the Val de Marne traffic engineers. Interesting features should be mentioned: the cycle durations are variable because no compensation is used from one stage to the other when the vehicle actuation is activated for a stage. Furthermore, the vehicle actuation ranges are wide and concern all intersection entries, with loops installed behind the stop line, leading to great flexibility of the strategy: the cycle duration can vary from one cycle to the next from 64 to 97 seconds. This flexibility allows this strategy to be adapted to the different traffic situations during the day. Furthermore, the neighborhood intersections are far from this one, allowing an efficient isolated control. L-STRAT was revised before the experiment. L-STRAT corresponds to the baseline strategy described in (Midenet *et al.*, 2004).

C-STRAT (C for centralized) is the usual centralized strategy for this intersection, integrated in the Val de Marne network management. C-STRAT is a coordinated strategy controlling a zone of several intersections in the neighborhood of the experimental intersection. It is a time-plan library switching from one plan to another according to the demand measured on several points of the zone. Each time plan, selected for the experimental intersection, also has vehicle actuation functionalities but which are more limited than for L-STRAT. The cycle duration varies from ± 5 seconds around the nominal value. One would expect this strategy to be less efficient than L-STRAT because the searched optimum for the entire zone will sometimes impose a sub-optimality for this particular intersection. Nevertheless, C-STRAT is useful for studying the loss or benefits of a centralized strategy compared to local ones.

Table 1 summarizes the main features of each strategy.

“Place Table 1 about here”

The experiment was performed over 8 months on weekdays. In order to make easier the data processing during the evaluation step and to favor recurrent traffic situations, the intersection was controlled during fixed hours from 8.00 to 12.00 and 14.30 to 18.30. One strategy out of the three controlled the intersection during an entire half-day. In order to combine all the situations encountered, the strategies were alternated from one half-day to the next according to a monthly schedule. Each week, each strategy controlled the intersection two or three times, also varying the days of the week, from week to week.

During each half-day experiment, data were collected every second: video-based traffic measurements and traffic signal group colors. The video images of the eight cameras were also recorded. Furthermore, during the entire experiment we supervised the experiment in order to note in a logbook any device dysfunction or traffic abnormality.

Finally around 550 hours of data were gathered with morning and evening peaks, fluid and low traffic periods.

4.5 The evaluation methodology

The evaluation methodology was designed in three steps: data selection, data classification and computation of the evaluation criteria.

4.5.1 Data selection

During this evaluation, our goal was to evaluate the strategies during the recurrent traffic situations of the intersection and during periods without technical failures of the installation or the evaluation devices. The reasons for these choices are obvious: for a first evaluation, the system needs to be evaluated under the recurrent situations of the intersection. Furthermore, the other situations are too rare to give reliable results from a statistical point of view. The situations without particular problems were chosen in order not to bias the traffic measurements on which the strategies and the computation of the evaluation criteria are based.

For that reason, data were selected and some half-day data (or part of them) were got rid of. They concerned situations of saturation with a queue spillback; when a camera or the system was out of order; when there was too much camera movement; periods of incident; the Christmas period where a Christmas tree hid part of the traffic scene. The objective was to collect "clean" samples, even if many samples where eliminated; and the high number of hours collected made this possible.

After this selection, 156 hours were chosen for L-STRAT, 75 for C-STRAT and 133 for CRONOS.

4.5.2 Data classification

The collected data represent peak and fluid hours, during day, dusk and night with various meteorological conditions. In the second step, the data were classified according to different classes of traffic situations. The other factors were presumed to have existed for all the strategies implemented. In order to classify the data, first of all, the one-half day data were separated into four sets of hourly periods with the classes [8.00, 9.00], [9.00, 10.00], [10.00, 11.00], [11.00, 12.00] and [14.30, 15.30], [15.30, 16.30], [16.30, 17.30], [17.30, 18.30]. The hourly period of interpretation seems to be sufficiently long to really evaluate the impact of the strategy on the traffic without frontier problems and sufficiently short to avoid mixing several traffic situations and to be able to characterize them. What is more, the first reason to use this classification by fixed hours is that it simplifies the processing of the data. A second reason is that the same recurrent traffic situations occur around the same hours from one day to the next.

This pre-classification is not sufficient because, for example, the traffic level [8.00, 9.00] in August is different from the corresponding traffic in February.

In the third step, four ranges of traffic level were defined in terms of total one-hour demand arriving at the intersection, summed up over the four entries. These ranges were defined by analyzing the data scattering and this analysis has produced the following classes: peak (from 3300 to 2600 veh/h), dense (from 2600 to 2100 veh/h), fluid (from 2100 to 1600 veh/h) and low traffic (from 1600 to 900 veh/h). Each one-hour sample has been classified in one traffic level according to its total demand measured during the entire hour of the sample. The peak traffic class corresponds to the morning and evening peaks. It is mainly composed of the [8.00, 9.00] and [17.30, 18.30] samples. The dense traffic class corresponds to the edges of peak periods and is mainly composed of the [9.00, 10.00] and [16.30, 17.30] samples. The fluid class is the off-peak hours class, usually from 10.00 to 12.00, and from 14.30 to 16.30. The low class mainly corresponds to July and August traffic.

At the end, four sets were defined, one for each traffic range. For each set, three sub-sets represent each strategy. The total number of samples per traffic class is respectively 97, 122, 200 and 42 for the peak, dense, fluid and low classes.

4.5.3 Computing the evaluation criteria

From the data collected every second, variables concerning the traffic or the traffic signals were defined and computed (generally summed) over every one-hour sample. These variables were averaged over all the samples of each range and per strategy. Most variables were also computed by distinguishing the inner intersection and the entries. They were studied per entry in order better to understand how the strategies functioned. Some of them were summed over the green (resp. red, amber) color periods of the traffic signals. Figure 4 shows most of the analyzed variables (their definition is provided as and when required).

“Place Fig. 4 about here”

5 The evaluation results

5.1 Data analysis

Before computing comparative results, the collected data were analyzed in order to ensure the non-existence of bias and that the average results correspond to the effective average behavior of each strategy. As it is not possible to report all the studies, only some of the most significant results are given.

5.1.1 Average total demand per range

The traffic flow at the entries of the intersection plays a special role in this study: firstly, it is the demand that must be served and secondly it is used to classify the traffic situations. Figure 5 shows the mean traffic flow per range and per strategy: it is obtained by averaging the one-hour total traffic flows of the intersection (summed over the four entries) over all the one-hour samples per range. These means per range are very close from one strategy to the other. The traffic flow scattering per one-hour sample would show no aberrant sample values and a satisfactory scattering uniformity.

“Place Fig. 5 about here”

5.1.2 Data scattering

To illustrate the one-hour sample scattering and their quality in terms of no outlying points, two data types were chosen: the total delay (Figure 6) and the average cycle duration of the traffic signals (Figure 7).

The total delay per one-hour sample is the delay summed over the four entries, over the one hour of the sample and divided by the demand of this sample. It corresponds to the average delay (in seconds) for one vehicle during its intersection crossing. Figure 6 shows the total delay value distribution according to the total demand of the sample for the three strategies. We see that the points concerning CRONOS are almost separate from the other two sets.

"Place Fig. 6 about here"

As no phase skipping is allowed, the average cycle duration is obtained by averaging the cycle durations of one particular traffic signal over one hour of a sample. We clearly see in Figure 7 that CRONOS uses smaller average cycle durations whatever the samples. L-STRAT has average cycle durations around 10 seconds higher and C-STRAT between 10 to 20 seconds higher than L-STRAT.

"Place Fig. 7 about here"

5.1.3 Statistical tests

For each analyzed variable, statistical tests were built. The t test (Student Law) was computed to test the equality between two mean values, at different confidence levels: 99%, 95% and 90%. The samples are independent. When the number of samples for each distribution is sufficiently high, this test is valid even if the distributions are not Gaussian. Otherwise, the distribution normality must be tested. If the normality is rejected and the means are different, the t test remains valid but is less powerful.

For each average value studied, the t test mainly shows a significant mean difference at a 99% confidence level between CRONOS and the two reference strategies. The case where this result is not obtained is when the difference is very close to zero. A very few cases (around 2%) rejected the normality of at least one distribution. In the following results, the cases where the mean values are not significantly different (less than 90%) will be mentioned.

5.2 Consequences of the control actions on the traffic

In order to compare the control strategy results according to the demand range, several evaluation traffic criteria were defined: total delay, total delay during the green (resp. red, amber) periods, number of stops, stop rate and the one-hour presence queue duration. The table 2 summarizes the results described below.

“Place Table 2 about here”

5.2.1 Delay

Delay is defined as the average delay per vehicle. It is obtained by summing every queue (measured in terms of number of waiting vehicles at a traffic signal) each second on the entries and on the inner intersection over the entire hour of a sample, divided by the total demand of this sample and averaged over all the samples of each sub-set.

The delay has been chosen as MOE (measure of effectiveness) rather than the travel time for two reasons: first, it is the CRONOS optimized criterion, so the benefit is evaluated directly. Second, one part in the travel time cannot be controlled by traffic signals and depends on the infrastructure (link lengths) or on the kinematic (vehicle free speeds, etc.). The result is less noticeable.

Figure 8 shows the benefits of CRONOS on the delay compared to the two reference strategies. The CRONOS benefit compared to L-STRAT is between 16.0% and 27.5% with almost uniform benefits from the peak to the fluid range and is 9% higher for the low period. The benefit compared to C-STRAT is higher with the same trend: from 24.8% to 25.1% from peak to fluid range and 40.4% for the low period.

