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Intelligent Traffic Signal – coordinated or isolated control?

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Abstract

This paper presents a review of traffic control strategies at the level of control scope, i.e., over what area the strategy is applied, namely coordinated or isolated. In addition, a novel traffic signal control approach is proposed for isolated intersection scope, which includes signal plan design and signal timing optimization with real-time information. The isolated control scope allows each intersection to operate independently from other intersections, so each intersection has the freedom and flexibility to calculate and implement any traffic control settings. In this way, the research contributes to the development of a new strategy, which breaks with the traditional concepts of traffic control such as: the cycle length, the maximum green, and a signal plan to follow. The case study investigates the application of the strategy to a network of two signalized intersections, in four demand periods. However, the proposed approach only shows better results for low demand periods.

Keywords: traffic signal control, control scope, signal timing optimization, signal plan design.

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1. Introduction

Traffic in a city is very much affected by traffic lights. They are not the only pieces in this puzzle, but they are important ones. To make traffic signal controllers more efficient, researchers exploit the emergence of novel technologies such as communication networks and sensor networks, as well as the use of more sophisticated algorithms for defining traffic control settings. However, at the control scope level there is some lack of research, i.e., suggesting effective guidelines as for over what area the strategy should be applied and which way it should operate, namely coordinated (arterial, network) or isolated.

The coordinated control captures the interaction between intersections. The traffic signal control scope can be area-wide, i.e., more than one intersection in an area, or along a corridor, i.e., consecutive intersections on the same "road". Contrarily to coordinated control, there is the isolated traffic control strategy which can also be called free or uncoordinated operating control (Gordon and Tighe, 2005).

Before exploring the control scope problems, it is important to clear up the importance of the controller response to local conditions. Due to the natures of traffic, fluctuations and unexpected situations are always happening, which could lead to decreased traffic control accuracy. Therefore, it is important to ensure adaptability of traffic control settings (signal group plan and timings) at any time. In this case, in which traffic flow is monitored and the values of the parameters are adapted accordingly, control is named **dynamic.** In the opposite case, which uses the above parameters calculated beforehand, control is named **static.**

The following main research question arises then: which strategies can be implemented in urban areas to achieve a better traffic management system? Therefore, it is important to identify and test various control management solutions that maximize the capacity and minimize delays of the network taking into account all the users.

This study presents and tests an innovative traffic control strategy, for isolated intersections, based on person instead of vehicles, including simultaneously signal plan design and signal timing optimization with real-time information on the network dynamics. In order to update the traffic signal control plan, the approach was towards looking into this process as a problem of efficient allocation of an available resource (green time period) to consumers (traffic lights). For this purpose, a negotiation process was developed to decide who gets the right of using the resources based on an auction process. The selected phase is the one that produces the most beneficial contributions for the intersection performance.

For demonstration purposes and in order to draw first conclusions, the proposed innovative control strategy is applied to modelling in a microscopic simulator a small network with two consecutive signalized intersections.

The paper is organized as follows. Section 2 presents a review of traffic control strategies at the level of control scope. Then, Section 3 presents the design of the methodology, whereas the proposed traffic signal control is detailed in Section 4. Empirical results based on a case study are rendered in Section 5, Finally, Section 6 draws conclusions and discuss on future directions.

2. Control Scope Level

2.1. Coordination

Regardless the type of strategy used to achieve coordination, all traffic signals have to operate with the same cycle length or multiples of it. The controller must find the intersection in the system that requires the greatest cycle length (master intersection) and then design the plans for the rest of intersections. Lastly, offsets must be determined, i.e., the time differential between the beginnings of green time of the coordinated traffic streams relative to the master intersection.

Coordinated control started by static logic, which consists of finding the appropriate traffic signal plans and timings to optimize traffic flow. This results in the so-called "green wave method" that flows through the main streets of a city, allowing the consecutive traffic signals to switch with an offset equivalent to the expected vehicle travel time between intersections ideally enabling vehicles to drive through them without facing a red light. Thus, waves of green light "move" through the street at the same speed as the vehicles.

Computer tools for generating coordinated timing plans were developed, generally, with one of 2 type of main goals: maximization of the bandwidth (green wave extension) of the progression, or minimization of the overall delay and stops (French and French, 2006). Bandwidth optimization techniques, such as MAXBAND (Little et al., 1981), PASSER II (Chang and Messer, 1991), and PASSER IV (Chaudhary et al., 2002), use traffic volumes, distance between traffic signals, and desired travel speed to determine the optimum width of progression band that can be accommodated onto an arterial. Because bandwidth optimization techniques are attempting to provide as wide of a progression band as possible, they generally result in longer cycle lengths so as to permit larger amounts of traffic to pass through an intersection during the green interval. The second approach, such as TRANSYT-7F (McTrans, 2010) and TRANSYT (Robertson, 1969), uses models to find a common cycle length that minimizes the amount of overall delay in the system and then computes the offset required for progression. As a result, these optimization techniques generally produce cycle lengths that are shorter than those produced by bandwidth optimization techniques. Because these two approaches are attempting to develop signal timing plans to achieve different design objectives (maximize bandwidth versus minimize delay), they can result in significantly different signal timing plans for similar traffic conditions.

