



On-field experiment of the traffic-responsive co-ordinated control strategy CRONOS-2 for under- and over-saturated traffic

Florence Boillot, Pierre Vinant, Jean Claude Pierrelee

► To cite this version:

Florence Boillot, Pierre Vinant, Jean Claude Pierrelee. On-field experiment of the traffic-responsive co-ordinated control strategy CRONOS-2 for under- and over-saturated traffic. *Transportation Research : Part A, Policy and Practice*, 2019, 124, pp 189-202. <10.1016/j.tra.2019.03.006>. <hal-03256392>

HAL Id: hal-03256392

<https://hal.science/hal-03256392v1>

Submitted on 10 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

On-field experiment of the traffic-responsive co-ordinated control strategy CRONOS-2 for under- and over-saturated traffic

Florence Boillot^{(a)(*)}, Pierre Vinant^(a), Jean-Claude Pierrelée^{(a)(†)}

^(a) Université Paris-Est, IFSTTAR, COSYS, GRETTIA, 25 Allée des Marronniers, 78000
Versailles, France

Abstract

Recurrent road traffic congestion in large cities is a blight that wastes a great deal of time and increases greenhouse gas emissions, fuel consumption, noise and stress. One way of combating such congestion is traffic control by means of traffic signals. The role of traffic signals is to temporally separate the different traffic flows at each intersection and alternately distribute the right of way with appropriate time durations. The real-time traffic control systems that have been developed during the three last decades include CRONOS-2 which has several advantages under congested situations, in particular, its capacity to control several intersections in a centralized way. A real-site trial has been performed on a zone consisting of five adjacent intersections. The results show significant benefits for total delay in the zone during congestion compared to the usual control strategy for this zone. These results vary for each intersection considered on its own. This trial has demonstrated the effectiveness of this system in complex and constrained traffic situations.

Keywords: Signalized intersection; Traffic congestion; Real-time traffic control strategy; On-site assessments.

1 Introduction

Recurrent congestion in large cities is still a major concern. Congestion continues to increase in many cities and new situations of congestion are developing in countries like China or India. Such congestion causes delays and nuisances like greenhouse gas emissions, noise and stress, all of which have an impact on health. In 2007 the European Community (EC) estimated that urban traffic accounts for 40% of all the CO₂ emissions from road transport. The European economy loses almost 100 billion euros per year (1% of the EC's Gross Domestic Product) due to this congestion (European Community, 2007).

Apart from drastically reducing the number of vehicles in cities, one way of combating congestion is to use traffic signals to perform traffic control, as the spacial and temporal separation of vehicle flows can help to decrease congestion. Of course Urban Traffic Control (UTC) systems cannot on their own resolve the problem, but they can help. Different types of traffic control systems exist: they differ according to their greater or lesser ability to adapt, to limit congestion and to control a network.

One such system, the CRONOS-2 real-time traffic control system is a highly adaptive system for the control of zones with several intersections and well adapted to situations of congestion. This system is a modified version of the CRONOS system developed in the nineties and described in (Boillot et al., 1992). CRONOS was first trialled at an isolated intersection with low congestion and almost no buses and no pedestrians (Boillot et al., 2006). This experimental site did not reveal all the features of the strategy such as its capacity to control several intersections or to manage congestion.

* Corresponding author. Tel.: +33 30 84 40 55; fax: +33 30 84 40 01.

† Retired from IFSTTAR.

E-mail addresses: florence.boillot@ifsttar.fr (F. Boillot), pierre.vinant@ifsttar.fr (P. Vinant)

A new trial with CRONOS-2 has been performed at a site with very different characteristics: a congested zone consisting of several intersections with high bus and pedestrian flows. The objective was to demonstrate the feasibility and effectiveness of the system in a constrained and complex traffic environment. This paper describes this new trial and presents our evaluation results.

After a survey of the main adaptive UTC systems, the principal features of CRONOS-2 are described, highlighting the improvements over the first version of CRONOS. The experimental site is then described and some simulation tests are summarized before an account is given of the trial, the evaluation methodology and finally the evaluation results. A general discussion on the use of the real-time UTC systems ends this paper.

2 Overview of UTC systems

In this paper, we shall define a “link” as a one-way section of street between two intersections. A link may have several lanes.

2.1 A proposed classification

World-wide, there are many adaptive UTC systems. Even though there only seems to be a small number of different types of system, it is difficult to classify the different types of UTC system because ultimately every system is unique with characteristics of its own. Furthermore, several classifications are possible depending on where we place the focus. This can be on the temporal aspect, the control method, the centralized nature of the system and so on. Moreover these different aspects are correlated.

If we consider the temporal aspect, three main classes can be identified:

- The first contains the adaptive pre-defined traffic signal plans whose green and red ranges are usually adapted according to traffic measurements made on each link separately. This class does not consider the traffic on all the links when adapting the timings on one of them. They use vehicle-actuated functionalities like green extension, blocking prevention or stage skipping. This class includes the control systems of the majority of the cities which are based on traffic signal plans.
- The second class consists of systems based on a heuristic or exact optimization method in which adaptation occurs once per cycle or about every minute (in particular SCOOT (Hunt, 1981), SCATS (Lowrie, 1982), TUC (Diakaki et al., 2003) and MOTION (Bielefeldt and Busch 1994)).
- The third class contains the UTC systems that are also based on an optimization method but which compute the next timing every few seconds. These systems may have cycle durations that vary from one cycle to the next (in particular PROLYN (Henry et al., 1983), OPAC (Gartner, 1982), UTOPIA (Mauro and Di Taranto, 1990), RHODES (Mirchandani and Head, 2001) and SURTRAC (Xie et al., 2012)). In this class, the cycle duration is not constrained except on safety grounds and can vary considerably from one cycle to the next.

The temporal aspect aside, some systems of one class may have some characteristics of another class.: for example, a traffic signal plan may have cycle durations that vary from one cycle to the next. This variability can be obtained when stage skipping is implemented or with adaptive ranges that are coupled to traffic signal synchronisation. The paper (Braban and Boillot, 2003) provides a survey of UTC systems which includes the major systems referred to in this section.

2.2 Main characteristics of the third class of control systems

In order to compare CRONOS-2 to the other UTC systems, we shall provide a more precise description of the third class of control system, highlighting their overall operating structure.

- These systems use traffic measurements which are generally provided by magnetic loops. In this case the measurements consist of traffic flows and temporal occupancy rates.
- These measurements may be processed by models in order to convert traffic flows into modelled queue lengths for example.
- Furthermore, these systems evaluate different traffic signal sequences for a short time horizon. They anticipate the traffic entering the controlled network by means of forecasting and traffic flow modelling.
- These systems have the capacity to update traffic signal timings frequently. They set stage duration constraints in order to specify those solutions which are acceptable from the safety point of view.
- Finally these systems implement an optimization method that enables them to identify the best traffic signal timing by optimizing one or more criteria within a short time horizon.

2.3 Discussion

The systems which provide frequent traffic control responses are a priori favoured in terms of traffic efficiency because they can take account of the traffic variations within a time horizon of a few seconds. This frequent optimization makes them less sensitive to traffic measurement errors and the system's modelling uncertainty which increases as one moves further into the future.

But the ability to perform high frequency optimization is generally incompatible with the centralized control of several intersections during the same optimization process. This is the case with systems like PRODYN or OPAC because their computational optimization time increases exponentially with the number of intersections.

However, the overall supervision of several intersections is essential in order to control congestion within a spatial zone. Otherwise, the control decision will be too local and fail to take account of how it will impact neighbouring intersections. This is the case of TUC for example which controls a network which may be congested, but its frequency of decision is the cycle duration.

Another constraint that limits attempts to combat congestion is the need to use sensors that are able to measure it. Magnetic loops are not very good at this. If in theory it is possible to model queue lengths on the basis of entering and exiting traffic flows, the model can deviate completely from reality because of the errors that affect traffic flow measurements each second. The model needs to be frequently re-set to bring it back to reality. This is generally done by considering that the queue length cancels itself out at the end of each traffic signal cycle. While this is the case during free flow, it is not during congestion.