“Place Fig. 8 about here”

These benefits represent 3.1 to 5.3 waiting seconds saved per vehicle for crossing the intersection, on average, compared to L-STRAT, and 5.1 to 9.5 seconds saved compared to C-STRAT.

Benefits are observed on the sum of the entries as well as in the inner intersection with higher results in the center compared to both reference strategies: 23.7% to 40.9% from peak to low compared to L-STRAT, 37.8% to 55.3% from peak to low compared to C-STRAT.

Considering each entry separately we see that, compared to L-STRAT, CRONOS privileges the main road with a high benefit. The secondary road has fewer benefits or even a loss in dense and peak situations. Compared to C-STRAT, every entry receives a high benefit except the N link on the main road where benefits are only observed during the peak and low periods.

The overall CRONOS benefit is high compared to the reference strategies, whatever the range. Despite the micro-controlled feature of L-STRAT and variable cycles from one cycle to the next, CRONOS has better results thanks to its greater flexibility, better information on the traffic situation in real-time and its overall traffic optimization. CRONOS obtains better results compared to C-STRAT, which is centralized and where the cycle duration is not specifically determined for this intersection. Furthermore, C-STRAT is less adaptive than L-STRAT.

The part best managed by CRONOS is the inner intersection compared to the reference strategies. This part is certainly the least well managed by L-STRAT or C-STRAT because no loops are installed in the inner intersection: these strategies don’t know if a stocking zone has reached its capacity or even if waiting vehicles are present. No adaptation can be made. On the contrary, CRONOS has information on the number of waiting vehicles on each stocking zone of the inner intersection. This information is taken into account in the control decision.

5.2.2 Delay during the green (resp. red, amber) periods

The delay during the green (resp. red, amber) periods is only summed over all the periods during the hour where the corresponding traffic signal is green (resp. red, amber). This variable only concerns the entries.

The delay during the green period is higher for CRONOS compared to the reference strategies except in the peak and low periods for C-STRAT. The delay during the red period is largely lower for CRONOS. The delay during the amber period is comparatively higher for CRONOS.

Furthermore, whatever the strategy and the range, the ratio between the delay during the green and the delay is between 1/4 and 1/3, with the lowest values for C-STRAT and the highest values for CRONOS. These ratios demonstrate that the delay during the green is a non-negligible part of the delay. The later the vehicles arrive during the red, the higher this ratio. Disparities are observed between the main and secondary roads: between 1/2 and 2/7 on the main road, between 1/4 and 1/8 on the secondary road. The disparity between the main and secondary roads can be explained: on the secondary road where the demand is less than on the main road, the red duration is greater for fewer vehicles in queue. The queue elapsed duration is faster than for a long queue.

Further investigations were carried out to understand why the delay during the green is higher for CRONOS. It seems that, on average, vehicles under the CRONOS management take more time to move off, but no satisfactory explanation has been found to explain this result.

5.2.3 Number of stops

The number of stops is defined as the average number of stops for one vehicle. It is obtained by summing the number of vehicle stops on the entries or inside the intersection during the entire hour of a sample divided by the total demand of this sample and averaged over all the samples of each sub-set. If a vehicle stops twice, the number of stops increases by two units.

This number of stops is high due to the infrastructure and the characteristics of the traffic. Generally, vehicles which turn left meet a red traffic signal inside the intersection. Moreover, from one entry (E link), the only possibility is to turn left and almost all vehicles stop at least once.

CRONOS obtains benefits on the number of stops compared to L-STRAT: from 8.3% to 13.7% depending on the demand range. The best benefits are obtained in the inner intersection from 12.5% to 24.2% as against 6.9% to 11.7% for the entries.

The benefits compared to C-STRAT are very low: around 1% (these differences are not significant) except in low traffic, with 15.5%. These benefits give very different results for the entries and the center: the benefits are high in the center (from 10.8% to 29.9%) and the entries have low loss from 0.3% to 3.9% (without significance in peak and dense traffic) except for benefits of 10% in low traffic.

Although this criterion is not optimized by CRONOS, benefits on the number of stops are obtained, especially with L-STRAT. The low benefit compared to the centralized strategy C-STRAT is not due to a synchronization of adjacent intersections, because this intersection is very far from its neighborhood. The reason is that C-STRAT gives long green durations on the main road where the demand is high and short ones on the secondary road, so a major part of the demand does not stop, at least on the entries. Furthermore, compared to the two strategies, the CRONOS benefits are the highest in the inner intersection for the same reason as for the delay above.

5.2.4 Stop rate

The stop rate is the percentage of stopping vehicles. It is the ratio between the number of vehicles stopping at least once on the entries or inside the intersection to the total number of vehicles crossing the intersection during the one-hour sample and averaged over all the samples of each sub-set. If a vehicle stops twice, the stop rate increases by one unit only.

This percentage has been reconstructed by a model described in (Midenet *et al.*, 2004) and is provided for each entry considering all its possible itineraries.

Compared to L-STRAT, the relative CRONOS benefits are obtained range from 6.4% to 12.1% corresponding to a stop-rate value decrease of between 5% and 9%. CRONOS decreases the number of vehicles that stop while crossing the intersection. These results correspond to high benefits on the main road and low benefits or even loss on the secondary road.

Compared to C-STRAT, CRONOS obtains smaller benefits ranging from 0.7% to 3.1%, and a very small loss (0.3%) for the fluid range. These results are only significant for the peak traffic (3.1%). The benefits correspond to the S and E links.

The results are more favorable in the comparison with L-STRAT than with C-STRAT for the same reason as for the number of stops.

5.2.5 The one-hour presence queue duration

Every second, the queue is measured on each entry and inside the intersection. The one-hour presence queue duration is obtained by summing the number of seconds where a queue is present at a traffic signal, summed over the eight traffic signals of the intersection and during the one-hour sample. It is averaged over the samples of each sub-set.

Figure 9 gives the one-hour presence queue duration for the three strategies for the total of the eight traffic signals, for the four entries and for the center. Compared to L-STRAT, the presence queue duration is lower for CRONOS whatever the range for the total, for the entries or the center as well. These benefits are low, except in the low traffic case with 14.8% on the total. Compared to C-STRAT, the same tendency is observed with higher benefits. These differences are not significant in peak traffic (for L-STRAT only on the entries) and in dense traffic (only for L-STRAT on the total and the entries).

"Place Fig. 9a about here"

"Place Fig. 9b about here"

When the presence queue duration is detailed for each entry, we see that the benefits are obtained on the main road compared to L-STRAT and on the secondary road compared to C-STRAT, except on the low case where benefits are obtained everywhere.

This variable is not the criterion optimized by CRONOS but it is related to it. Globally, over one hour CRONOS leads to fewer seconds where at least one vehicle waits at a traffic signal.

The second part of the results concerns studies on the traffic signal: these results not only explain the characteristics of CRONOS but also clarify the first set of results.

5.3 Consequences of the control actions on the traffic signals

5.3.1 The average cycle duration and cycle scattering

The average cycle duration of a traffic signal is the duration between the beginning of two successive identical colors of this traffic signal, averaged over the one-hour of a sample and over the samples of each sub-set. As no stage skipping has been allowed on this intersection, all the traffic signals have the same average cycle duration.

Figure 7 shows that the average cycle duration decreases, for all strategies, from the peaks to the low demand range: the strategies increase the cycle duration when the demand is high and decrease it when it is lower. They try to increase the intersection capacity and reduce the lost times per traffic signal due to each switchover and the clearance times (these lost and clearance times are fixed per cycle, whatever the strategy). Furthermore, CRONOS always has a lower average cycle duration than L-STRAT and C-STRAT with 65 seconds on average for the peak range and 55.8 seconds for the low one. C-STRAT has the highest values.

The consequence of this result is that, for CRONOS, the clearance time and the lost time over an hour increases but without increasing the delay and the number of stops, as seen above.

Figure 10 represents the minimum and maximum cycle durations obtained during the entire hour of each sample averaged over the samples. CRONOS has a lower minimum and maximum with a relatively greater difference for the minimum. This difference is around 20 seconds with L-STRAT, from 31 to 40 seconds with C-STRAT.

The highest amplitude of the cycle duration variation for CRONOS illustrates its flexibility for reacting to a given traffic situation. Very low cycle durations can be chosen, increasing the cycle duration the next cycle if necessary.

“Place Fig. 10 about here”

5.3.2 The one-hour global red duration

It is because the clearance time per hour increase for CRONOS, that the total amount of red duration summed over all the traffic signals also increases. As the delay does not increase, it is interesting to study how this additional amount of red is dispatched.

Let us recall that, every second, any traffic signal color is known and registered. The one-hour global red duration is obtained by summing the number of seconds where a traffic signal is red, over the eight traffic signals of the intersection, over the one-hour sample and averaged over the samples of each sub-set.

Figure 11 shows the one-hour global red duration summed over the four traffic signals of the entries and over the four traffic signals of the center for the three strategies. Whatever the range, CRONOS gives more red duration for the entries compared to L-STRAT and C-STRAT, and less red duration for the center. CRONOS gives more red duration on the total of the eight traffic signals due to the clearance time. But this additional amount of red is not equally distributed between the entries and the center since CRONOS gives less red duration on the center and provides the complement on the entries. The detail on the four entries shows that the surplus of red principally concerns the secondary road compared to L-STRAT and the main road compared to C-STRAT.