On the one hand, the main advantage of coordination is achieved when most of the traffic flows in the direction of the green wave. On the other hand, disadvantages can be of three types (Gershenson and Rosenblueth, 2012). First, since only one traffic corridor can have “green waves”, the vehicles flowing in the opposite directions of the green wave may be delayed. Second, once coordination behaviour is static, current state of the traffic is generally disregarded. If there is a high traffic density, vehicles entering a green wave will be stopped by vehicles ahead of them or vehicles that turned into the corridor, and once a vehicle misses the green wave, it will have to wait the whole duration of the red light to enter the next green wave. Third, when traffic densities are very low, vehicles might arrive too quickly at the next intersection, having to stop at each intersection.

To overcome the aforementioned disadvantages, a number of **dynamic coordination** strategies was developed so traffic signal control could react to incidents. In order to be able to respond to real-time varying traffic conditions, such strategies require sensors to collect traffic data, which are incorporated into the control system. Dynamic traffic control strategies are more reliable and efficient, but demand a big engineering effort and more expenses due to higher installation and maintenance costs (Papageorgiou et al., 2003).

Concerning dynamic coordination there are three main strategies, namely centralized, decentralized and distributed, as presented in Fig. 1 and described in the next three subsections.

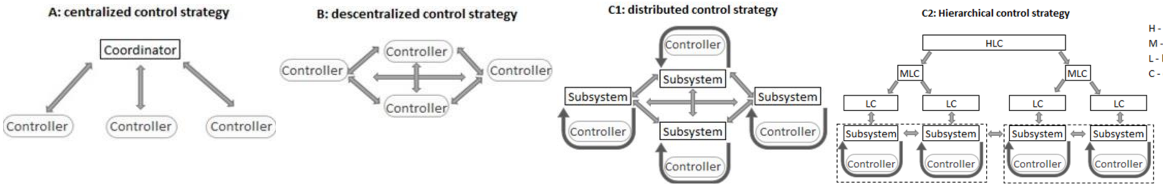

Fig. 1 Control strategy: centralized (A), decentralized (B) and distributed (C1, C2)

2.1.1. Centralized

Centralized approaches, as SCOOT (Hunt et al., 1981), are very appealing from the traffic control management point of view, for their supposed simplicity, effectiveness and their ability of controlling everything from a control centre. However, not all the information processing and decision making is best done in a centralized fashion. Islam and Hajbabaie (2017) review several studies that used central optimization architecture, aimed at finding optimal signal time settings (i.e., phase plan, cycle length, green times, and offsets) of all intersections, at the same time, in one mathematical program. However, coordination network signal timing optimization is an NP-complete problem (Lämmer and Helbing, 2008, Papadimitriou and Tsitsiklis, 1999) and a central optimization technique will not be scalable and applicable to large transportation networks. It is greatly due also to the need to collect all the inputs distributed across the large system and communicate this information to central control so as to generate control actions for the whole system. As a result, they cannot find optimal signal time settings when the size of the network increases. The main reason is the exponentially increase of the size of the optimization problem, and solving this in real time may be too computationally intensive. Furthermore, in case of system failures, this structure offers no graceful degradation. For these reasons, adaptive network control algorithms and strategies are still very much under development (Gordon and Tighe, 2005).

Another challenge for this type of management strategies is to model the traffic network in a simple but representative way, in order to devise an effective control with a relatively low computational cost.

In order to overcome such difficulties in the centralized approaches, decentralized control schemes can alternatively be considered for controlling large-scale systems.

2.1.2. Decentralized

In decentralized approaches, the network is decomposed into regions with varying number of intersections leading to simpler controller. As a result of decentralization, these approaches should be scalable and can change traffic control settings in real time; however, rather than global optimization, they mostly locally control signals and may find a sub-optimal solution.

The ALLONS-D (Porche and Lafortune, 1999) is probably the most well-known software with decentralized architecture. They decomposed the network to the intersection level and used dynamic programming based on tree searching algorithm to select the phase receiving green signal at each time interval. Due to the incorporation of data from upstream, there is an implicit coordination among intersections in arterial. For network application, authors proposed a two-layer hierarchy approach (explained below 2.1.3). The application of such hierarchical version in arterial scope has improved system performance when compared to unbiased (i.e., with unity weights for all phases) decentralized controllers. However, ALLONS-D is computationally expensive and cannot solve the problem in real time (Islam and Hajbabaie, 2017).

The self-organizing traffic signals use a decentralized optimization scheme, which enables global coordination of the traffic streams on road networks (Placzek, 2014). The global coordination is adaptively achieved by local interactions between vehicles and traffic signals, generating flexible green waves based on traffic demand. Self-organization systems are defined as elements that interact in order to achieve dynamically a global function or behaviour. This function or behaviour is not imposed by either one single or a few elements, nor is it determined hierarchically. It is however achieved autonomously as the elements interact with one another. Traffic signals are called self-organizing because each traffic signal control makes a decision based only on local information about its own state (Gershenson and Rosenblueth, 2012). This gives time for other vehicles to join them. As more vehicles join the group, vehicles will wait less time behind red lights. With a sufficient number of vehicles, the red lights will turn green even before they reach the intersection, generating “green corridors” (Gershenson, 2004). If there are no vehicles approaching a red light, the complementary one can stay green.

