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Real-time traffic signal settings at an isolated signal control intersection

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Abstract

In this paper, we present a method for traffic signal control including simultaneously signal plan design and signal timing optimization with real-time information on the network dynamics. The problem is formulated so as to find the signal plan design, the green and inter-green time for each signal group in response to recurrent traffic flow demand at an intersection. The approach used was the group-based Akçelik method for determining critical path, cycle length and green time split for each possible signal plan design. The signal plan design selection was formulated to minimize the total delay. The resulting algorithm was coded in Java and used TraSMAPI to dynamically link it to Aimsun’s API, which allows an automatic change of the signal settings at an isolated signal control intersection.

A theoretical three arms intersection with a time varying origin-destination demand example is tested to demonstrate the proposed method. The paper contributes to the development of an integrated design of signal plan design and signal timings. The proposed method aims to be sufficiently general for its application in different networks, with few inputs dependent on the local geometry layout. This strategy is able to react to non-schedulable events or unpredictable events without requiring human manipulation.

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1. Introduction

Traffic signal control is considered a competitive traffic management strategy for improving mobility in urban networks. Over the years with the increasing of traffic demand and congestion, it was realized the impact of traffic lights in terms of efficiency of network operation for the same level of safety. Signal timing offers the opportunity to improve the mobility and contribute to address environmental issues. Nevertheless, the inefficient operation of traffic lights is a common problem certainly experienced by all network users. This problem annoys the drives and affects negatively the local economy. It represents costs in different levels like increasing fuel consumption, longer time trips, more traffic emissions and noise in the cities.

Our problem is formulated to find the optimal combination of traffic signal plan design and signal timings calculation, including order sequence of signal groups, duration of green time for each signal group and inter-green duration at same time. These variables are calculated in every simulation interval defined in response to recurrent traffic flow fluctuations at an intersection.

The algorithm was coded in Java and used TraSMAPI framework (Timóteo et al.) to dynamically link it to Aimsun’s Application Programming Interface - API (C/C++), which allows the user to change the traffic signal plan design and signal timing of each signal group.

The paper contributes to the implementation of a novel real-time traffic control where signal plan design and signal timing calculation are optimized at same time in response to recurrent traffic flow fluctuation at an isolated intersection. The algorithm is tested in the simulated environment of traffic simulator model (Aimsun, 2013). Furthermore, we are interested in developing a computational scheme that is efficient enough to be implemented in real-time. And also to be sufficiently general and less demanding in input data for its easy application in the different networks.

The outline of this paper is as follows. Section 2 is background, containing a brief literature review. In section 3, the proposed traffic signal control is described. In section 4, the simulation study results of a single intersection are presented, in section 5, conclusions and future work directions are discussed.

2. Background

Since the introduction of traffic lights in road networks, extensive literature has been devoted to the case of signal timing. The signal timing determination for each stage of the cycle can be performed using two different methodologies: the stage method and the group method. The group-based is a more recent method, also called phase-based, movement-based or stream based depending of the author.

In the stage-based control method, the signal groups are divided into a number of stages before calculation. For the signal timing purpose is considered the traffic flow of the representative traffic stream of each stage. A priori it must be defined the stage sequence, the inter-green time between stages, the traffic flows and the saturation flows. The optimal green splits and cycle time are calculated (Allsop, 1971, Allsop, 1972, Yagar, 1974, Webster, 1958). The usually goal of this type of control is to minimize the total delay or to maximize the intersection capacity. The stage-based description is often used as the basis of optimization methods for signal timings. A number of constraints are applied to ensure that green time duration of each stage exceeds a minimum acceptable value, an adequate capacity is provided, and the cycle length lies in a suitable range. In this method, stages cannot normally be eliminated from or introduced into the sequence by any automatic process because of difficulties that this would cause with the associated inter-greens (Heydecker, 1996).

While in second method, the group-based (Improt and Cantarella, 1984, Heydecker and Dudgeon, 1987, Gallivan and Heydecker, 1988a) each traffic stream is associated independently of the stage. The group-based provides a higher degree of flexibility for the specification of traffic signal. The group-based method determines the cycle length, the green time duration for each signal group and staging combination, respecting the compatibility of traffic streams known a priori. The traffic flows and saturation flows are still information known a priori. The optimal signal timing is calculated according to the possible sets of different signal groups (Akçelik, 1989). The group-based model requires a preliminary decision about the definition of the traffic streams and their assignment to the lanes. Lam et al. (1997) and Wong and Wong (2003) have extended the group-based approach to lane-based, where the lane markings and traffic streams are not know a priori. Group-based control has been the most
commonly used control since this control is more flexible than the stage-based control, therefore it is better able to adapt to traffic conditions and to bring considerable benefits in complex intersections (Heydecker & Dudgeon, 1987). The disadvantage comes from the fact that this flexibility requires a greater number of variables and constraints.