“Place Fig. 11 about here”

Less red on the center partly explains the high benefit on the delay for CRONOS in the center. Nevertheless, benefits are also obtained for the entries despite the additional amount of red.

This result has led us to define a new variable to characterize the red periods. This new variable has been called the one-hour “red but nobody” duration and is detailed below.

5.3.3 The one-hour “red but nobody” duration

Every second, the system detects if a vehicle is present on a link, in movement or stopped, and if the corresponding traffic signal is green, amber or red. We define the entity called the “red but nobody” for a traffic signal as the period of red - possibly equal to zero - between the beginning of the red and the instant of the first presence of a vehicle on the link (as seen by the video sensors). It represents the period of red with an empty link. The one-hour “red but nobody” duration is thus obtained by summing the “red but nobody” over all the traffic signals, over the one-hour of the sample and averaged over all the samples of each sub-set. This entity is only analyzed on the entries.

By nature, this entity is a “good” value from a control and safety point of view, because when the traffic signal switches to red without the presence of vehicles, it avoids the possibility of red light running at the beginning of red while enabling the conflicting traffic signal to be green to let potential vehicles pass.

Figure 12 represents the additional amount of the one-hour global red duration for CRONOS compared to L-STRAT and C-STRAT. This amount is split between the one-hour “red but nobody” duration and the one-hour red duration “with presence of vehicles”.

“Place Fig. 12a about here”

“Place Fig. 12b about here”

Compared to L-STRAT, the one-hour “red but nobody” is higher, whatever the range. This surplus of red given by CRONOS represents 14% to 27% of “red but nobody” according to the range. One also sees in Figure 12 that, from peak to fluid, almost the entire surplus of global red duration is “red but nobody” and the red with presence of vehicles is near zero. For the low case, the CRONOS performance is better as the global red duration difference (which does not increase compared to the other three traffic ranges) corresponds to a very high amount of “red but nobody” (twice more than the global red duration difference) and a red with presence of vehicles difference that is strongly negative. Compared to C-STRAT, the trend is the same with a surplus of one-hour “red but nobody” between 36% and 50% and the same phenomenon for the low case.

The results for each entry show that a higher one hour “red but nobody” is provided by CRONOS whatever the entry, the reference strategy and the range. In more detail, compared to L-STRAT, on the main road CRONOS has less global red duration (except for the N link in the fluid and low ranges), adds more one-hour “red but nobody” and less red with presence of vehicles. For the secondary road, the additional global red is principally red with presence of vehicles, except for the fluid and low ranges where the phenomenon described in the previous paragraph (for the low case) is reproduced. The dominant CRONOS behavior compared to C-STRAT is reversed between the main and the secondary roads, with respect to the results described between CRONOS and L-STRAT.

The number of cycles which have a “red but nobody” duration not equal to zero can be considered. It is averaged over the one hour of the sample and averaged over all the samples of each sub-set. This average number of cycles with “red but nobody” duration not equal to zero is higher for CRONOS whatever the range. As CRONOS has more cycles on average per hour than the other two strategies, the average percentage of cycles with “red but nobody” not equal to zero is considered. This entity remains higher for CRONOS whatever the range. In Figure 13b, the difference is not significant in peak traffic in comparison with L-STRAT. With respect to each entry and compared to L-STRAT, CRONOS always has a greater average number of cycles with “red but nobody” not equal to zero. Furthermore, a higher percentage of cycles is obtained for CRONOS on the main road and approximately equal percentage between CRONOS and L-STRAT on the secondary road. Compared to C-STRAT, a higher average number of cycles and a higher percentage is obtained for CRONOS whatever the entry.

"Place Fig. 13b about here"

These results show that CRONOS switches more often from amber to red when no vehicles are present at the beginning of the red (in terms of number of cycles as well as in percentage of cycles). Compared to L-STRAT, this phenomenon is true for the entire intersection and each entry considering the number of cycles, and it is true for the entire intersection and on the main road considering the percentage of cycles. Compared to C-STRAT, this phenomenon is true for the entire intersection, on the main and secondary roads considering the number of cycles and the percentage of cycles. These results are very good from a fluidity and safety point of view.

5.3.4 The one-hour "green for nothing" duration

Symmetrically to the "red but nobody", we denote by "green for nothing" the period of green time between the last presence of a vehicle on a link and the end of green for the traffic signal of this link. It represents the last period before the end of green with an empty link. The one-hour "green for nothing" duration is obtained by summing the "green for nothing" over all the traffic signals, over the one-hour sample and averaged over all the samples of each sub-set. This entity is only computed on the entries.

From a fluidity point of view, this duration for a traffic signal is useless because this green period does not serve vehicles any more while vehicles are generally waiting on the corresponding conflicting traffic signal. Furthermore, less "green for nothing" is also better for pedestrians in order to avoid them crossing the link during the green vehicle traffic signal.

Whatever the range, CRONOS provides less one-hour "green for nothing" than L-STRAT and C-STRAT, representing a benefit of between 19% and 56% compared to L-STRAT and 2% to 26% compared to C-STRAT (the low traffic case, 2%, is not significant, see Figure 14).

Compared to L-STRAT, the one-hour “green for nothing” duration is lower whatever the entry, but the difference is more accentuated on the secondary road. Compared to C-STRAT, similar results are obtained except for the low range for three entries out of the four. But the differences are lower on the secondary road than for the comparison between CRONOS and L-STRAT.

“Place Fig. 14 about here”

In terms of average number of cycles with a “green for nothing” duration not equal to zero, CRONOS has fewer such cycles than L-STRAT (except for the low traffic case) and more than C-STRAT (except for an equal number for the peak traffic case between CRONOS and C-STRAT). These tendencies are due to the secondary road in the comparison with L-STRAT and principally to the main road in the comparison with C-STRAT.

Considering the percentage of such cycles and compared to any reference strategy (Figure 13a), CRONOS has a smaller percentage whatever the range (the difference is not significant in the low traffic for C-STRAT). This is also true for each entry (the differences are more accentuated on the secondary road) except for the S link where this percentage is equal or higher for CRONOS.

“Place Fig. 13a about here”

Considering the percentage of cycles with a “green for nothing” duration not equal to zero, one can conclude that CRONOS more often switches a traffic signal from green to amber when vehicles are present on the link (except for the S link). In terms of number of cycles per hour, the results are more heterogeneous. CRONOS also switches more often with vehicles present on the link compared to L-STRAT (except in the low case) but this is only due to the secondary road. Compared to C-STRAT, it switches less often with vehicles present on the link (except in the peak case) principally due to the main road.

In conclusion, CRONOS provides less “green for nothing” duration per hour on each entry. This result is also true in percentage of cycles with a “green for nothing” duration not equal to zero (except for the S link). It is a good result from a fluidity point of view. Concerning the safety angle (which is beyond the scope of this paper), more detailed studies considering the traffic flow over the temporal sequences of green, amber and red are under way.

6 Conclusion

The real-time CRONOS strategy and experimental evaluation results have been described. Despite the adaptive character of the two reference strategies, CRONOS obtains higher benefits on almost all of the traffic variables studied whatever the traffic situation, from peak to low. These results are due to the CRONOS characteristics, i.e. its high flexibility and its global traffic optimization of the intersection, and due to the use of real-time video-based measurements. It is nevertheless not possible to separate the benefits according to these points of view.

A second evaluation part concerned the correlation study between traffic light colors and traffic to describe the strategy behavior from a fluidity point of view. Innovative variables such as the “red but nobody” or the “green for nothing” have been elaborated and measured in the field thanks to the video-based measurement system.

The variables presented in this paper demonstrate the possibility to describe an average behavior of CRONOS per traffic class despite its “black box” character.

Following these results from the fluidity angle, the comparative impact of CRONOS on safety in terms of risk exposure and red light running is under study.