Furthermore, when a queue extends beyond the magnetic loop, the traffic flow measurements deteriorate in quality and with them the queue modelling. Direct measurement of queue length by video camera is more effective.

The CRONOS-2 system, which is described in the next section, belongs to the third class of system. It is based on an optimization method with a high update frequency. Nevertheless, this system differs from the others of this type in two important respects: its capacity to centralized control several intersections and its capacity to take full advantage of video-based spatial measurements, which are of great value for congestion. Its main characteristics are described below.

3 CRONOS-2

3.1 The previous version

A first system named CRONOS was developed in the nineties (Boillot et al., 1992). It minimizes total traffic delay over a time horizon within a zone consisting of several controlled intersections. The minimization process is based on a modified version of the so-called Box

optimization heuristic (Kuester and Mize, 1973). This method provides good local minima, and even very often the global minimum depending on the complexity of the problem. CRONOS looks for the next optimal switchovers for all the traffic signals in the zone over a time horizon of around one minute. Traffic modelling is applied to calculate the total delay up to the time horizon for a given set of switchovers. CRONOS, like PRODYN or OPAC, uses the rolling horizon principle: the traffic signal states are applied at the intersection for the next few seconds (two seconds for CRONOS, five seconds for PRODYN...) and the whole process is run again a few seconds later.

Experimental results from a real site have already been reported in 2005 and 2006 (Midenet et al., 2005), (Boillot et al., 2006). The site in question was an isolated intersection with dense but not congested traffic and almost no buses or pedestrians. The results showed that CRONOS considerably reduced total delay compared to the two reference control strategies which consisted of one local and one centralized strategy. These results covered all traffic situations, from peak to low traffic. More details about the CRONOS system can be found in the papers cited above.

3.2 The new version

Between 2007 and 2012, major improvements were made to this basic version. However, the framework described above has been retained. The improvements involve a new method for constructing each alternative that is to be tested by the optimization module, the capacity to manage stage skipping or exclusive stages, the improvement of traffic modelling and the management of bus priority, the ability to take account of specific recommendations from an external congestion supervisor, named Claire system (Scemama, 1995). In view of these major improvements, the system has been renamed CRONOS-2. These improvements will be detailed in another paper devoted to them. In what follows we shall describe only the most significant improvements which are relevant to our experiments.

The traffic modelling implemented in CRONOS-2 to compute the optimization criterion has been improved to take better account of congestion situations. It should be borne in mind that the different versions of CRONOS include the spatial extent modelling of the queue length, which is preferable to a vertical queue modelling in congestion situations. Three improvements are reported below.

One modelled situation involves left-turning movements (Fig. 1a). In major French urban intersections, left-turning movements have no dedicated stages. The left-turning vehicle must find a gap between the oncoming priority vehicles. The modelling in CRONOS-2 adjusts the flow of left-turning vehicles on the basis of the priority traffic. This results in more accurate traffic flow forecasting.

Another situation concerns the blocking of a link (Fig. 1b). Depending on the narrowness of an intersection, our traffic modelling, by parameterization, can take account of the complete blocking of an upstream link of this intersection when at least one of its exit links is blocked.

Furthermore, when there is a long queue on a link, when the traffic signal turns green it takes several seconds for the vehicles at the end of the queue to begin to move. This delay is modelled in order to better represent the available space at the end of the queue for the vehicles arriving on the link. This means that queue spillback is better taken into account in order to calculate the flow that can exit from an upstream link (Fig. 1c).

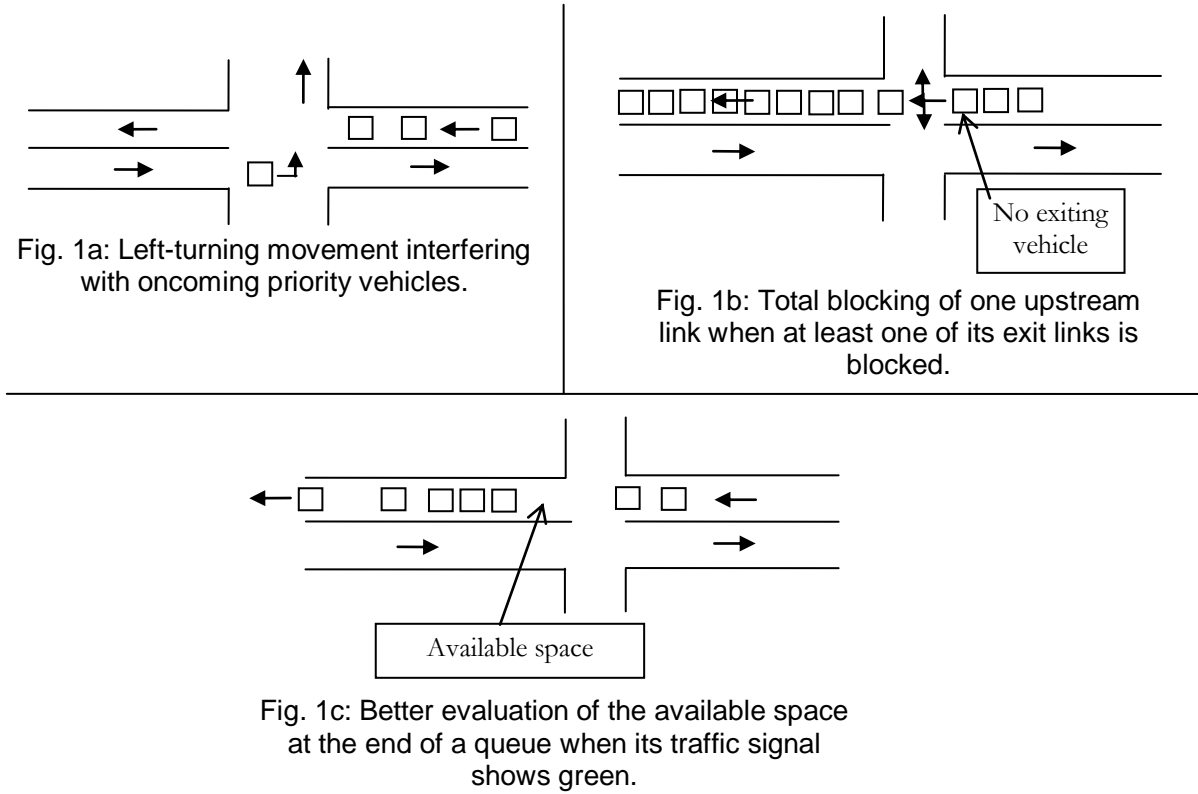


Fig. 1: Illustration of the modelling improvements in CRONOS-2

These improvements appeared to be necessary because of the high level of congestion at the experimental site. But it is difficult to evaluate the benefits they confer on our experimental results. Formally, the more accurate traffic modelling becomes, the better able the control system is to take appropriate decisions.

Let us summarize the characteristics of CRONOS-2 that were fully used in this experiment. Due to the polynomial time of its optimization algorithm, several intersections (typically ten) can be optimized in a single optimization process in order to improve the consistency of the traffic modelling and thus generate more effective traffic signal commands. This ability does not prevent the system from finding an appropriate solution every second throughout the chosen time horizon.

CRONOS-2 has the ability to manage congestion situations thanks to its modified traffic modelling and its use of video-based traffic measurements. With image-processing-based measurements, the length of the queue, the spatial occupancy rate and the available space at the end of the queue can be measured. Better queue modelling over the time horizon is achieved because the queue length is measured rather than modeled at the beginning of the horizon. CRONOS-2's ability to manage congestion is also due to the centralized control of zones.

If we return to our classification of systems, CRONOS-2 belongs the third class of systems with frequent optimization and additional features: CRONOS-2 now performs optimization every second, is centralized by zone and is able to manage congestion. The decision to use a heuristic as the optimization method is both a strength and a weakness. It is a strength from the standpoint of centralisation and congestion management, but also a weakness because it does not always find the global minimum. Nevertheless, the presence of traffic measurement errors, traffic modelling errors and forecasting errors, means that use of an exact method to find the global minimum would certainly not reach the exact minimum in the real world. This

remark puts into perspective [relativise] the difference between a good local optimum and a global optimum.