These methods are used to determining the signal timings plans which can be implemented as fixed timed or vehicle-actuated.

The traffic signal plan design is a task usually based on traffic engineering experience. Literature such as Traffic Engineering Handbook (Kraft et al., 2009) contains some guidelines about design traffic plans but not sufficient for generating the wide variety of traffic signal plan design that can be implemented in real network (Wang et al., 2001). Krogh (1992) introduced the concept of inference engine for finding the sequence design in which the green signal should be given, once its time duration is not handled by the author. Several researchers (Sang and Silcock, 1989, Gallivan and Heydecker, 1988b, Cantarella and Improta, 1988) used graph approaches knowing that the approach works in most of the time but not always. Tavakolian (2011) presents examples in the literature where the minimum cycle length is not ruled by the conflict group as should be. Another method consisted of inviting experts in traffic plan design to share their experience and in this way develop a plans library where based on intersection geometry and traffic flows, an initial plan is selected (Wang et al., 2001).

3. Description of Signal Timing Control

3.1. General method description

A real-time traffic signal control is proposed, based on a signal plan design enumeration and a group-based signal timing method for a fixed operation. It is an online algorithm for calculating signal settings at an isolated intersection. In short the overall information flux between the several components is presented in fig. 1.

Our method has, as shown in fig. 1, two main elements: traffic simulation model and signal optimizer algorithm.

To initialize the system, an initial signal setting, the network supply data and the demand data is set on traffic simulation model. An initial signal setting (plan design and timings), for the first simulation interval of scenario, is required in order to have some input before our signal optimizer algorithm starts to calculate new signal settings. The traffic simulation model simulates traffic behavior in network and calculates measure of effectiveness in order to measure network/intersection performance.
The algorithm is a traffic signal optimizer learning on a real or simulated road network. As shown in fig. 1, traffic simulation model feed the algorithm with simulation data. In the first simulation interval, algorithm is inactive once traffic simulator controls traffic signal control. Forward in beginning of every simulation interval, the algorithm receives traffic flows information of each turning movement. It assumes that the traffic flows are uniform in each simulation interval. In the second simulation interval, the algorithm enumerates all possible signal design plans respecting safety and operation constraints such as traffic streams groups, number of lane allocated for each movement and incompatible pair of movements. The second step is the application of Akçelik group-based method for determining new cycle length and green time durations for each possible traffic signal plan design defined in the previous step. It is also determined the inter-green values for each possible traffic plan design. Finally the signal setting selection is based on the minimum total delay of the intersection. The algorithm feeds the simulation model with the optimum signal settings. For the next simulation intervals the algorithm begins in the second step.

To include the algorithm of traffic signal control (see description in 3.2), it was necessary to develop a communication protocol to link it to the traffic simulator (Vilarinho et al., 2013). The proposed signal timing control is carried out by a multi-agent framework leveraging MAS-based simulation over multiple microscopic simulators, coined TraSMAPI. The Aimsun’s API module allows the interface of almost any external application that may need access to some internal data of Aimsun during simulation run time since it has direct access to the simulation functions. The interaction between Aimsun simulator and its API module is performed by a set of functions provided by an interface of Aimsun (Aimsun, 2011). The communication between our algorithm and traffic simulator allows us get information from the simulation model and modify the simulation state during the simulation. The road network is modeled in traffic simulator. The TraSMAPI framework allows building an abstraction of this traffic light, and controlling the simulation lifecycle.

Every simulation step traffic simulator communicates with our algorithm (fig. 2). In the first simulation interval, the algorithm handles back no changing request. In the second simulation interval, traffic simulator beginnings by giving information about turning movement flow statistics to the algorithm where new traffic signal settings are determined and implemented in traffic simulator during the simulation interval. The traffic signal becomes exclusively controlled by the algorithm. Every simulation step, the algorithm sends to the traffic simulator a signal state (red, yellow or green) of all signal groups at the signalized intersections. This continuous communication does not increase substantially traffic simulation time experienced by user.

Simulation interval is determined according to equation 1.

\[
\begin{align*}
\text{if } i > 0, \quad t_i &= \left(\text{Round} \left(\frac{t_0}{C_i}\right) + 1\right) \times C_i \\
\text{otherwise } t_i \text{ is user defined}
\end{align*}
\]
where \( t_i \) is the simulation time of the interval \( i \), \( t_0 \) is initial simulation interval, and \( C_i \) is cycle length of interval \( i \). All values are in seconds.

Traffic simulator stores the measure of effectiveness of system and for each simulated element (section, turn, etc) and the algorithm stores optimal signal settings determined at each simulation interval.