This method is self-organizing because the global performance is determined by the local rules followed by each traffic signal: they are “unaware” of the state of other intersections and still manage to achieve global coordination. The method uses a similar idea to the one used by Porche and Lafortune (1999) but with a much simpler implementation, without arrivals prediction at intersections, or communication between traffic signals.

Recent approaches make use of intelligent agents to act upon the traffic system in a completely decentralized fashion. In general, a decentralized signal control system can be modelled as a multi-agent system (MAS) in which each signal controller is considered as an agent, i.e., each intersection operates individually and autonomously without coordinating explicitly with the agents. Due to the ease of implementation and the development of cheap communication devices, there have been increasing efforts for promoting decentralized signal control systems based on the MAS metaphor.

In fact, in a decentralized multi-agent system, the agents are scattered all over the environment. Each agent has a limited sensing capability because of the range and coverage of the sensors connected to it, which limits the view available to each agent in the environment.

The emerging technology of autonomous vehicles even furthers the possibility of sharing and exploring information of vehicles and their environment to improve control performance. So decentralized approaches have been gaining territory in literature once each intersection determines its own control policy based on the information received from other vehicles on the road (Dresner and Stone, 2008, Vasirani and Ossowski, 2012).

2.1.3. Distributed

In case of strong interactions among the subsystems, the local optimization of each system can lead to conflicts. In order to overcome these conflicts, the distributed strategy decomposes the traffic signal time optimization problem into several interconnected sub-problems. Therefore, the difference to decentralized approaches is that it allows sub-systems to exchange some information about constraints and variables, and to share resources. In a typical case, the information propagates from intersection to intersection with a decreasing weight. By doing so, it can yield coordination among the controllers and achieve better system performance. However, this approach poses many challenges such as coordination increasing the computational complexity and the communication overhead, as well as the associated costs.

Another way of doing the distributed control, namely the hierarchical approach, is to include a central control unit. The control is distributed among the multilevel hierarchy of subsystem as shown in Fig. 1. The underlying concept of most hierarchical approaches is to handle slow-varying and wide-area-level decisions at upper levels and perform real-time and small-area computations in lower levels (Islam and Hajbabaie, 2017). As a result, the upper and lower levels may have objective functions that compete with each other. This approach decomposes the system structure in such a way to improve the computational efficiency. Therefore, designing signal control methods with a reasonable balance between these levels is quite challenging (Dion and Hellinga, 2001).

The most widely-used hierarchical approach is SCATS (Sims and Dobinson, 1979, Lowrie, 1990), where an intersection, in each sub-network, is set to be the critical one, and cycle lengths and splits are optimized for this particular intersection. There are other systems known but less widely used, such as: RHODES (Head et al., 1992, Mirchandani and Head, 2001); OPAC (Liao et al., 1998); and UTOPIA (Mauro and Di Taranto, 1989). The algorithms above use pre-specified plans for the signals phases. Therefore, these control systems have limitations in finding the phase composition, the sequence order, and the traffic signal times.

2.2. Isolated

This control strategy only captures the traffic conditions around the intersection. Therefore, the green time periods assignment is independent from other traffic signals, allowing the flexibility to assume the optimal cycle length and signal plan. This means that the control algorithm can be much simpler and have a higher degree of freedom to choose traffic control settings than coordinated control counterparts (Kronborg et al., 1997), awarding this type of control a worthy advantage.

Albeit last years, the research community has given more attention to coordinated than to isolated intersections; isolated control is still quite present in cities. The number of isolated traffic signal control intersections exceeds 50% of the implemented equipment's in a large number of countries throughout the world (Guberinic et al., 2007). Nowadays, in Municipality of Porto (Portugal), 57% of traffic control follows an isolated control approach. Therefore, it is also important to develop good algorithms for isolated traffic signal control.

The main drawback of isolated approaches is not being able to capture the interaction between intersections, as coordinated control does. In case of saturated conditions when adjacent intersections are closely, the traffic queues forming up at downstream intersections spill back and deteriorate the performance of upstream intersections. There are a few systems purposely designed for optimizing isolated intersection operation in literature, such as MOVA (Vincent et al., 1988) and SOS (Kronborg et al., 1997).

3. Strategic Control

In the last century, traffic signal control strategies have been developed due to some fundamental shifts in the way of thinking intersection control, adding a new dimension to traffic control as the traffic signals could respond to vehicle demand (Hamilton et al., 2014). Nevertheless, various traffic control systems were already developed, endowing some ideas not yet addressed and features never yet explored that could potentially improve the performance of traffic signals in urban areas.

As shown previously, traffic signal time optimization for a road network is an NP-Complete problem and a central approach is not able to yield the optimal solution in a reasonable amount of time. For that reason, the centralized traffic control methods are based on adaptation of some pre-calculated signalization schedules, i.e., an optimization of signalization cycle length, offset and split (Hamilton et al., 2013). So centralize strategy has no flexibility to design and implement new traffic signal control settings.

The distributed approaches decompose the problem into several interconnected sub-problems. Still these approaches pose many challenges such as coordination, increasing computation complexity and appropriate communication infrastructure, as well as the associated costs. The hierarchical approaches, while able to find solutions faster, require significant investment in infrastructure to provide communication between a central unit and each local optimizer. This strategy has no flexibility to design and implement the best traffic signal control settings because of a central unit that imposes some limitations.