4 The experimental site

In this section we shall describe the infrastructure, traffic, traffic signals and sensors at the experimental site.

4.1 The road infrastructure

The experimental site is located in the centre of Versailles, a suburban town to the west of Paris. The site is not far from the well known Château. It consists of five adjacent signalized intersections (A, B, C, D, E) located along a route around 700 metres long (Fig. 2a). The streets all have two-way traffic, except for three which are shown on Fig. 2a.

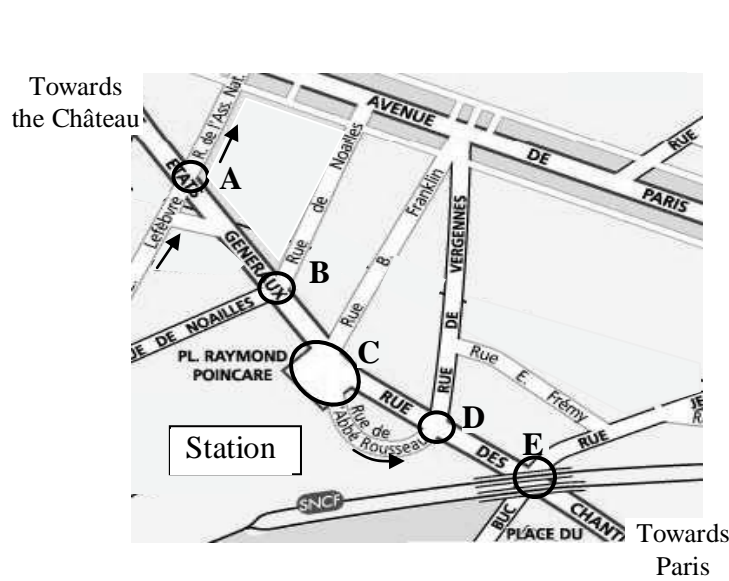


Fig. 2a: Experimental site

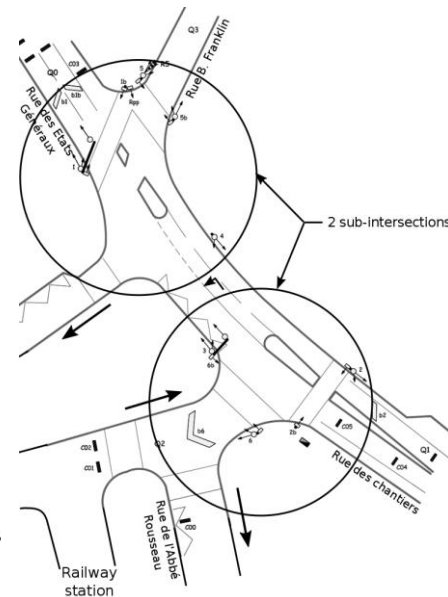


Fig. 2b : Intersection C

The main intersection (C) includes the accesses to a large railway station. It is made up of two signalized sub-intersections with connecting zones with several lanes. One of these lanes, which does not have a traffic signal, is used by vehicles to turn left towards the railway station (Fig. 2b).

The main road has one lane on each link in both directions except in two cases. From A to C in one direction there is an additional bus lane. The four links entering E have two lanes on their last twenty five meters, in order to provide a dedicated left turn lane on each link in each of the four entries. The connecting zones inside the intersection are very small: only one or two vehicles can remain in them before turning. These movements have no specific stage. Left-turning vehicles need to wait for a gap in the priority flow before turning.

Furthermore, two bus stops at the exits of the main road at intersection C have no bus bay so the buses have to stop on the vehicle lane.

4.2 The traffic

As the experimental site provides access to the second busiest railway station in the area near Paris in terms of traveller flows, it has a large number of bus stops and bus routes: 18 bus routes pass through the site. There are therefore heavy pedestrian flows away from or towards the railway station.

Congestion during peak hours is not only, and perhaps not principally, due to high traffic demand. Congestion comes from a variety of sources: the presence of a large number of buses at the same time at intersection C (up to eight, some of them articulated); the buses that stop at the two bus stops without a bus bay at the exit of intersection C block the vehicles behind them; the high pedestrian flows which pose a problem for left-turning vehicles; a pedestrian crossing near the station which has no traffic signal so pedestrians always have the right of way and can block almost all vehicle and bus flows inside intersection C; numerous pedestrians cross the links even when they do not have the right of way (at the stop line or outside a pedestrian crossing); narrow roads (most of the links only have a single lane); heavy left-turning traffic at intersection E; a traffic policeman four times per day for thirty minutes at intersection D to allow pedestrians to cross a road near a school.

In addition to these features of peak traffic and the infrastructure, the slightest incident, such as a double-parked delivery van, can also cause congestion that lasts for several signal cycles.

4.3 The traffic signals

The experimental site consists of five two-stage intersections. The usual control strategy for this network, which in what follows we shall call TP-STRAT (for Timing Plan Strategy), is a fixed timing plan that was set by the Versailles traffic engineers and checked again before the experiment. This timing plan is used throughout the day. There is a fixed offset between each pair of adjacent intersections. Its value differs between each pair. The pedestrian clearance times at the pedestrian signals at the five intersections are exceptionally long. They have been calculated for a pedestrian moving at 0.5 m/s instead of the usual 1 m/s. These clearance times are between 9 to 19 seconds with half of them being 15 seconds or longer. The consequence for CRONOS-2 is two-fold. These long durations mean that the adaptive ranges are more constrained because the minimum cycle durations are already high. Furthermore the responsiveness of CRONOS-2 is decreased because a long time is required to make a traffic signal switching and this cannot be reduced.

4.4 The sensors and data collection

Fixed video cameras have been installed at the site. They cover all the links except one exit on intersection A which never has queue spillback. A few magnetic loops that had already been installed on the site were also used.

Automatic image processing was used to extract video-based traffic measurements on a one-second basis in order to supply CRONOS-2 with data. The following were measured:

- an indicator of flow in front of the stop line of each link and at the entry of each link (except for the entry links of the zone). Only one flow indicator per link was input to CRONOS-2, preferably for the entry of the link, but the choice (whether at the entry or the stop line) was made on the basis of the reliability of the measurements;
- the queue length at the stop line of each link;
- the available space between the end of a queue and the link entry;
- the spatial occupancy rate on each link. This measurement was obtained for each portion of link by dividing each link into three equal parts.

It is difficult to make a qualitative evaluation of the reliability of these measurements. Two major problems can be highlighted: low angle sunlight and camera obstruction. Some cameras at the site may be dazzled for up to 30 minutes during the time of the year when the sun is low in the sky resulting in the non-detection of some vehicles. Camera obstruction due to non-optimal camera location leads to different problems: vehicles on one lane can be masked by buses or lorries on another lane or a lorry can be detected on two lanes simultaneously. Finally we should also mention a much rarer problem: when complete blocking occurs that lasts several cycle durations, the queue length may not be correctly detected when no vehicle

moves for several minutes on a link. This last weakness means that a strategy which generates such complete blockings will be favoured, from an efficiency evaluation point of view, because it will result in a falsely low estimate of delay.

5 Preliminary traffic simulation studies

Before undertaking the experiment on the real site, two studies were carried out using a traffic simulation tool. The first study concerned the parameterization of the duration of the CRONOS-2 optimization horizon for this site, and the second related to an evaluation of the efficiency of CRONOS-2 in terms of its ability to find the global optimum during the optimization process.

The simulation tool we used was ARCHISIM (Esp   and Auberlet, 2007) which simulates traffic on urban sites with the ability to implement external real-time traffic signal commands. This tool was configured for the five intersections and interfaced with CRONOS-2. The simulated traffic demand was set at the average real demand during peak hours for both studies. The extent to which the traffic used for simulation was representative of the real traffic at the site was limited for several reasons:

- The tool did not simulate pedestrian flows which can block vehicles and buses, especially at intersection C.
- The presence of the traffic policeman at a pedestrian crossing near a school at intersection D could not be simulated.