7 Acknowledgements

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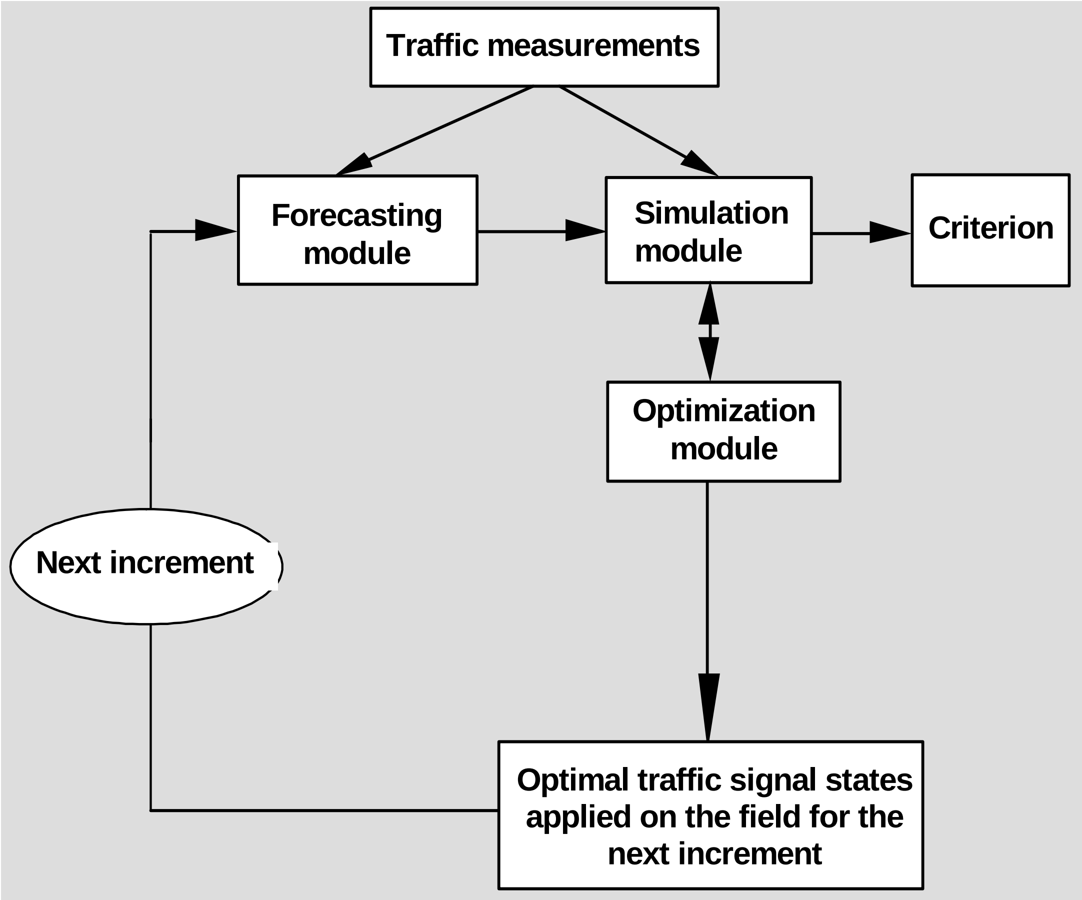

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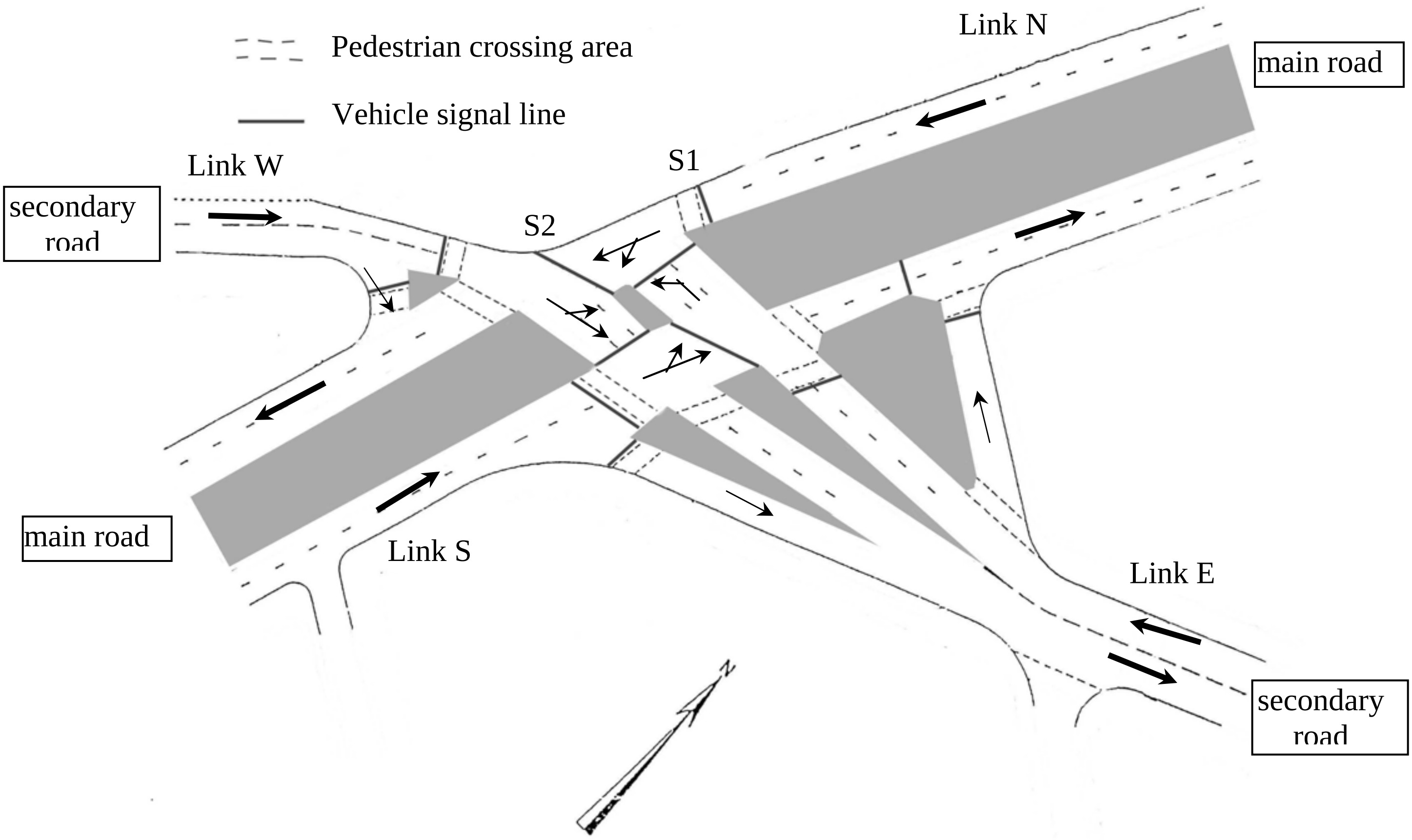

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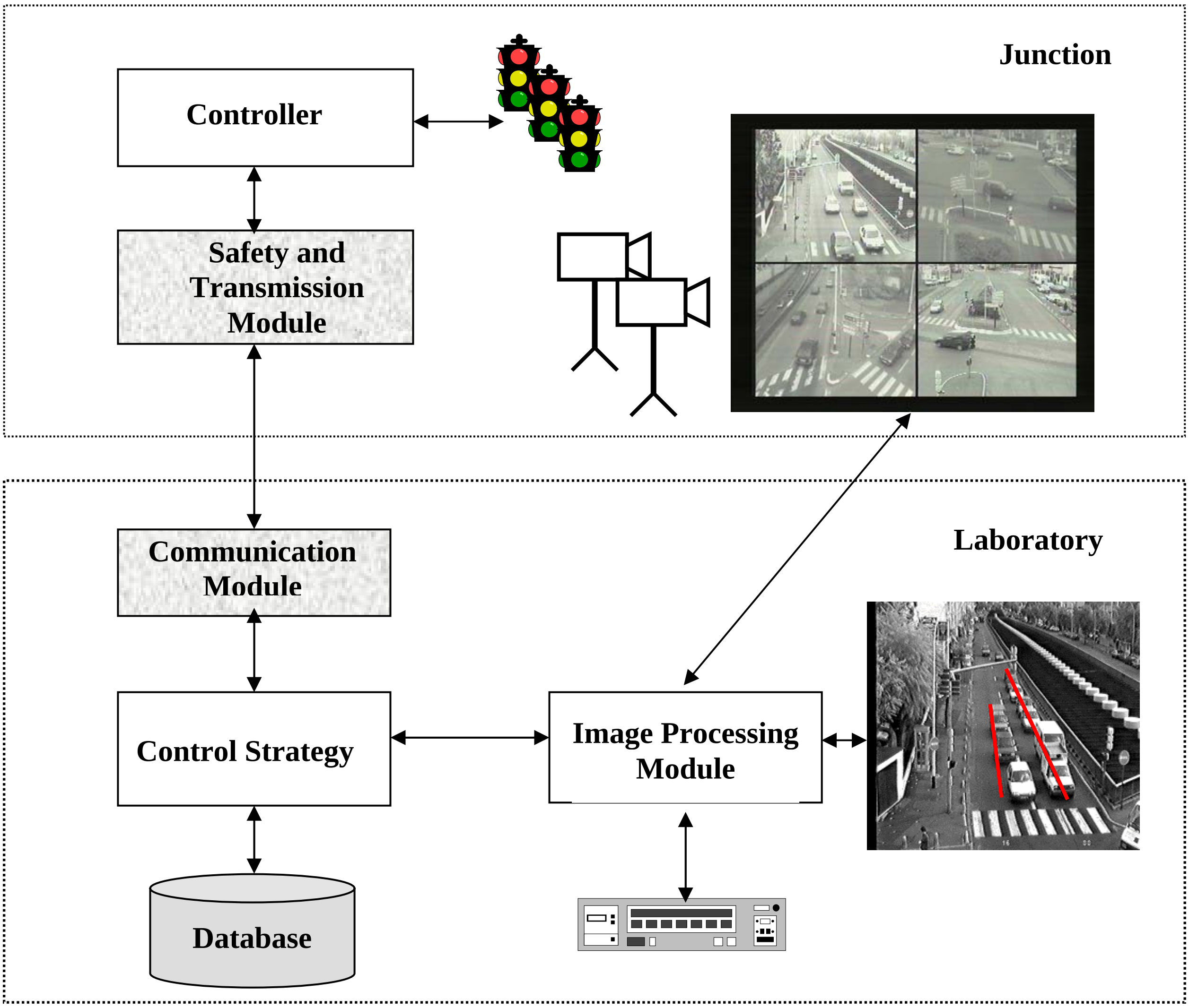