As Bazzan (2009) appointed out, coordinated control also presents some limitations. In case of changes in traffic patterns, the optimization of control synchronization may face difficulties in handling the situation; with high traffic flow, the situation becomes even more complex. The implementation of a new cycle length or a different offset cannot be introduced immediately since it is necessary a transition period to adjust the traffic control settings, which probably brings similar disturbance to the system with the risk of large queue formation. Therefore, coordination approaches restrict the flexibility of the system.

In research efforts to demonstrate the traffic control systems, grid networks are typically used. In European cities, long straight arteries are not common, which have a negative impact on coordination strategies.

The emerging technology of connected autonomous vehicles has been focusing on the development of decentralized approaches. By taking advantage of vehicles' "intelligence", traffic signal control receives information from vehicles, therefore improving the decision based only on local information. In general, a decentralized signal control system can be modelled as a MAS in which each signal controller is considered as an agent (Jin and Ma, 2017). In such a way, the scope level has return to the intersection level in decentralized strategies, especially due to the freedom and flexibility that they allow. As a downside characteristic however, the decentralized approaches are much proper to finding sub-optimal signal time settings instead.

The scope of the proposed traffic signal control is the isolated intersection. The main reason for this choice is the fact that each intersection operates independently from other intersections, so each intersection has the freedom and flexibility to calculate and implement any traffic control settings. Since the dimension of the optimization problem is now reduced, traffic signal settings can be defined in real time as well as can their deployment, once there is no common cycle length to update. At the level of communication and detection, the complexity of the control problem also decreases, as well as investment and maintenance costs, which makes it more attractive for infrastructure owners. In such a way, isolated control strategies are similar to the decentralized ones.

The proposed strategy defines an optimal approach for controlling traffic signals that relies on the flexibility and the maximal level of freedom in the design of traffic control settings, where no fixed plan and phase compositions have to be undertaken. The control system should be updated frequently to meet the current traffic demand in the same way as of the different traffic users.

The methodology proposed can efficiently find “good” solutions without needing to resort to a central unit or to communicate to other intersections. It is based on MASs in which each traffic stream of the intersection is considered as an agent (Vilarinho et al., 2016).

Once industry is moving towards a period of abundance of traffic data, collected in real time by road sensors (Smartphone, Bluetooth, Wi-Fi) or/and vehicle/infrastructure communication (V2V and V2I), it seems that traffic signal control could take more advantage of significantly higher granularity of data.

The road sensors, widely spread over the network, have the limitation of giving only vehicle information at a fixed location. However, new initiatives known as vehicle-infrastructure communication allow the wireless transmission of the positions, and speeds of vehicles for use by the traffic controller (Goodall et al., 2013). As it is a new technology, it will take some time until all vehicles can benefit from such communication platform.

Dealing with the technology to adopt data collection is beyond the scope of this work. Thus, the traffic data that the proposed traffic controller needs to “know” is defined, as follows: the traffic flow, in each arm, by the next turning movement, including pedestrian traffic; delay time of each vehicle due to the traffic signal and vehicle occupancy, in each vehicle.

As a means to answer a predictable question “What are the differences and similarities of this system compared to existing systems?” Table 1 presents a comparative analysis of existing systems. For the sake of space and in order to avoid an extensive discussion on similarities and difference, which is out of scope in this study, only a selected range of existing systems is considered, but sufficient enough to allow a proper support to the decisions made throughout the process of designing the proposed approach herein presented.

Table 1. Differences and similarities of proposed traffic control system compared with existing systems

ID	Similarity	Difference
Scoot UK, 1980	1) Actuated	1) Centralized strategy; 2) Performance for a region of traffic signal network; 3) PI based on vehicle delays and stops, on each link
Scats AUS, 1970	1)Actuated; 2) Includes skip an un-demanded phase	1)Different control levels, constrained by coordination; 2) Library of plans; 3) Update at a cycle-by-cycle
Rhodes USA, 1990	1) No planned traffic signal plan	1)Different control levels; 2) Phase composition fixed; 3) Optimize performance of a corridor/network; 4) Re-solves planned phase every 5s
Allons-D FR, 1995	1)Permitted any phase sequencing and phase splits; 2) Priority option for vehicles of different types and/or occupancy levels in the traffic stream	1)Phase composition fixed; 2) Maximum green time
Opac USA, 1990	1)Actuated; 2) Includes skip an un-demanded phase; 3) Green and Red times determined by time steps	1)Different control levels; 2) Maximum green time; 3) Phase sequence fixed; 4) Phase composition fixed; 5) Maximize throughput
Prodyn FR, 1980	1)Actuated; 2) Loss sequence phase order (phase included/omitted); 3) Green and Red times determined by time steps	1)Different control levels; 2) Phase composition fixed; 3) Maximum green time
Mova UK, 1980	1)Actuated; 2) Isolated; 3) Look-ahead horizon for a small interval on 1-2s; 4) Loss/Benefit change signal	1) Phase composition fixed; 2) Phase sequence fixed; 3) 2 operational modes: delay min or capacity max
Sos SW, 1995	1)Actuated; 2) Isolated; 3) Look-ahead horizon for a small interval on 1-2s; 4) Loss/Benefit change signal	1)Conflict signal group sequence fixed; 2) Test different extensions; 3) Queue clearance function for stability

As it can be concluded from Table 1, the proposed traffic control shares some similarities and differences with existing methods. With RHODES, OPAC and PRODYN, the proposed system shares the evaluation of green and red times by time step. With MOVA and SOS, the proposed system shares the look-ahead strategy for small horizon, the evaluation of losses and benefits of signal change and the control scope.