Despite these limitations, the tool provided useful information for the configuration of CRONOS-2 and about its intrinsic efficiency.

5.1 Horizon duration study

The first study set out to identify an appropriate duration for the time horizon at the studied site. We remind readers that the horizon is the temporal range over which the delay is calculated in order to compare the different solutions and choose the optimum.

The problem is as follows: the impact of traffic signalling decisions on traffic cannot be evaluated by the system beyond the horizon. If the horizon is too short, the close consequences on traffic will not be evaluated. However, an excessively long horizon does not provide additional efficiency benefits because of traffic modelling and forecasting errors. These errors increase as one moves towards the end of the horizon. On the other hand, the CPU time also increases greatly. A good compromise must be found.

The delay obtained over the entire simulated zone when the traffic signals were controlled by TP-STRAT was compared with the delay obtained when the traffic signals were controlled by CRONOS-2. This comparison was performed with several different horizon durations. Fig. 3 shows the variation in the relative difference between the delay obtained with TP-STRAT and CRONOS-2 according to these different horizon values.

We can see that the relative difference increases with the horizon value up to 70 seconds and remains approximately constant above this value. As the final horizon value is a compromise between system efficiency and CPU time, two horizon durations were tested on the real site at the beginning of the experiment: 60 and 70 seconds. Finally, 70 seconds was selected for the entire experiment as it led to better qualitative results than 60 seconds.

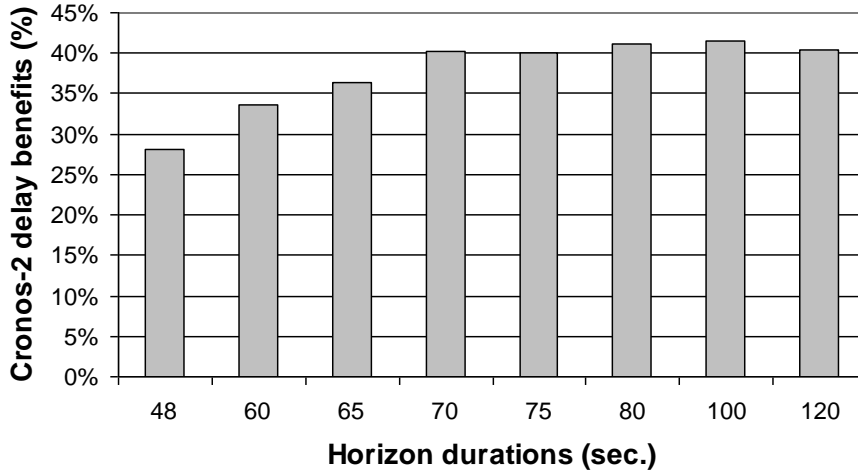


Fig. 3: CRONOS-2: simulated delay benefits according to the horizon duration

5.2 Global optimum study

As CRONOS-2 uses a heuristic optimization method, the global optimum is not always reached. It is interesting to study the disparity between the optimum found by CRONOS-2 and the global optimum, as well as how frequently CRONOS-2 finds the global optimum. To do this, an exact method was devised to compute the exact solution for each optimization process. This exact method allows us to determine the number of solutions, and also the best and the worst one. Of course, with this method processing requirements increase exponentially, so the study only optimized three of the five intersections. Traffic simulation was performed for the entire zone. The three central intersections (B, C, D) were controlled by CRONOS-2 and the two others (A and E) by TP-STRAT. CRONOS-2's optimization criterion was calculated for all five intersections. The fixed sequence of traffic signals from TP-STRAT for intersections A and E was input to CRONOS-2. For each one second time step the exact method determined the shortest and longest delay for the entire zone produced by actions covering the three intersections B, C, D.

The optimization process for one time step (one second) is referred to as "iteration". 336 iterations were performed. The result shows that CRONOS-2 obtained the global optimum in 43% of the iterations. In 61% of the cases the difference between the optimum found by CRONOS-2 and the global optimum was less than 0.5%, in 68% of the cases it was less than 1%, and in 88% less than 5% with regard to the range of criterion values for the iteration in question. The number of possible solutions according to the iteration was between 120,000 to 622 million, with an average of 64 million. CRONOS-2 tested between 25 to 154 possible solutions, 75 on average. Fig. 4 shows a significant sample of the position of the optimum found by CRONOS-2 according to the worst and the best criterion value for several successive iterations.

It would have been interesting to compare these results with the optimization of the five intersections instead of three and to study the deterioration in the results. But as we have seen above this was not possible because of the exponential increase of the computational optimization time of the exact method.

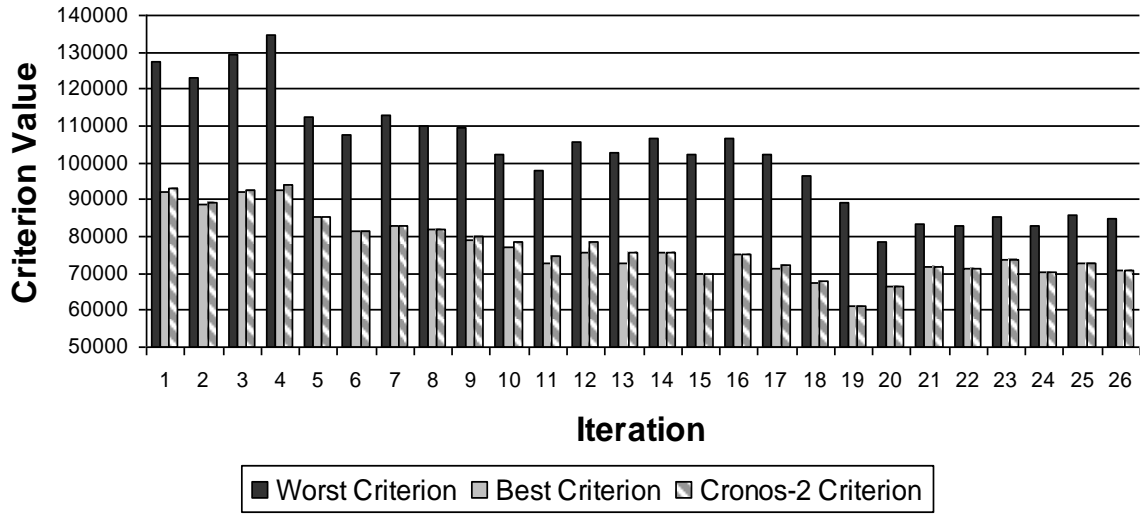


Fig. 4: Worst, best and CRONOS-2 optimum value for some successive time steps.

What conclusions can we draw from these results? As long as generalization to five intersections does not lead to excessive deterioration, these results show the quality of the optimum obtained. Furthermore the value of the criterion is calculated over the entire horizon but only one second is applied on site before a new optimization process is performed. Finally, as mentioned in 3.2, taking account of the other sources of errors (modelling, forecasting and measurements), such an optimization heuristic is well suited to the problem.

6 The experiment

The experiment was performed on weekdays between February and June 2012. Two control strategies were applied alternately to the five intersection network: CRONOS-2 and the usual TP-STRAT control strategy described in 4.3. The experiment ran from 7.30 to 11.30 in the morning and from 14.00 to 17.00 in the afternoon. Each strategy controlled the network for an entire half-day. The strategy was chosen in order to alternate between the two strategies for the same half-day period from one week to the next. In addition, within the week, both strategies were evenly distributed between the different half-day periods. This methodology was adopted for two reasons. Firstly in order to achieve a mix of exogenous parameters such as luminosity, meteorological conditions and seasonal traffic variations, because this makes it possible to balance out traffic measurement errors between each strategy. Secondly in order to prevent drivers from adapting to CRONOS-2 which could lead them to adopt new driving behaviours.

During the experiment, video- and loop-based traffic measurements and the traffic signal colours of all the intersections were recorded every second. The video footage taken by all the cameras was also recorded. A mimic diagram of the entire zone showing the real-time occupation rates of the links allowed us to monitor overall changes in the traffic within the zone.

Around 660 hours of data were collected during the five months of the experiment, which included four weeks of school holidays.