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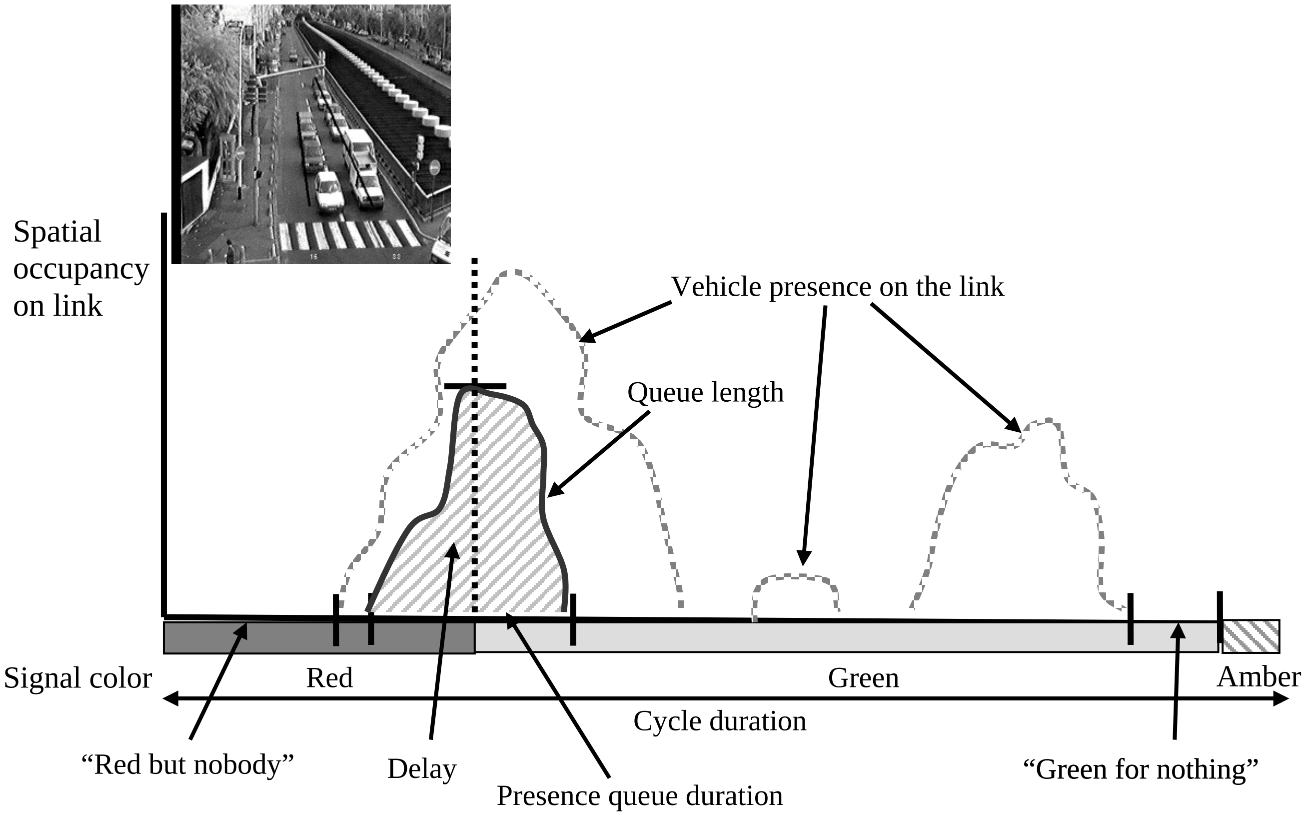

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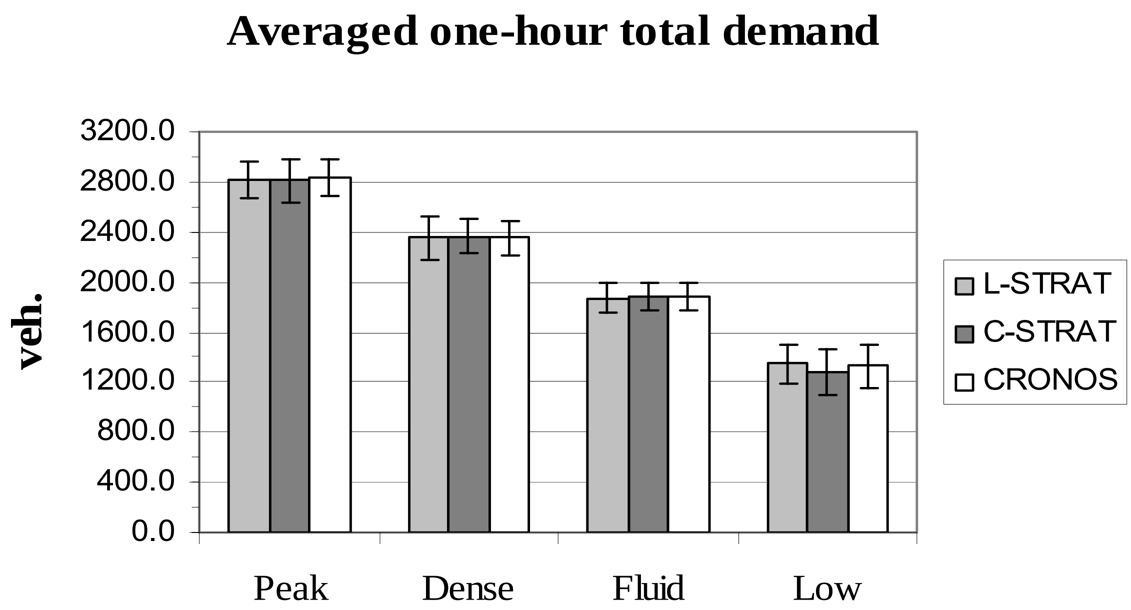

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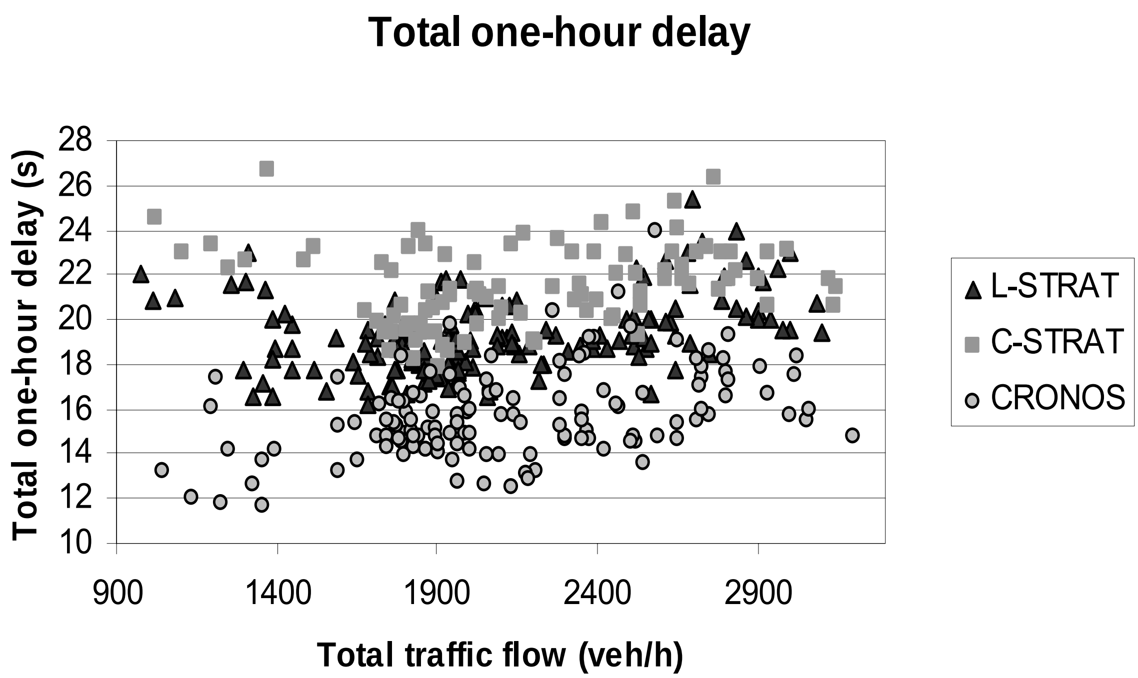