Specific contributions of this work were identified by highlighting the major differences/advantages of the proposed control against the reviewed traffic control systems.

- No control levels: agents at same level decide the green time;
- No maximum green time period while the evaluation of green time is favorable to continue, the green time is kept;
- No phase order sequence: This control system is able to select any possible phase, based on the most beneficial phase at any given time period considering all traffic users present/expected at the intersection;
- No Cycle length: during operation. Once phase can assume any order, cycle length concept is lost;
- No phase/signal group composition fixed: during decision time of actuation operation, the following phase or green light can be assumed by any possible set of traffic stream;
- Person based, looking at the traffic conditions distinguishing vehicles with different occupancy allowing a control based on people present/expecting at intersection;
- Optimization includes pedestrian delay: This control system minimizes vehicle and pedestrian delay.
- Possible to change topology: The proposed control is an online system with ability of creating all possible signal plan designs, with few inputs only based on the local geometry (Vilarinho and Tavares, 2014):
- Single intersection: all traffic signal control settings are optimized for an isolated intersection.

To the best of authors' knowledge, there is no traffic control system, at the moment, able to combine all the above characteristics as described and implemented in the present approach.

4. Proposed Traffic Signal Control

As mentioned before, the intersection control problem uses the MAS approach as described in Vilarinho et al. (2016). The proposed traffic signal control is organized in two stages as described in Vilarinho et al., (2017), whose main goal is to improve person mobility at intersections.

- 1st stage aims to find a signal plan including phase composition and respective green time periods;
- 2nd stage is responsible for the optimization of actuation operation, which includes two decisions: firstly, to define when the current phase should be terminated and secondly to define the next phase to implement. This second stage, intersection control problem is treated as an auction-based mechanism or negotiation process where there are traffic stream managers who negotiate the use of the intersection on behalf of the drivers making a specific turning movement.

In this work a new feature is tested on the proposed traffic signal control. For the negotiation process, a set of initial traffic control settings is defined *a priori*. Two approaches for finding the initial control settings are developed, respectively without (ITC_NoPlan) and with (ITC_Plan) traffic signal plan design as summarized in Table 2. The ITC_NoPlan approach is simpler than the ITC_Plan approach, but more disruptive.

Table 2. Resume of proposed traffic control.

Stage	**ITC_Plan** – with a Traffic Signal Plan	**ITC_NoPlan** – without a Traffic Signal Plan
1st	For each traffic signal plan determines: green time periods (veh, ped), cycle length and saturation flow by traffic stream **Result**: Find a traffic signal plan concerning: Good mobility conditions and Equitability for all traffic users **Update**: when intersection budget ≤ 0 • Traffic signal parameters are determined again using traffic flow collected from last 150s • New traffic signal plan is selected • Intersection budget is updated to the cycle length value • Changes to the traffic plan are deducted in budget value	For each possible phase determines: minimum green time (veh, ped) and saturation flow by traffic stream, dependent on phase composition **Result:** Phase selection uses 2nd stage method **Update**: when intersection budget ≤ 0 • Traffic signal parameters are determined again using traffic flow collected from last 150s • Intersection budget is updated to 300 units • Budget value is subtracted in 1 unit/s
2nd	**Decision: 1)** when current phase is terminated and 2) define the next phase to implement from the traffic plan **Negotiation process:** Bids by traffic stream and they are organized by phase	**Decision: 1)** when current phase is terminated and 2) define the next phase from all possible phases **Negotiation process**: Bids by traffic stream and by phase and they are organized by phase

5. Case Study

The proposed traffic signal control is tested on a case study network with two signalized intersections (AQ, ZA) within the city of Porto (Portugal). All traffic movements are controlled by traffic lights, where pedestrians and vehicles compete for green time. The case study network has 7 links, and 14 origin-destination pairs (6 of vehicle demand, 8 of pedestrian demand), as shown Fig. 2 a).

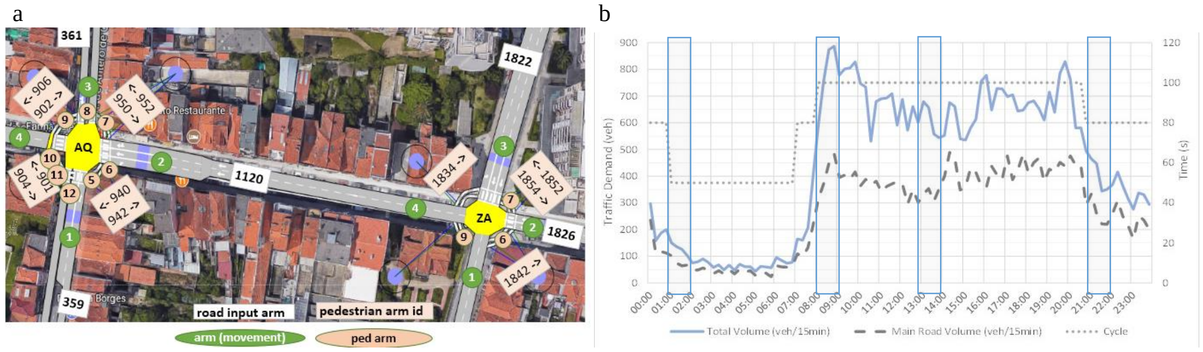

Fig. 2 (a) Case study network; (b) 24h traffic distribution and the tested periods