3.2. Traffic signal plan design

Traffic signal plan designs are determined after first simulation interval. All possible signal plan designs are created by the algorithm for each intersection. The traffic signal plan design includes grouping the maximum compatible traffic streams by stage. In this way, all traffic streams that can run at same time are allowed to be part of stage bringing more flexibility for the real-time traffic control.

The method was developed to be implemented in any intersection geometry without requiring much effort in parameterization. Every intersection is described as having \( n \) traffic arms, with each arm \( i \) having \( l_i \) approaching lanes, where \( i \in [1; n] \). Traffic arms are numbered consecutively in counterclockwise direction from any traffic arm. Traffic lanes also numbered consecutively from the right to left hand. The number of exit lanes was not included in algorithm. Turning movement is described as a vector \((m,n)\) where \( m \) is origin arm and \( n \) is destination arm in total of \( p \) movements.

Input data includes three matrices: \( M_{\text{mov}} \) where all possible movements are listed, using as notation origin and destination arm; \( M_{\text{lanes}} \) describes the first and last lane number allocated for each movement and \( M_{\text{conf}} \) – for each pair of movement a conflict degree (cd) as defined in fig.3. The algorithm supports both shared lanes and exclusive traffic lanes.

![Intersection geometry index and input data.](image)

In a protected pair of movements, movements can safely cross the intersection because no conflicting is present. In a permitted pair of movement, movements can be given simultaneously but there is conflict and they should move carefully within a gap of opposing movement to pass through the shared space at intersection. The algorithm allows defining the degree of conflict that we can admit in traffic signal plan design.

Traffic signal plan design starts by searching possible signal stages (see description in fig. 4). The method starts by fixing the first movement (dark grey) followed by searching the next movement compatible (light grey) and so on. The movements recently added has to be compatible with all movement already selected for this stage. In next iteration maintains the same fix movement (dark grey) and the second next compatible movement is searched followed by search the next compatible one and so on. As soon as all possible and different stages are found, the second movement is fixed and the process repeated until all movements have been fixed. Every time a movement is selected to integrate the stage, it is necessary to verify if traffic movement belongs to a traffic stream. In case of a traffic stream, all movements of the traffic stream should verify compatibility with movements already selected to be part of the stage. If movements respect the degree of conflicting defined, all traffic stream movements are included,
otherwise no one is included. Traffic stream arrangement is extrapolated from $M_{lane}$ by looking for movements with shared lanes.

$$\begin{align*}
(m,n)_1 & \quad (m,n)_2 & \quad \ldots & \quad (m,n)_{p-1} & \quad (m,n)_p \\
1 & \quad 1 & \quad 0 & \quad 1 & \quad 1 \\
1 & \quad 0 & \quad 0 & \quad 1 & \quad 0 \\
1 & \quad 1 & \quad 0 & \quad 1 & \quad 0 \\
\ldots & \quad \ldots & \quad \ldots & \quad \ldots & \quad \ldots \\
1 & \quad 1 & \quad 0 & \quad 0 & \quad 1 & \quad 1 \\
\end{align*}$$

Figure 4 – Example of how to create stages.

The next step comprises the strategic grouping stages in order to have signal plans design. This traffic signal plan design process should respect the following rules:

- Each signal group receives at least once a green time period during cycle length;
- Each stage has at least one movement assigned;
- Each stage should have maximum signal groups respecting the degree of conflicting defined;
- Each plan should have all signal groups;
- No repeat stage is allowed in a plan;
- Plans with exactly the same stages can be different, if the order of stage appearance is different and plans should be seen as a cyclic process.

### 3.3. Traffic signal plan timing

We propose a traffic signal timing control based on the Akçelik method (Akçelik, 1989) for a fixed-operation signal. For each possible plan design is performed the signal timing calculation using the Akçelik approach. The method is based on critical movement search where it begins by identifying all possible paths, followed by calculating the total time for each path and finally finding the path which needs the largest time value called the critical.

The signal groups responsible for determine the signal timings of the intersection are called critical signal groups. In case of all signal groups are non-overlapping, there will be one signal group in each stage. An overlap signal group is a signal group which receives the right of way during more than one single stage.

A critical movement identification method is presented as a procedure which automatically satisfies the green signal time needs (and minimum green time constraints) in every signal group and respecting the conflicts between them and it allows the use of different degrees of saturation. The critical movement search is therefore a matter of identifying all paths calculating the total time for each path and finding the path which gives the largest value. The process involves the elimination of non-overlap signal group with smallest time needs. The method is applicable to both isolated and coordinated intersections. Another feature is that a signal group may receive green signal during non-consecutive stages within one cycle (needs two lost times).