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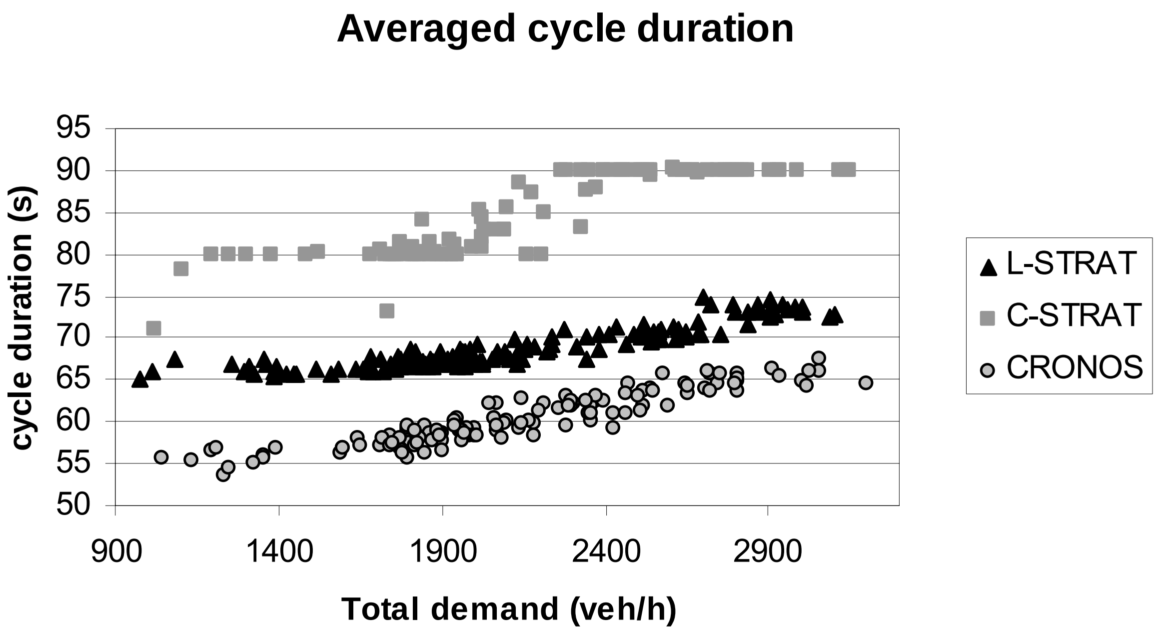

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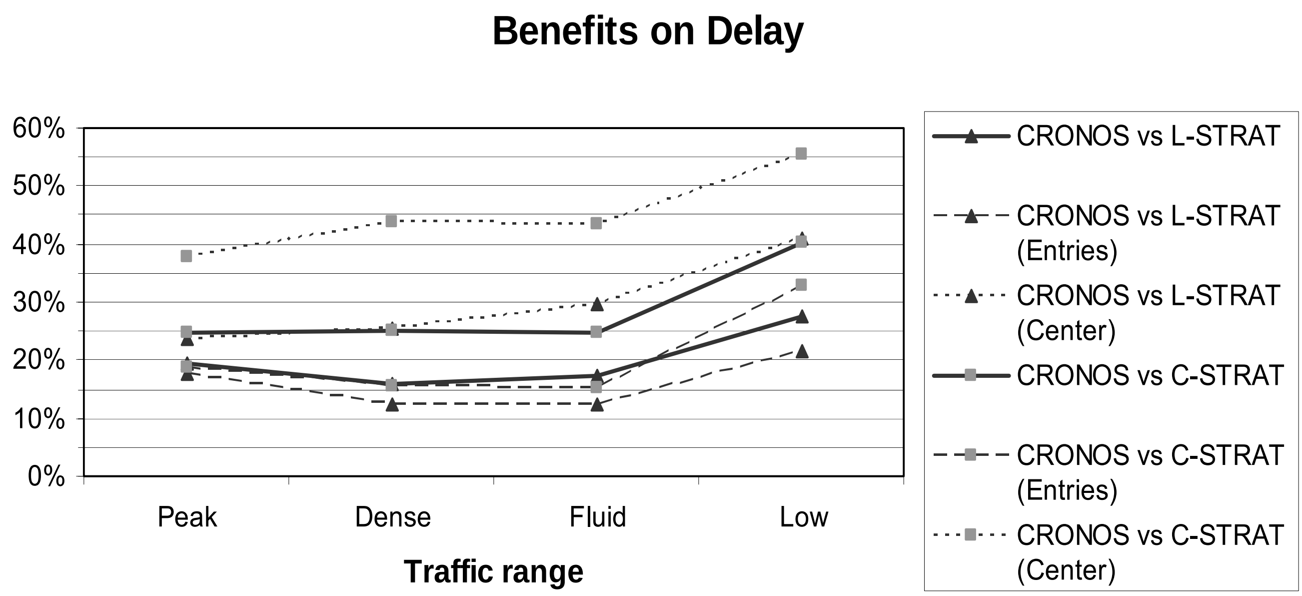

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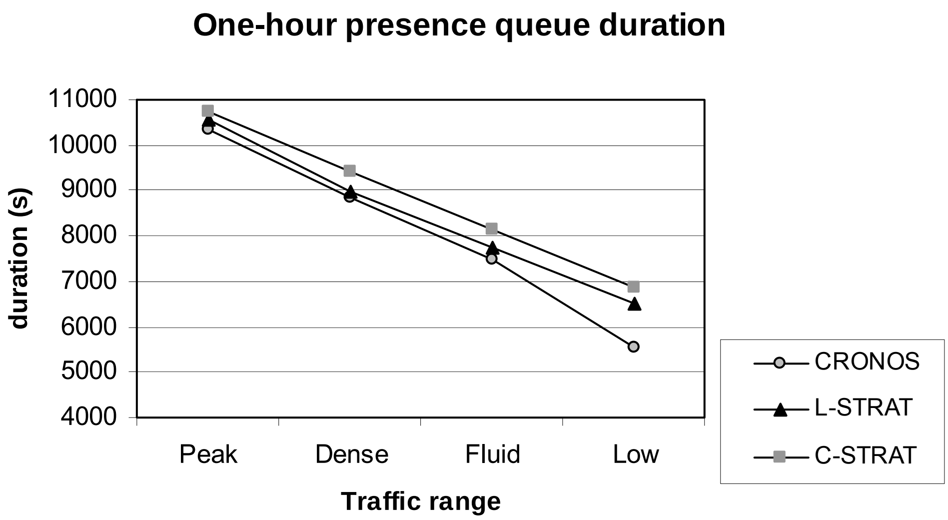

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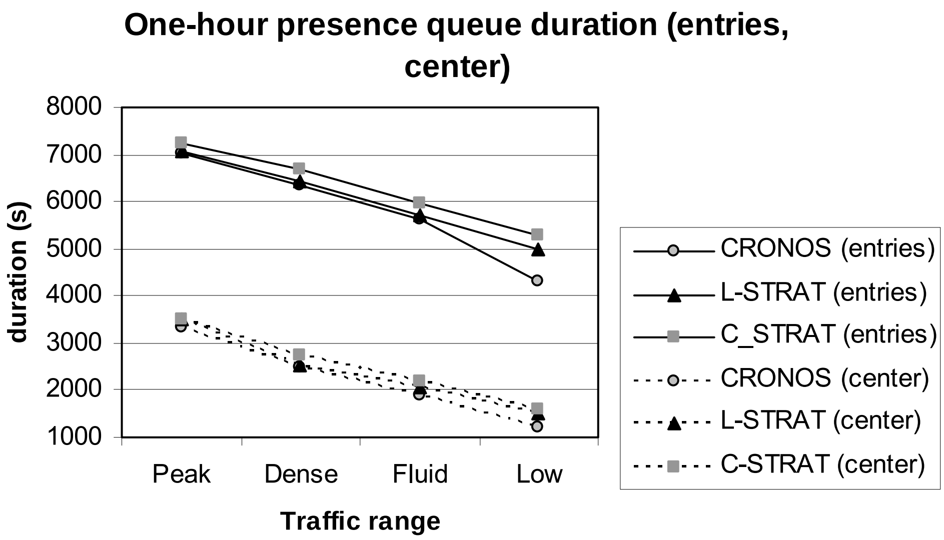

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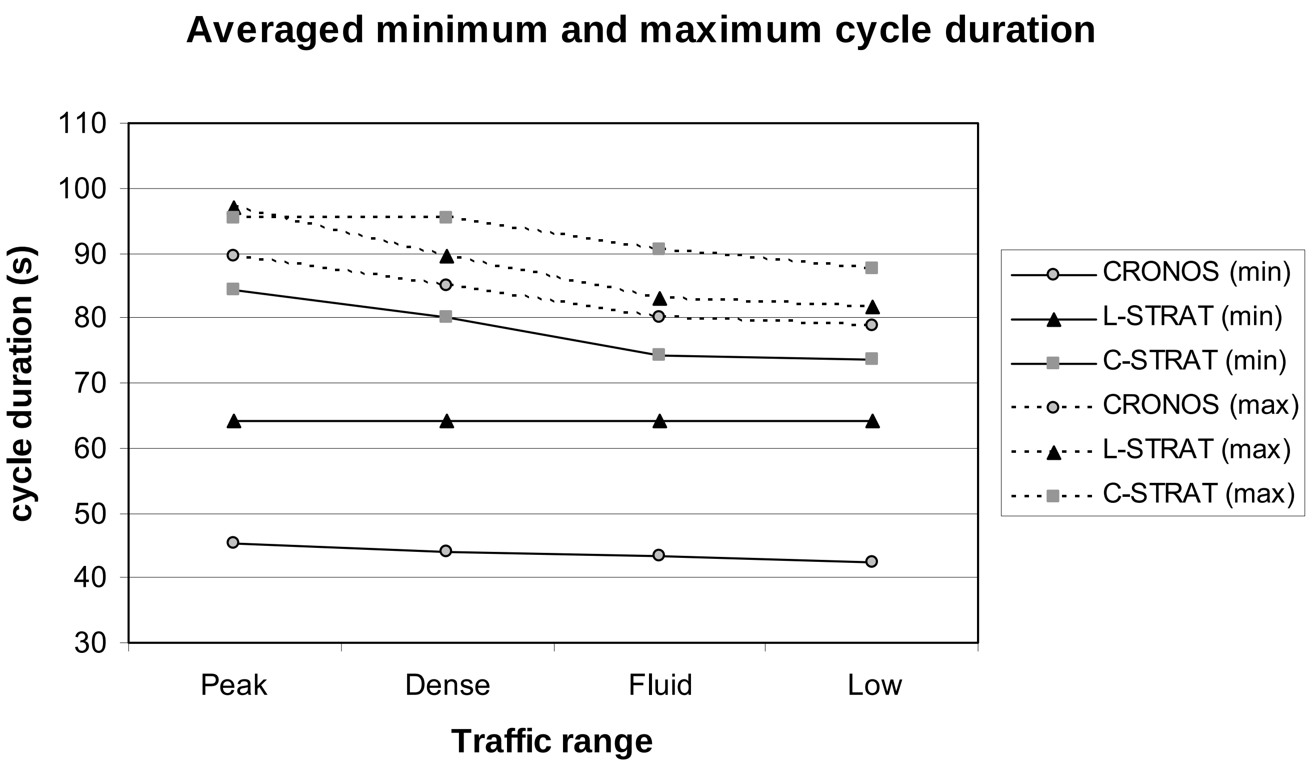