To test the ability of the proposed approach to respond to different demand conditions, it was tested in four different periods of one-hour each, extracted from a 24-hour period of a working day (Fig 2 b), covering different demand patterns with both undersaturated and oversaturated flow conditions. The four periods are: 01:00-02:00 (low demand, <600veh/h), 08:00-09:00 (high demand, >2300veh/h), 13:00-14:00 (high demand, >2300veh/h), and 21:00-22:00 (medium demand, 600veh/h – 2000veh/h).

The demand profile includes pedestrians and vehicles with different occupancy. The vehicle fleet has the following distribution: 70% with occupancy of one, 25% with occupancy of two, and 5% with occupancy of three people. Pedestrian demand was simulated as 25% of vehicle traffic demand within the period 08:00-20:45.

In order to evaluate the performance of the two proposed methods (ITC_NoPlan, ITC_Plan) described before, three comparison scenarios were implemented:

- Baseline 1: A total of three signal plans were calculated with an established benchmark software named TRANSYT for reference traffic conditions. Traffic control is coordinated and fixed-time;
- Baseline 2: Actuated time operation using the signal plans as describe above. During actuated operation, traffic signal control loses coordination, being catch when a new cycle length is adopted;
- Baseline 3: Case study is a real network with dynamic centralized operation. Traffic signal control operation of a workday was analyzed resulting in definition of three traffic demand profiles with cycle length of 50s, 80s, and 100s respectively. Once dynamic operation would be difficult to replicate, coordination based on fixed-time operation is adopted.

The implementation of this traffic control strategy resort to a microscopic traffic simulation model, namely AIMSUN (Aimsun, 2011). To include the algorithm of traffic signal control, a communication protocol was used to link it to the traffic simulator (Vilarinho et al., 2013). The communication between the algorithm and the traffic simulator allows information from the simulator to feed the algorithm, which in turn modifies the simulation state during the simulation.

Results of the proposed traffic control application to the case study is presented and discussed in this section. In order to evaluate the performance of the proposed traffic control, 25 replications of each scenario were run and compared against baselines, the cumulative distribution functions (cdf's) of average travel time (s/veh), of all vehicles (includes vehicles with different occupancy and pedestrians) were plotted, respectively, in Fig. 3.

Fig. 3 shows that in low demand periods (01:00-02:00, 21:00-22:00), the proposed ITC_NoPlan (defined on section 4) has lower average travel time, followed by ITC_Plan (defined on section 4). In the period spanning 08:00-09:00 the Baseline 2 has the best results followed by the ITC_Plan traffic control strategy. It is possible to have an average reduction of 25% of average vehicle travel time with Baseline 2 and 17% with ITC_Plan comparing with the Baseline 1. The results of next spanning period from 13:00 to 14:00 are similar to period 20:00-21:00, where Baseline 2 follow by ITC_Plan have the less average travel time. In these last two periods, traffic demand is higher. The cdf curvature is very similar between series of the same plot, where the curvature means the variability of the indicator. Although the Baseline 2 approach (actuated operation TRANSYT) achieved in two of four scenarios better results of average travel time for all simulation time than the proposed traffic control and other two baselines. The negotiation process implemented on proposed traffic control reduces average delay time in the arm with high value, distributing and balancing the delay between all intersection arms. As a consequence, the arms with low average delay tend to increase it. The impact on the network average delay time depends on the traffic demand level of the arm.

The ITC_NoPlan strategy has a better performance in low demands. For medium/high demands the results are disappointing. The ITC_Plan strategy has a more balance performance.

In general, the proposed traffic signal control ITC_NoPlan changes oftener the active phase than the ITC_Plan. So, the ITC_NoPlan approach achieves lower values of average green time than the ITC_Plan. This is probably a consequence of the higher flexibility of the ITC_NoPlan strategy.