7. The evaluation methodology

7.1 The sample classification

7.1.1 Hourly periods

For evaluation purposes, each half-day period was divided into hourly periods: four fixed hourly periods in the morning ([7.30 - 8.30], [8.30 - 9.30], [9.30 - 10.30], [10.30 - 11.30]) and three in the afternoon ([14.00 - 15.00], [15.00 - 16.00], [16.00 - 17.00]). This division gave us 576 hourly periods instead of the 660 hours initially recorded. This methodology had been already applied in the previous experiment described in (Boillot et al., 2006).

Each one-hour sample corresponds to (i) a specific day, (ii) one fixed hourly period, (iii) the strategy which controlled the zone. An evaluation criterion (total delay) was calculated for each sample. This is described in 7.2. The large range of hours each day results in several traffic situations ranging from congested to fluid periods. In order to better characterize the ability of CRONOS-2 to control the zone, it is interesting to distinguish between several classes of traffic situations and study the efficiency of CRONOS-2 for each of them.

7.1.2 Determination of the traffic classes

In order to identify a set of classes based on the traffic situations, we unsuccessfully sought exogenous traffic variables that are sensitive to the traffic situations but independent of the control strategy. The traffic demand that enters the network is not well measured on a few entries and cannot be representative in the case of queue spillback on the entries. Furthermore in the case of traffic saturation, vehicles may turn away to take an alternative route and not enter the experimental zone. So even if we had error-free sensors, the traffic control strategy has an influence on the level of traffic demand in the event of saturation. In other words, traffic demand is strategy-dependent. The queues and the spatial occupancies are also partly a consequence of the control strategy.

Consequently, we have made a classification on the basis of hourly periods because they are generally good indicators of the level of congestion. But on its own this is not sufficient: the weekday and the type of period (school or holiday period) must be also taken into account. Two classes have been defined: the “peak” class and the “off-peak” class.

The TP-STRAT evaluation criterion values for the entire zone in each one-hour sample were calculated. These values were studied correlatively with the fixed hourly period, the weekday and the type of period. The present study allowed us to decide which hourly period (correlated with the weekday and the type of period) is dedicated to the “peak” class and which is dedicated to the “off-peak” class. The TP-STRAT strategy was chosen for this study for two reasons: the strategy is fixed and does not react in real time to the traffic in the way that CRONOS-2 does. It is therefore our reference strategy.

Finally, it was decided that, outside holiday periods, the “peak” class was made up of the following hourly periods: [7h30-8h30] and [8h30-9h30] and the hourly period [16h00-17h00] for Friday only; The “off-peak” class contained all the other hourly periods, that is every hourly period during holidays, plus all the periods [9h30-10h30], [10h30-11h30], [14h00-15h00], [15h00-16h00], plus the period [16h00-17h00] for Monday to Thursday.

The separability of the two classes is shown in Fig. 5: the histogram of the total number of one-hour samples for the TP-STRAT strategy is plotted according to its evaluation criterion value. The separability is fairly good and the chosen hourly period classification method is an effective way of separating the one-hour samples into two traffic levels. In order to obtain a quantitative point of view, if a threshold on the criterion values between the range numbers six and seven is defined, only 4.6% of the total of samples are not well classified. But as mentioned above, it is not possible to apply a threshold to the criterion values in order to define the classification because the criterion value is strategy-dependent. In other words for

an equivalent real traffic level, two strategies of differing efficiency could have led to a different classification of the samples.

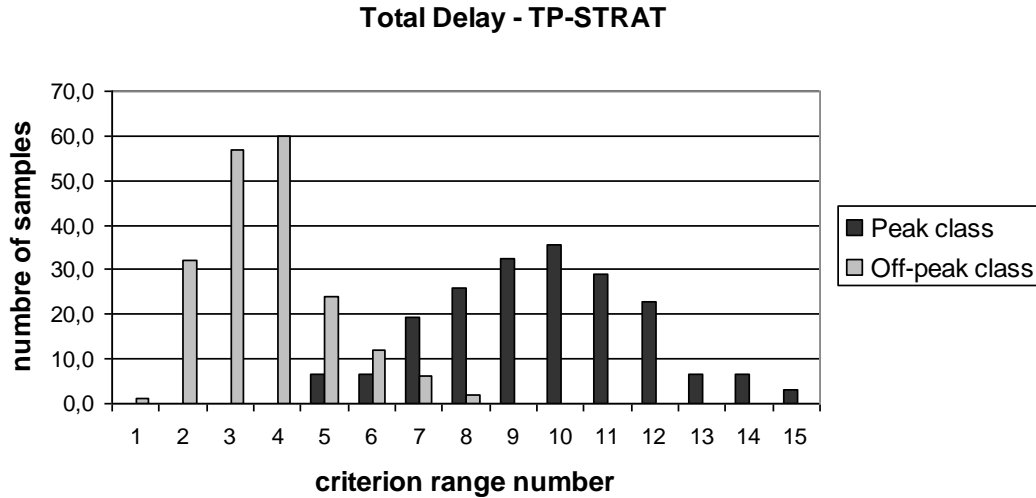


Fig. 5: Histogram of one-hour samples for each class according to the evaluation criterion

To summarize the method, the evaluation criterion values of TP-STRAT were studied in order to obtain a classification by hourly periods correlated with the weekday and the type of period. It is this classification which will be applied to CRONOS-2 and to the comparison between the two strategies.

7.1.3 Number of one-hour samples for each strategy

Before the evaluation process, a clean-up of the one-hour samples was performed. As a result of this 63 samples were rejected. These periods involved situations where magnetic loops or cameras had broken down or atypical types of congestion.

Finally, we obtained a total of 513 one-hour samples with the following characteristics: for the “peak” class, 60 samples for the TP-STRAT strategy and 60 samples for the CRONOS-2 strategy; for the “off-peak” class, 194 samples for the TP-STRAT strategy and 199 samples for the CRONOS-2 strategy.

7.2 The evaluation criterion

The criterion that was chosen in order to evaluate the benefits of CRONOS-2 compared to TP-STRAT is the one-hour delay, which is defined as the total vehicle waiting time at traffic signals over a one hour period within a given spatial zone. This evaluation criterion was measured for a number of different spatial zones.

The main criterion is the total delay over the entire network. The additional evaluation criteria provide more precise information on CRONOS-2’s effectiveness. Two additional types of spatial zones were also defined: the routes and the intersection.

- Two different routes were defined: The “main route” (M-Route) is the road between the Château and Paris and vice-versa. The “secondary route” (S-Route) is the set of links that cross the “main route”.

- For intersections, five zones (A, B, C, D, E) were defined, i.e. each of the five intersections in the network.

From these definitions, we defined the one-hour delay d for each zone by:

$$d_{sample}^{zone} = \sum (Q_l^t; t \in \{\text{seconds of sample}\}, l \in \{\text{links that enter or that are inside the zone}\})$$

where “zone” is one of (Network, M-Route, S-Route, A, B, C, D, E). Network is the entire network. The exit links of the zone are never included. Q_l^t is the queue length at the stop line of link l at step t . d_{sample}^{zone} is obtained by summing Q_l^t over all the seconds in the sample and over all the links that enter or are inside the zone.

The queue lengths which make up the evaluation criteria were obtained with image processing-based measurements.

It should be noted that the CRONOS-2 optimized criterion was also calculated from the queue lengths, like the evaluation criterion. But these queue lengths were modelled for the future and only over the rolling horizon of 70 seconds.

7.3 The averaged evaluation criterion

The total delay was evaluated over every one-hour sample. The average total delay for each class and strategy was calculated from the total delay for each one-hour sample. Likewise, the criterion for the other spatial extents, described above, was averaged in order to obtain the averaged criterion for each class and strategy for each spatial zone.

This averaged criterion D is written:

$$D_{class, strategy}^{zone} = \text{Average} \{ d_{sample}^{zone}; sample \in \{\text{samples of class for strategy}\} \}$$

where “class” may be either the “peak” or the “off-peak” class. The strategy may be TP-STRAT or CRONOS-2. The zone is one of (Network, M-Route, S-Route, A, B, C, D, E).