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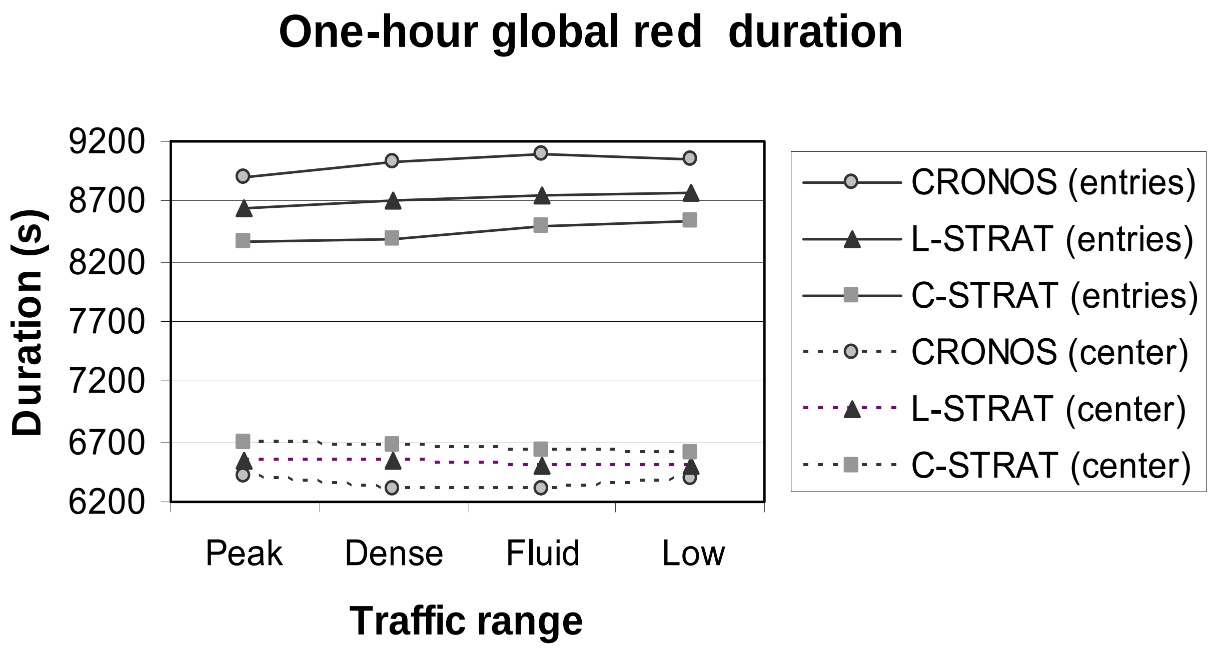

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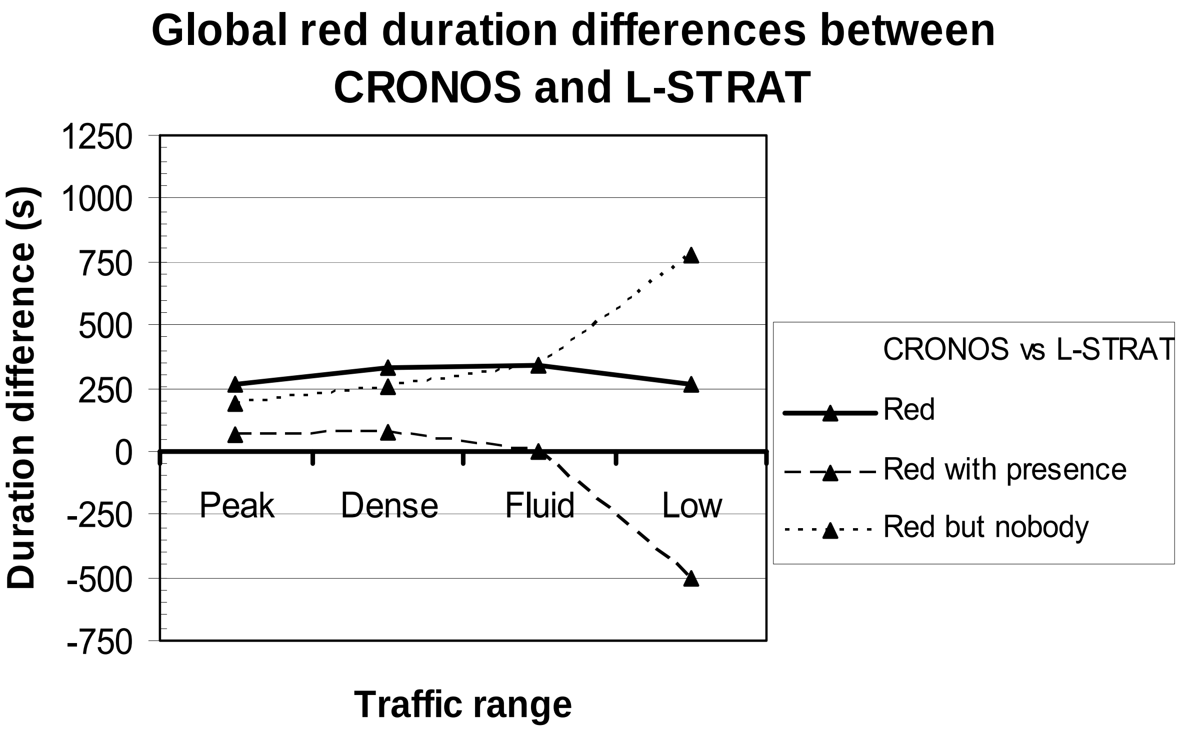

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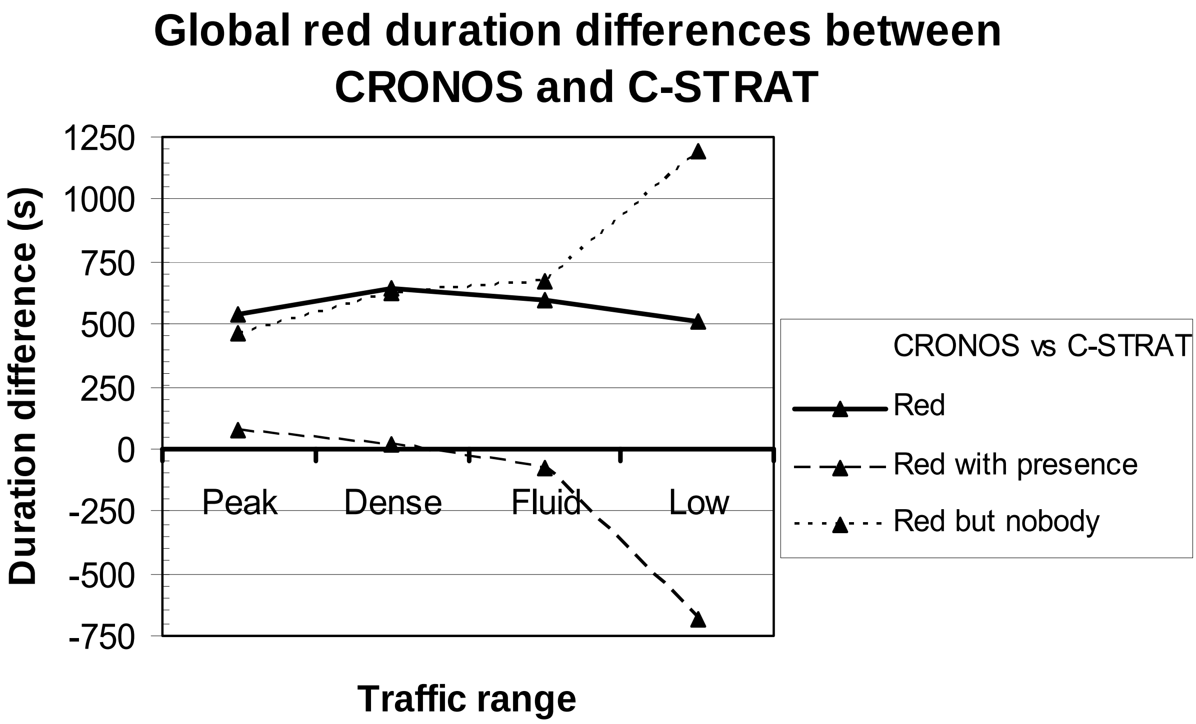