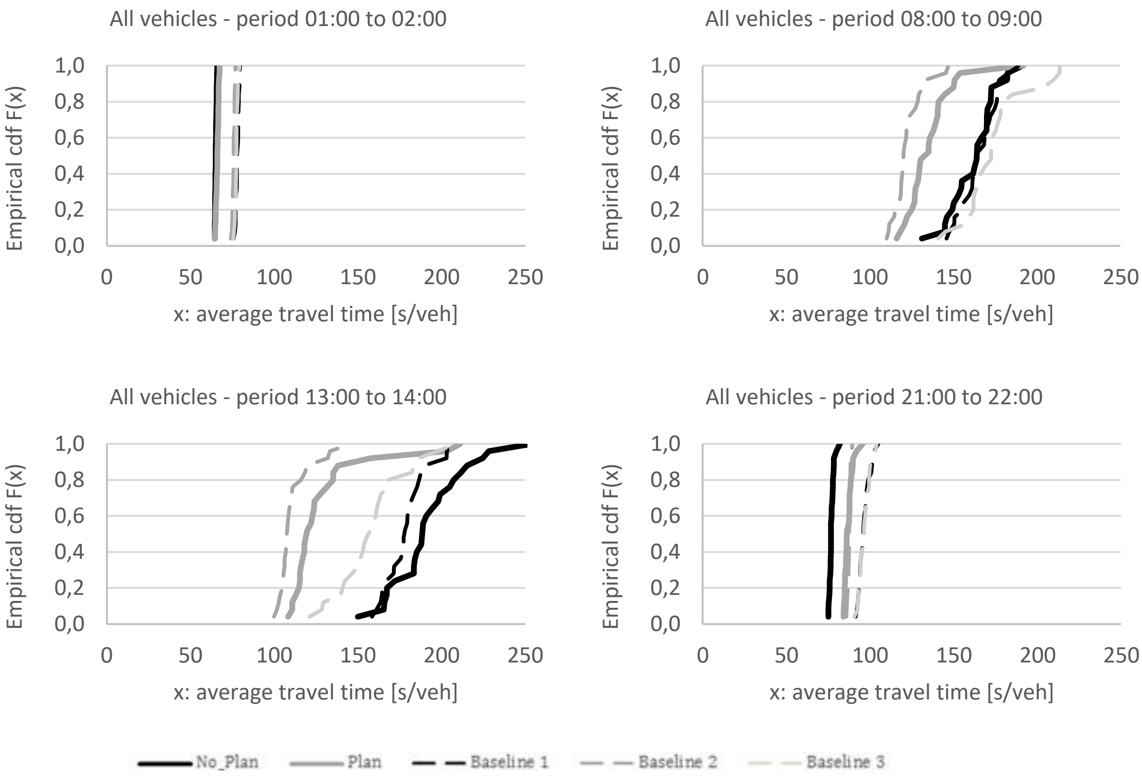

Fig. 3 Empirical cdf's of average travel time

In proposed traffic signal control strategy a few traditional variables were discarded including the maximum green time. The results showed adequate maximum green time (around 60s) even without an establish limit. Only in low traffic demand level, the green time achieved bigger values (around 200s) probably due to absence of cars in the opposite arms, so the active phase rested in green. These peak values are achieved independently of the proposed traffic control strategy (ITC_NoPlan. or ITC_Plan). In terms of computational efficiency of this approach, the calculation of the possible phases takes 50ms on intersection AQ (11 phases), and 1ms on intersection ZA (3 phases). Calculation of the possible signal plans takes 50ms on intersection AQ (9 plans), and 1ms on intersection ZA (1 plan). As expected, the time of negotiation process increases with intersection complexity (number of possible movements) and traffic demand, the average timing is less than 50ms. The results of execution time are promising becoming possible the strategy implementation in real-time. Although there is still room to improve its efficiency of the algorithm since it was not the objective of this research work.

6. Conclusion

This paper proposes a traffic signal control method using the isolated intersection scope, which includes signal plan design and signal timing optimization. The main reason for selection of isolated control scope is the fact that each intersection operates independently from other intersections, so each intersection has the freedom and flexibility to calculate and implement any traffic control settings. The case study investigates the application of the two methods of the proposed traffic control strategy, developed for isolated intersection, on a small network of two consecutive signalized intersections, in four periods of one-hour each.

The performance of the two methods using the proposed traffic control is compared against the performance of three baseline scenarios, where control plans were calculated with an established benchmark for reference traffic conditions, implementing both fixed and actuated operation modes. For lower demand and pedestrians'movements, ITC_NoPlan presents better performance for low demand. For higher traffic demand, the ITC_Plan shows lesser average travel time than fixed time coordination (baseline 1 and 3) and ITC_NoPlan.

Due to the reduced dimension of the optimization problem, i.e. isolated intersection, traffic signal settings can be calculated in real time. Since there is no common cycle length to update, the signal plan can be immediately implemented. In terms of computational efficiency of this approach, the calculation times of the different steps encompassing the method are reasonably aligned with reality.

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References

Aimsun 2011. Aimsun Microsimulator API Manual, TSS. 7.0 ed. Barcelona, Spain: Transport Simulation System.

Bazzan, A. L. C. 2009. Opportunities for multiagent systems and multiagent reinforcement learning in traffic control. *Autonomous Agents and Multi-Agent Systems,* 18**,** 342-375.

Chang, E. & Messer, C. J. 1991. Arterial signal timing optimization using PASSER II-90-Program user's manual.

Chaudhary, N. A., Kovvali, V., Chu, C., Kim, J. & Alam, S. 2002. Software for timing signalized arterials.

Dion, F. & Hellinga, B. A methodology for obtaining signal coordination within a distributed real-time network signal control system with transit priority. Proc. 80th Annual Meeting of the Tranportation Research Board (TRB'01), 2001.

Dresner, K. & Stone, P. 2008. A Multiagent Approach to Autonomous Intersection Management. *J. Artif. Intell. Res.(JAIR),* 31**,** 591-656.

French, L. J. & French, M. S. 2006. Benefits of signal timing optimization and its to corridor operations.

Gershenson, C. 2004. Self-organizing traffic lights. *arXiv preprint nlin/0411066*.

Gershenson, C. & Rosenblueth, D. A. 2012. Self-Organizing Traffic Lights at Multiple-Street Intersections. *Complexity,* 17**,** 23-39.