In what follows, these average criteria are referred to as the total delay throughout the network, the average delay on each route or the average delay at each intersection.

8. The evaluation results

The evaluation results consist of comparing the results from CRONOS-2 to those from TP-STRAT. For a zone and a traffic class this benefit B_{class}^{zone} is defined as:

$$B_{class}^{zone} = \frac{D_{class, TP-STRAT}^{zone} - D_{class, CRONOS-2}^{zone}}{D_{class, TP-STRAT}^{zone}}$$

8.1 Total delay throughout the network

The evaluation results for the average total delay over the entire network are provided in Fig. 6. The benefits of CRONOS-2 regarding delay compared to TP-STRAT have been plotted for each traffic class.

The benefit provided by CRONOS-2 compared to TP-STRAT for the “peak” class $B_{peak}^{network}$

was 13.2% and for the “off-peak” class $B_{off-peak}^{network}$ was 9.7%.

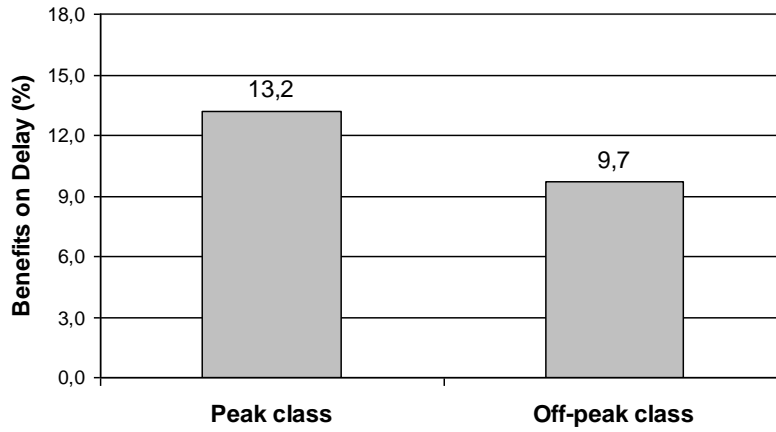


Fig. 6: Benefits of CRONOS-2 on the average total delay (in %) for the “peak” and the “off-peak” classes

The criterion values (in meters x seconds) for CRONOS-2 and TP-STRAT are shown in Table 1 in order to show readers the ranges of values. The difference between TP-STRAT and CRONOS-2 for each criterion is also shown. A positive value means CRONOS-2 resulted in a benefit (shorter delays), a negative value means it resulted in an impairment (longer delays).

| Average total delay | “Peak” class (m.s) | “Off-peak” class (m.s) |
|---------------------|--------------------|------------------------|
| TP-STRAT | 1179313 | 646538 |
| CRONOS-2 | 1023719 | 583966 |
| Difference | 155594 | 62572 |

Table 1a: TP-STRAT and CRONOS-2 average total delay values (in m.s) for both classes

Table 1a shows that the “off-peak” class for TP-STRAT generated approximately half the total delay of the “peak” class.

In order to study the distribution of the one-hour samples according to their total delay ($d_{sample}^{network}$), all the samples were grouped into fifteen delay ranges for each strategy and each traffic class. Range 1 consisted of the lowest delay values, and range 15 consisted of the highest. These ranges were the same for the two classes. The histograms of the samples have been plotted on Fig. 7a for the “peak” class and Fig. 7b for the “off-peak” class. We can clearly see that in both cases, the histogram for the CRONOS-2 strategy has moved towards the lower ranges. This shift is more apparent for the “off-peak” class because the total number of samples is higher than for the “peak” class. It should be borne in mind that the number of samples in each class for each strategy was identical (60) for the “peak” class and almost identical (194 and 199) for the “off-peak” class.

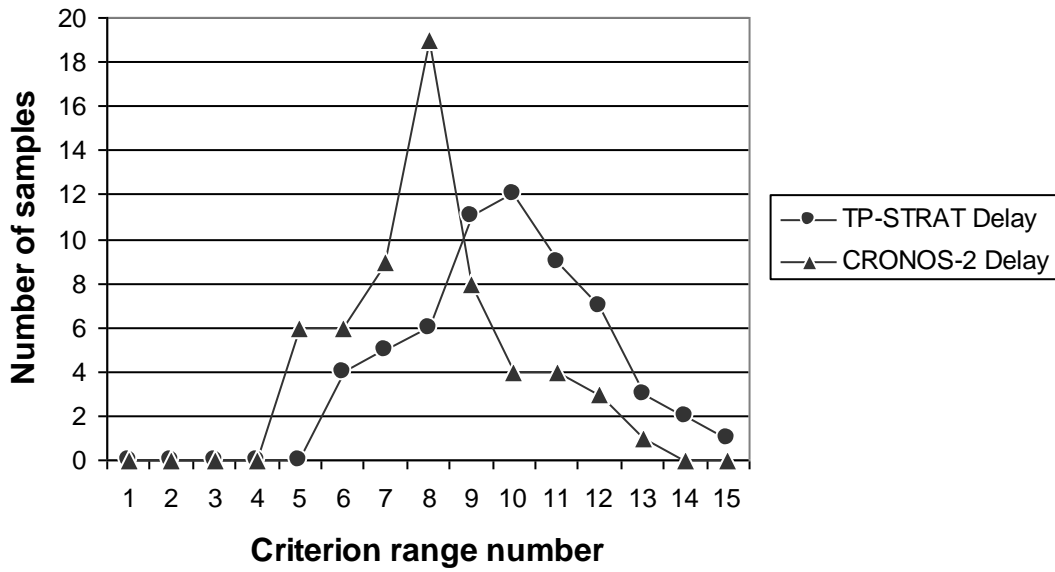


Fig. 7a: Histogram of the distribution of one-hour samples for the “peak” class

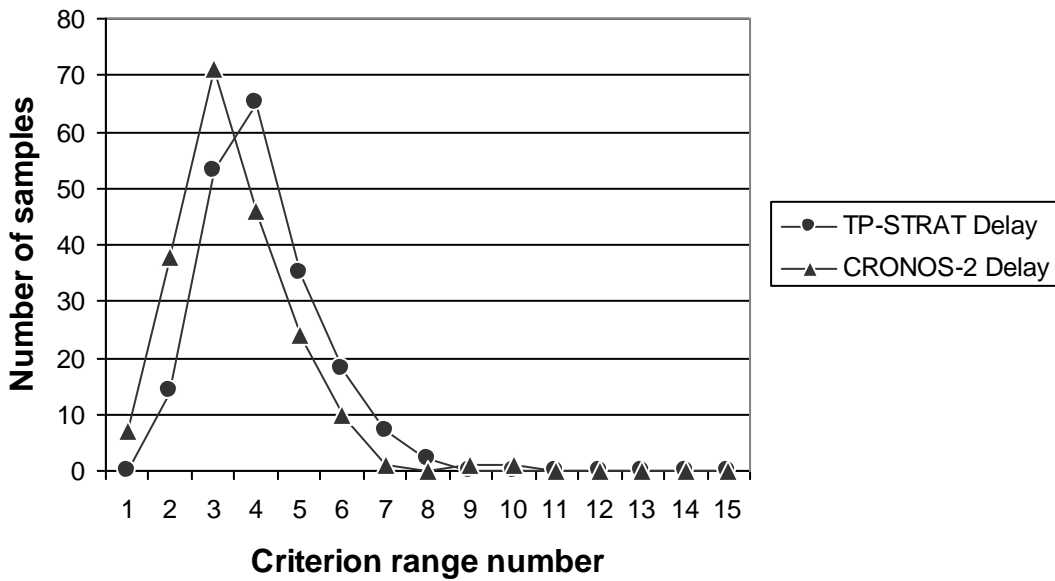


Fig. 7b: Histogram of the distribution of the one-hour samples for the “off-peak” class

Table 1b below also sets out the standard deviation of the total delay for each strategy and each class calculated on the set of the one-hour samples (Table 1b).

| Standard deviation | “Peak” class (m.s) | “Off-peak” class (m.s) |
|--------------------|--------------------|------------------------|
| TP-STRAT | 199579 | 126483 |
| CRONOS-2 | 181323 | 127746 |
| Difference | 18256 | -1263 |

Table 1b: Standard deviation for TP-STRAT and CRONOS-2 (in m.s) for both classes

For the “peak” class, the standard deviation was 10% better with CRONOS-2. For the “off-peak” class, the standard deviation was 1% worse with CRONOS-2.