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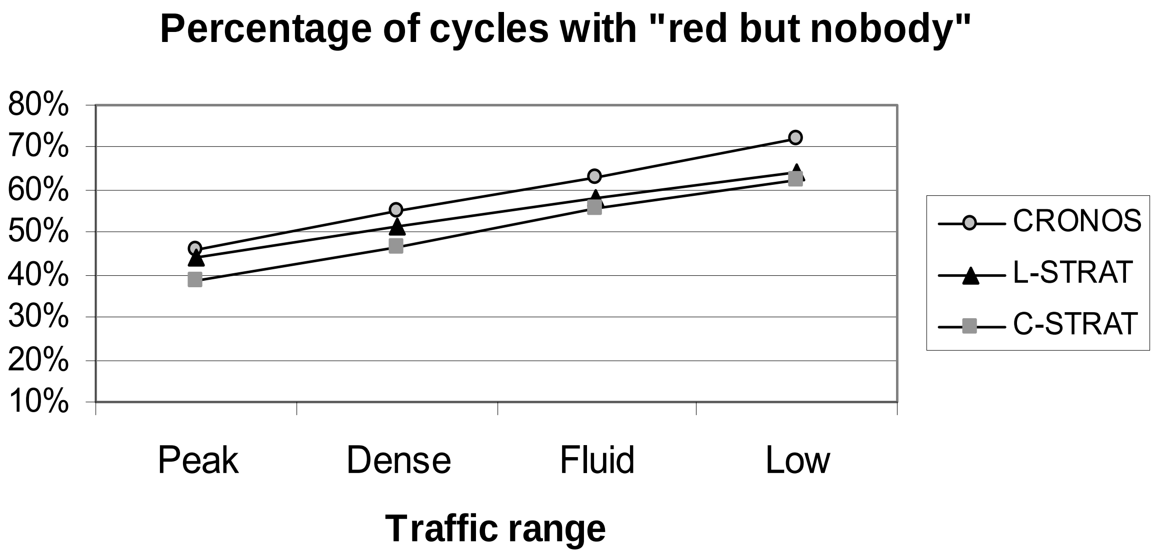

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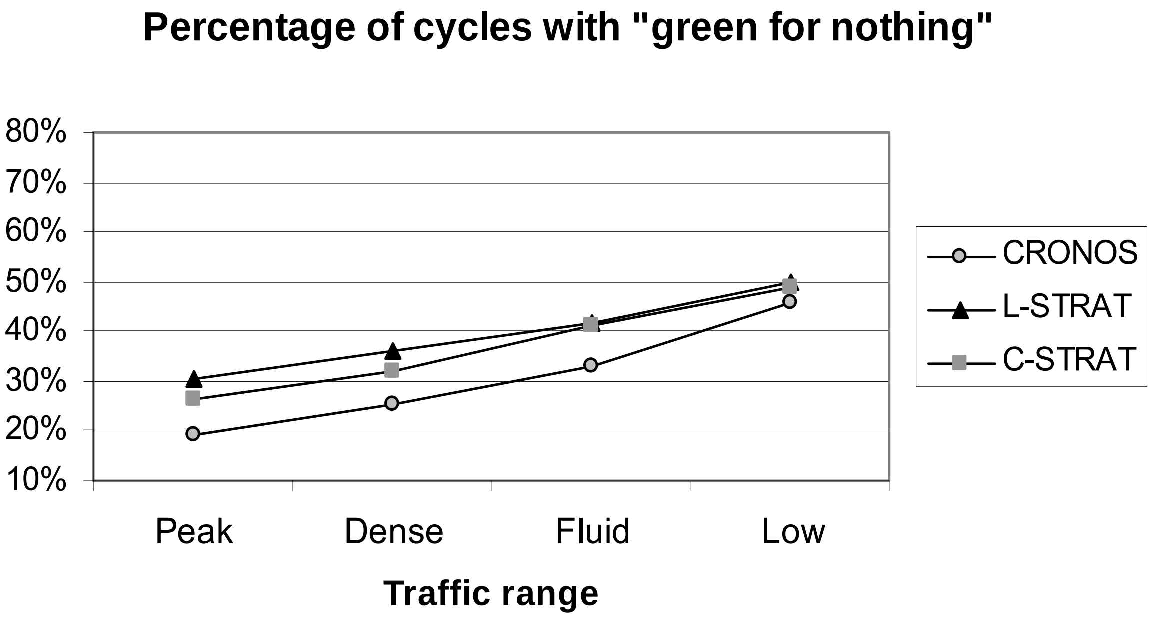

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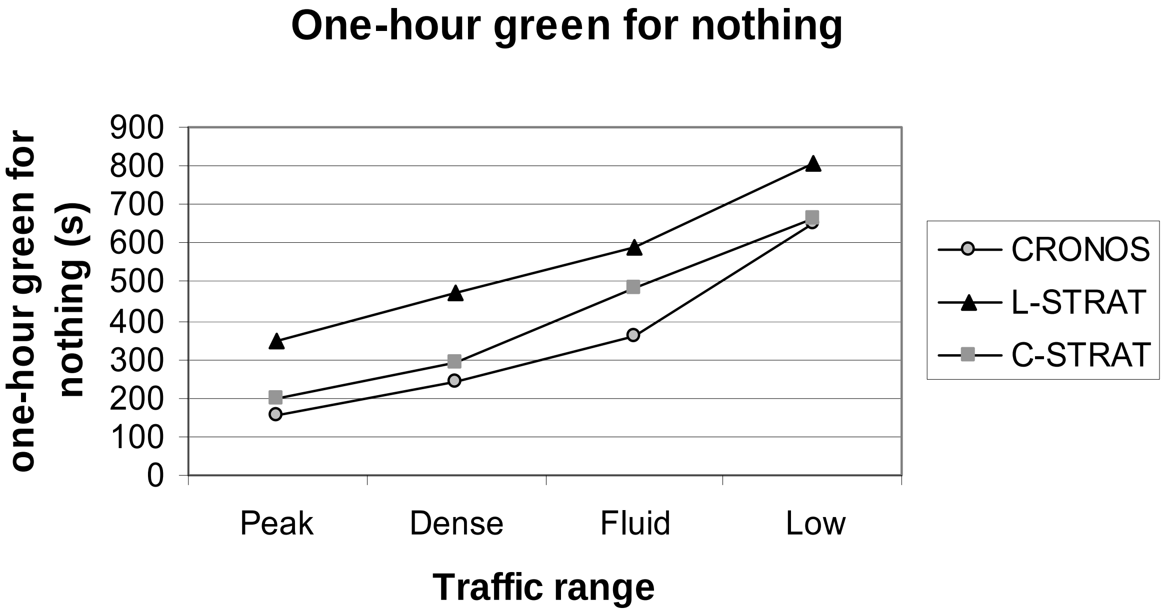

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Table 1. Comparative features of CRONOS and baseline control strategies

	L-STRAT	C-STRAT	CRONOS
Type of control:	Isolated	Centralized	Isolated or a zone of some intersections
	Time-plan based Variable cycle	Time-plan based library Slightly variable cycle	Real-time: variable cycle and stage
Adaptivity to traffic:	Slightly adaptive Vehicle actuated	Very slightly adaptive Vehicle actuated and macro-control	Highly adaptive Permanent optimization
Traffic sensors:	Magnetic loops on entries	Magnetic loops on entries	Video sensors on entries, exits and inner sections
Design:	Local traffic engineers	Local traffic engineers	INRETS

Table 2. Benefits of CRONOS for the delay, the number of stops and the percentage of stops compared to the reference strategies

Traffic variable	Demand range	Total (in %)		Entries (in %)		Center (in %)	
		CRONOS vs L-STRAT	CRONOS vs C-STRAT	CRONOS vs L-STRAT	CRONOS vs C-STRAT	CRONOS vs L-STRAT	CRONOS vs C-STRAT
Delay	Peak	19.3 (99)	24.8 (99)	17.6 (99)	18.8 (99*)	23.7 (99)	37.8 (99)
	Dense	16.0 (99)	25.1 (99)	12.2 (99)	15.5 (99)	25.3 (99)	43.7 (99)
	Fluid	17.5 (99)	24.9 (99)	12.2 (99)	15.3 (99)	29.5 (99)	43.3 (99)
	Low	27.5 (99)	40.4 (99)	21.5 (99)	32.9 (99)	40.9 (99)	55.3 (99)
Number of stops	Peak	13.1 (99)	2.4 (-)	11.7 (99)	-0.3 (-)	17.7 (99)	10.8 (99)
	Dense	8.8 (99)	0.7 (-)	7.0 (99)	-3.7 (-)	14.3 (99)	12.8 (99)
	Fluid	8.3 (99)	0.9 (-)	6.9 (99)	-3.9 (90)	12.4 (99)	13.5 (99)
	Low	13.7 (99)	15.5 (99)	10.0 (99)	10.0 (95)	24.2 (99)	29.9 (99)
Percentage of stops	Peak	12.1 (99)	3.1 (99)				
	Dense	8.2 (99)	0.7 (-)				
	Fluid	6.4 (99)	-0.3 (-)				
	Low	8.2 (99)	2.8 (-)				

Test of a significative difference between the two means

(99): significant at 99% of confidence level

(95): significant at 95% of confidence level

(90): significant at 90% of confidence level

(-): no significant at 90% of confidence level at least.

(n*): at least one of the two distributions does not follow a normal law.