Goodall, N., Smith, B. & Park, B. 2013. Traffic signal control with connected vehicles. *Transportation Research Record: Journal of the Transportation Research Board***,** 65-72.

Gordon, R. & Tighe, W. 2005. Traffic Control Systems Handbook. Washington: Federal Highway Administration.

Guberinic, S., Senborn, G. & Lazic, B. 2007. *Optimal traffic control: urban intersections*, CRC Press.

Hamilton, A., Waterson, B., Cherrett, T., Robinson, A. & Snell, I. 2013. The evolution of urban traffic control: changing policy and technology. *Transportation Planning and Technology,* 36**,** 24-43.

Hamilton, A., Waterson, B., Snell, I. & Andrews, M. Performance evaluation of stage skipping and new data sources compared against MOVA control. Intelligent Transportation Systems (ITSC), 2014 IEEE 17th International Conference on, 8-11 Oct. 2014. 2535-2540.

Head, K. L., Mirchandani, P. B. & Sheppard, D. 1992. *Hierarchical framework for real-time traffic control*.

Hunt, P., Robertson, D., Bretherton, R. & Winton, R. 1981. SCOOT-a traffic responsive method of coordinating signals.

Islam, S. M. & Hajbabaie, A. 2017. *Distributed coordination and optimization for signal timing in connected transportation networks*.

Jin, J. & Ma, X. 2017. A Decentralized Traffic Light Control System Based on Adaptive Learning, *IFAC-PapersOnLine,* 50**,** 5301-5306.

Kronborg, P., F., D. & Edholm, J. 1997. SOS - Self Optimising Signal Control. Sweden: TFK - Transport Research Institute.

Lämmer, S. & Helbing, D. 2008. *Self-Control of Traffic Lights and Vehicle Flows in Urban Road Networks*.

Liao, L. C., California, Department Of, T., Partners for Advanced, T., Highways, University of California, B. & Institute of Transportation, 1998. *A review of the Optimized Policies for Adaptive Control strategy (OPAC),* if.], California PATH Program.

Little, J. D., Kelson, M. D. & Gartner, N. H. 1981. MAXBAND: A versatile program for setting signals on arteries and triangular networks.

Lowrie, P. 1990. Scats, sydney co-ordinated adaptive traffic system: A traffic responsive method of controlling urban traffic.

Mauro, V. & Di Taranto, C. 1989. UTOPIA. *IFAC Symposium of Control Communications in Transportation.* Pergamon Press, Oxford.

Mctrans 2010. *TRANSYT 7F Manual,* University of Florida.

Mirchandani, P. & Head, L. 2001. A real-time traffic signal control system: architecture, algorithms, and analysis. *Transportation Research Part C: Emerging Technologies,* 9**,** 415-432.

Papadimitriou, C. H. & Tsitsiklis, J. N. 1999. The complexity of optimal queuing network control. *Mathematics of Operations Research,* 24**,** 293-305.

Papageorgiou, M., Diakaki, C., Dinopoulou, V., Kotsialos, A. & Wang, Y. B. 2003. Review of road traffic control strategies. *Proceedings of the IEEE,* 91**,** 2043-2067.

Placzek, B. 2014. A self-organizing system for urban traffic control based on predictive interval microscopic model. *Enineering Applications of Artificial Intelligence,* 34**,** 75-84.

Porche, I. & Lafortune, S. 1999. Adaptive Look-ahead Optimization of Traffic Signals. *ITS Journal - Intelligent Transportation Systems Journal,* 4**,** 209-254.

Robertson, D. I. 1969. TRANSYT: A Traffic Network Study Tool Crowthorne: Road Research Laboratory.

Sims, A. & Dobinson, K. SCAT the Sydney coordinated adaptive traffic system: philosophy and benefits. International Symposium on Traffic Control Systems, 1979, Berkeley, California, USA, 1979.

Vasirani, M. & Ossowski, S. 2012. A Market-Inspired Approach for Intersection Management in Urban Road Traffic Networks. *Journal of Artificial Intelligence Research,* 43**,** 621-659.

Vilarinho, C., Soares, G., Macedo, J., Tavares, J. P. & Rossetti, R. J. F. 2013. Capability-Enhanced AIMSUN with Real-Time Signal Timing Control. *Procedia - Social and Behavioral Sciences,* EWGT2013 – 16th Meeting of the EURO Working Group on Transportation**,** 262.

Vilarinho, C. & Tavares, J. P. 2014. Real-time traffic signal settings at an isolated signal control intersection *Transportation Research Procedia (TRPRO264)***,** 1021-1030.

Vilarinho, C., Tavares, J. P. & Rossetti, R. J. F. 2016. Design of a Multiagent System for Real-Time Traffic Control. *IEEE Intelligent Systems,* 31, 68-80.

Vilarinho, C., Tavares, J. P. & Rossetti, R. J. F. 2017. Intelligent Traffic Lights: Green Time Period Negotiaton. *Transportation Research Procedia,* 22**,** 325-334.

Vincent, R. A., Peirce, J. R., Transport, Laboratory, R. R., Transport & Division, R. R. L. T. M. 1988. *MOVA: Traffic Responsive, Self-optimising Signal Control for Isolated Intersections*, Transport and Road Research Laboratory Traffic Management Division.