8.2 Delay on each route

In order to provide further details of the average total delay result, three additional studies were undertaken with regard to traffic. The first related to differences between the main and the secondary routes.

The average delay for the two strategies on each route was compared for each class. Fig. 8 shows the benefits of CRONOS-2 on the average delay on each route in percentage terms (B_{class}^{M-Road} and B_{class}^{S-Road}).

For the “peak” class, the percentage benefit was higher for the secondary route than the main route. The opposite applied for the “off-peak” class. These results also show that CRONOS-2 provided benefits on both routes which means that no route considered in its entirety would be severely disadvantaged. The results are particularly remarkable for the “peak” class where the benefits were high for both routes. For the main route these benefits were similar for both classes. For the secondary Route, the benefits were high for the “peak” class and almost zero for the “off-peak” class.

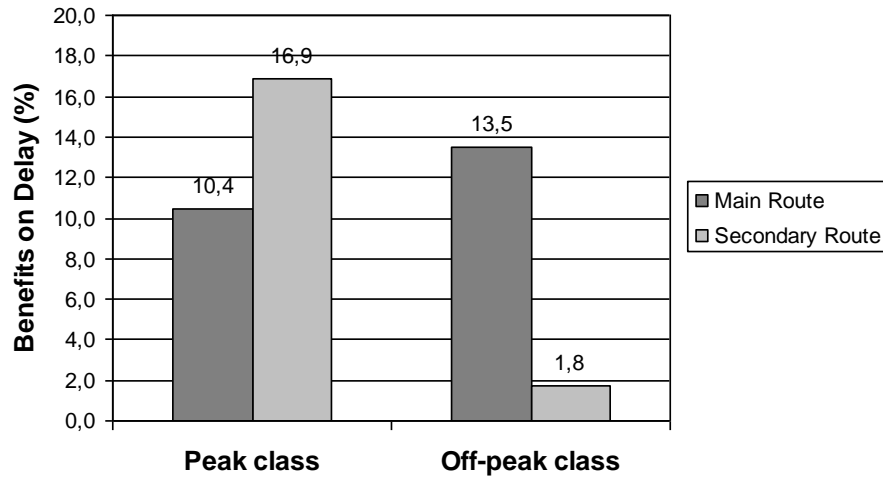


Fig. 8: Benefits of CRONOS-2 on the average delay on each route (in %) for the “peak” and the “off-peak” classes

Concerning the value ranges, the average delay for each route for CRONOS-2 and TP-STRAT are shown in Table 2.

| Average delay per route | “Peak” class (m.s) | | “Off-peak” class (m.s) | |
|-------------------------|--------------------|-----------------|------------------------|-----------------|
| | Main Route | Secondary Route | Main Route | Secondary Route |
| TP-STRAT | 673855 | 505458 | 435423 | 211114 |
| CRONOS-2 | 603558 | 420161 | 376582 | 207384 |
| Difference | 70297 | 85297 | 58841 | 3730 |

Table 2: TP-STRAT and CRONOS-2 average delay per route (in m.s) for both classes

Table 2 shows that, for the “peak” class, CRONOS-2 provided greater benefits (85297) on the secondary route than on the main route (70298). This finding held for both percentages (Fig. 8) and absolute values (Table 2). This result is made possible because the traffic on the secondary route was nearly as heavy as on the main route. Indeed, if the delay on the secondary route was low for TP-STRAT, the benefit in percentage terms could be higher even though the difference in value would remain low. We should bear in mind that the percentage benefit is calculated in comparison to TP-STRAT.

For the “off-peak” class, the traffic on the main route remained high but the flow on the secondary route was more fluid than on the main route. The benefits of CRONOS-2 during “off-peak” traffic on the main route remained substantial.

8.3 Delay on each intersection

The second result, which is complementary to this, is the benefits for average delay at each intersection ($B_{class}^{Intersection}$). This shown in Fig. 9 where for each class, intersection A is on the left and the intersection E is on the right. The location of the intersections from A to E is shown on Fig. 2a.

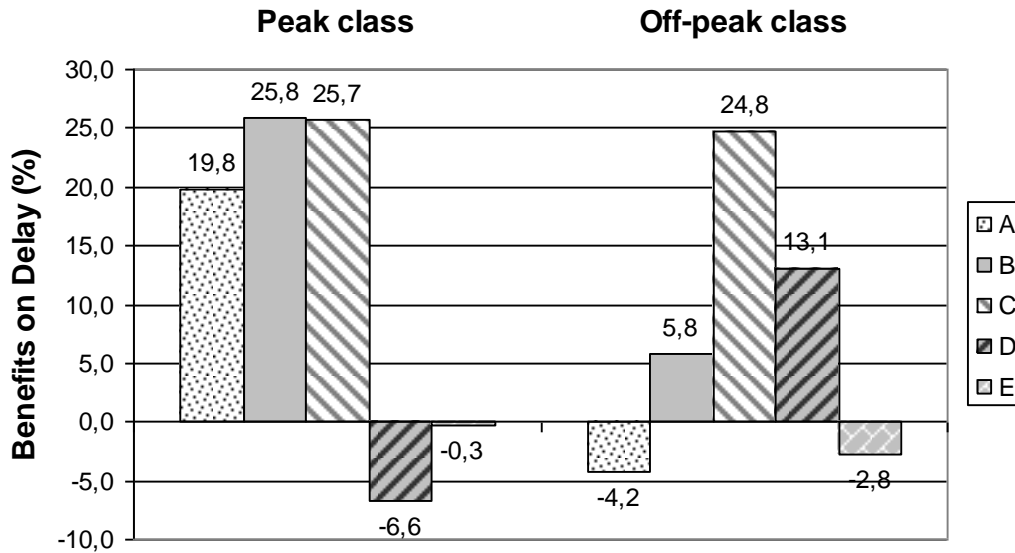


Fig. 9: Benefits of CRONOS-2 on the average delay for each intersection (in %) for the “peak” and “off-peak” classes

For the “peak” class, CRONOS-2 provided substantial benefits for three intersections (A, B and C), between 19.8 and 25.8%. It increases delay by 6.6% at intersection D and by a small (insignificant) amount at intersection E. On average, the outcome of control by CRONOS-2 and TP-STRAT was very different within the zone.

For the “off-peak” class, CRONOS-2 provided a considerable benefit at C (24.8%) a moderate benefit at D (13.1%) and a small one at B (5.8%). It provided small increases in delay at intersections A (-4.2%) and E (-2.8%). The results take a different form for the two classes.

We could interpret the result for the “peak” class by saying that to optimize average delay in the entire zone, CRONOS-2 favours the three adjacent intersections A, B, C and disadvantages to a lesser extent the intersection D and does not act on the intersection E. Indeed as CRONOS-2 minimizes overall delay in the zone, it may disadvantage some intersections on average.

However, this interpretation is inadequate. Some recurrent events with an important impact on traffic flows and which could not be modelled by CRONOS-2 were observed at intersection D.

At intersection D, the presence of a traffic policeman (see 4.2) blocks the incoming flow from the secondary route to the north, a large proportion of which turns left towards Paris.

Furthermore the same flow is also hampered by the flow which has the same right of way and which contains a lot of slow articulated buses travelling straight ahead.

Another phenomenon sheds light on the results: the low-angle sunlight during a certain time slot at some times of the year. This low-angle sunlight dazzles some of the traffic cameras leading to inaccurate traffic measurements. This phenomenon affects both TP-STRAT and CRONOS-2 but there was an impact on CRONOS-2 because its modelling depends on the observed queues. If no queue is detected due to the sun shining into the camera, CRONOS-2 may behave as if the link is empty and change the traffic signals too early.

Table 3 sets out the values of the average delay at each intersection. For both classes, the cumulative average delay at the intersections with a deterioration is always less than at any of the intersections with an improvement.

| | “Peak” class (m.s) | | “Off-peak” class (m.s) | |
|-------|--|----------|--|----------|
| | Difference between TP-STRAT and CRONOS-2 | TP-STRAT | Difference between TP-STRAT and CRONOS-2 | TP-STRAT |
| A | 25196 | 127178 | -2944 | 69726 |
| B | 63438 | 245637 | 8032 | 138789 |
| C | 82406 | 321111 | 45032 | 181481 |
| D | -14627 | 220573 | 16200 | 124104 |
| E | -818 | 264815 | -3748 | 132438 |
| Total | 155595 | 1179314 | 62572 | 646538 |

Table 3: TP-STRAT and CRONOS-2: average delay at each intersection (in m.s) for both classes

In conclusion our evaluation results have shown that CRONOS-2 reduced total delay inside the controlled zone during both “peak” and “off-peak” periods. Additional results for each intersection and each route have allowed us to identify the source of the improvement or deterioration.

9 Discussion

Based on the experience gained during this and the previous experiment, this section attempts to identify some key principles regarding the operation and use of real-time UTC systems.

These systems have the ability to adapt to traffic that is measured in real time on the site. They do this not only throughout the day or during every cycle like other adaptive systems (classes 1 and 2 of classification presented in section 2.1) but also every second or every few seconds depending on the instantaneous presence of vehicles. This responsiveness allows the system to take account of the immediate traffic and include it in the overall optimization process which helps the system to reduce total delay in the controlled area. But in addition to reducing the delay and therefore congestion in the area, although no explicit demonstration was made during this experiment, it is reasonable to expect that the onset of congestion will be delayed due to the continuous management of delay in the zone. Similarly, it will probably

be possible to avoid recurrent low level congestion in a zone. However, this generalization to all real-time UTC systems is not straightforward. Global control of the zone is an important aspect of CRONOS-2, while other real-time UTC systems are controlled on an intersection-by-intersection basis.

On the other hand, reducing the delay in the controlled zone does not mean that there is an improvement for each intersection. Average waiting time for vehicles crossing the zone is shorter, but this is not automatically the case for vehicles crossing a given intersection in the zone because delay is optimized for the entire zone.

In order to take full advantage of a real-time UTC system, it is important to know the factors that can adversely affect its effectiveness or acceptability to users.

When the system does not measure or model certain flows, such as pedestrians in this experiment, their waiting times depend on the measured traffic flows. In our experiment, the number of pedestrians was not controlled.

When recurring events that disrupt the traffic occur and these are neither measured nor modelled by the system, the global and local efficiency of the system may decrease. In our experiment, two events had a daily impact on traffic flows: the presence of a police officer at an intersection and the many pedestrians who may cross the roads outside their right-of-way and block vehicles. These events (at least the police officer) appear to have impaired the responses of CRONOS-2. In addition, deterioration of the system's responses may be caused by a sensor malfunction that prevents the system from taking account of the traffic flows normally measured by these sensors. In our experiment, the low-angle sunlight, which dazzled some poorly positioned videocameras, interfered with the measurements and therefore impaired the system's response. We were able to measure and model a number of such factors that degrade the system's response. It is not possible to assess the benefit derived from this additional knowledge. However, despite these shortcomings, this experiment shows that this type of system has advantages over more traditional control systems.

A real-time UTC system's degree of adaptivity to traffic depends on its characteristics but also on the traffic signal parameters fixed by the traffic engineers (clearance times, offsets, stage sequence, minimum and maximum green durations...).

These constraints depend on the infrastructure, the safety rules that apply in the country in question, the types of users and on rules that depend on the traffic signal plan system, main type of systems in France. In other words some constraints can be described as "safety constraints" and others as system-related "management constraints". While the safety constraints are necessary, the others can be relaxed in order to allow the system greater freedom.

Finally for a zone for which traffic settings are highly constrained for safety reasons, we wonder if a real-time UTC system will provide significant benefits. As the severity of constraints increases, the benefits will diminish.

Conclusion

A real experiment of the CRONOS-2 control strategy on a zone of five intersections has been reported. The results have shown the value of using a real-time acyclic control strategy in a complex, constrained, network.

The CRONOS-2 strategy provides significant benefits over the reference strategy (TP-STRAT) in both congested and fluid traffic conditions. Benefits were obtained on both the main and secondary routes.

The results for each intersection show that the same benefits were not obtained at every intersection: benefits were high at some, with moderate losses at others.

The next step, in order to add to these findings, will be to study CRONOS-2 in terms of signalization and traffic signal sequences.

Furthermore, an experiment in which bus priority was added to CRONOS-2 has been performed in the same zone. Evaluation work for these two studies is under way.

Acknowledgements

The authors would like to thank the Ville de Versailles, for their permission to control the intersections and their help during our experiment. This work was funded by the “National Research Agency” (ANR) as part of the CIPEBUS project.

References

- Bielefeldt, C., Busch, F., 1994. MOTION: A New One-Line Traffic Signal Network Control System. Road Traffic Monitoring and Control, IEE London, 391, 55-59.
- Boillot, F., Blosseville, J.M., Lesort, J.B., Motyka, V., Papageorgiou, M., Sellam, S., 1992. Optimal signal control of urban traffic networks, Sixth International Conference on Road Traffic Monitoring and Control, IEE London, n° 355, 75-79.
- Boillot, F., Midenet, S., Pierrelée, J.C., 2006. The real-time urban traffic control system CRONOS: algorithm and experiments, Transportation Research Part C, vol 14, issue 1.
- Braban, C., Boillot, F., 2003. Les systèmes temps réel de commande de feux en milieu urbain, Actes INRETS n°44.
- Diakaki, C. M., Dinopoulou, V., Aboudolas, K., Papageorgiou, M., Ben-Shabat, E., Seider, E., and Leibov, A., 2003. Extensions and new applications of the traffic signal control strategy TUC. Transport. Res. Rec., vol. 1856, 202–216.
- Espié, S., Auberlet, J.-M., 2007. ARCHISIM: a behavioural multi-actors traffic simulation model for the study of a traffic system including ITS aspects. International Journal of ITS Research, vol. 5, n°1, 7-16.
- European Community, September 2007. Towards a new culture for urban mobility. Green Paper, n° 551, 25.
- Gartner, N. H., 1982. Development and Testing of a Demand Responsive Strategy for Traffic Signal Control. Proceedings of American Control Conference, 578-583.
- Henry, J.J., Farges, F., Tuffal, J., 1983. The PRODYN Real Time Traffic Algorithm. 4th IFAC, IFIP, IFORS Conference on Control in Transportation Systems, Baden Baden, 307-312.
- Hunt, P.B., Robertson, D.I., Bretherton, R.D., Winton, R.D., 1981. SCOOT, A Traffic Responsive Method of Co-Ordinating Signals. TRRL Laboratory Report 1014.
- Kuester, J.L. and Mize, J.H., 1973. Optimization Techniques with Fortran. M.c.Graw-Hill Book Company, 368-385.
- Lowrie, P.R., 1982. The Sidney Co-ordinated Adaptive Traffic System: Principles, Methodology, and Algorithms. Proceedings of the IEE Conference on Road Traffic Signalling, London, 207, 67-70.
- Mauro, V., Di Taranto, C., 1990. UTOPIA. IFAC Proceedings Volumes, vol. 23 (2), pp 245-252.

- Midenet, S., Boillot, F., Pierrelée, J.C., 2004. Signalized intersection with real-time adaptive control: on-field assessment of CO₂ and pollutant emission reduction, *Transportation Research D* 9, 29-47.
- Mirchandani, P. and Head, L., 2001. A real-time traffic signal control system: architecture, algorithms, and analysis. *Transportation Research Part C* vol. 9, 415-432.
- Scemama, G., 1995. CLAIRE: an independent, AI-based supervisor for congestion management. *Traffic Engineering & Control*, vol. 36, n°11, 604-612.
- Xie, X.-F., Smith, S. F., Lu, L., Barlow, G. J., 2012. Schedule-driven intersection control, *Transportation Research Part C* vol. 24, 168-189.