Once critical movement are identified, critical lost time, critical flow rate and critical green time ratio are defined as the sum of the critical path. The sum of all critical movement time is cycle length. The cycle length value should be in the range between practical cycle length ($C_p$) and optimal cycle length ($C_o$) without exceeding the maximum cycle length ($C_{max}$). In the case of cycle be out of these limits, cycle length takes the value closest acceptable. Optimal cycle length determination uses as criteria the traditional method of delay minimization (Webster, 1958) (Eq.2). The practical cycle optimum (Eq. 3) is the minimum cycle time required to achieve various maximum acceptable degree of saturation (less than 1.0 value). These cycle lengths calculations use critical movements’ parameters as input values.
\[
C_o = \frac{1.5 \times L + 5}{1 - \sum_{i=1}^{n} y_i} \quad C_p = \frac{L}{1 - \sum_{i=1}^{n} u_i}
\]

(2, 3)

where \(L\) is the total lost time per cycle in seconds, \(\sum_{i=1}^{n} y_i\) is the intersection critical flow ratio and \(\sum_{i=1}^{n} u_i\) refers to the intersection critical green time, i.e., the sum of all critical movements \(i\).

All identified paths are calculated again using the new cycle length value. If critical path is the same as before and respects the cycle length rage, green times duration are determined. Otherwise critical path process is repeated until convergence is achieved.

The calculation of green time duration for a selected cycle length beginnings with defining the signal group green time of the critical path, followed by the non-critical and for last determine the stages green time duration. The last step is to check the degrees of saturation, using the allocated green time. This condition will be satisfied unless the practical cycle length is greater than the maximum value admitted.

For signal timing calculation, input data includes the minimum green time, lost time, practical degree of saturation, saturation flow and inter-green, values can be defined for each signal group or intersection scope.

In this paper, the saturation flow of a turning lane is defined with three values according to movement direction: straight-ahead, left-turn and right-turn. Only for opposed turning movement, saturation flows are initialized with a predefined value and a new one is calculated according to the actual traffic conditions. New saturation flow is recalculated until convergence is achieved.

All traffic on the same lane is subject to a single set of signal settings, for operational and safety reasons. In this algorithm each signal group has only one movement unless movement is part of a traffic stream and all movements of traffic streams are part of same signal group.

All possible signal plan designs are automatic generated for each intersection obeying several rules being possible to define plans with stages without an exclusive movement. So we named these stages as fictitious stages and force them to have a green time duration of 2 seconds, working as an early cut-off or an early release on, Inter-green values can be zero, if two consecutive stages have not incompatible movements.

3.4. Traffic signal setting selection

There are usually three criteria for signal setting optimization: capacity maximization, delay minimization and cycle length minimization (Wong and Wong, 2003). In our proposed method, the criteria selection is the minimum total delay of the intersection using as base the formulation developed by Akçelik (Akçelik, 1989) for each traffic stream. The delay model used is one of the first models developed and has the following formulation (Eq. 4):

\[
D_i = q_i \times C \left[ \frac{(1 - u_i)^2}{2 \times (1 - y_i)} + x_i \times \left( Q \times T_i \left( (x_i - 1) + \sqrt{(x_i - 1)^2 + \frac{12 \times (x_i - x_p)}{Q \times T_i}} \right) \right) \right], \text{ if } x_i > 0.67 + \frac{s_i \times g_i}{600}
\]

\[0, \text{ if } x_i < 0.67 + \frac{s_i \times g_i}{600}\]

(4)

where \(q\) is traffic flow in veh/s, \(C\) is cycle length, \(u\) is ratio of effective green in veh/s, \(y\) is the flow factor in veh/s, \(Q\) is capacity in veh/h, \(T_i\) is flow period in hours, \(x\) is the degree of saturation, \(s\) is the saturation flow in veh/s and \(g\) is the green time in s; where \(i\) refers to each traffic stream.

The first term in the model represents uniform delay, and the second term represents random or "overflow queue". Delay time is determined for all signal groups of each traffic signal plan design. The plan with lesser amount of delay is selected to be implemented in traffic control of intersection.

4. Application

4.1. Case study and scenario description
We tested the proposed traffic signal setting algorithm and communication protocol through a case study based on a theoretical isolated intersection controlled by traffic lights (fig. 5).

A simple three-arm intersection for road traffic is selected to evaluate the proposed algorithm. The geometric characteristics of the intersection are shown in fig. 5. Each arm has two approaching lanes, where arms 1 and 3 have exclusively lanes for movements and arm 2 has shared lanes. There is only one traffic stream with two movements (2.1 and 2.3). Input data can be consulted in fig. 5.

The saturation flows for straight-ahead movements, right-turn movement and left-turn movements are taken as 1800, 1600 and 1700 veh/h/lane, respectively. The maximum cycle length is set to be 120s, and the maximum acceptable degree of saturation is 80%. The inter-green time is 5s (3s yellow, 2s red) and minimum green duration are 8s for all traffic movements.

A demand profile with nine matrices was tested with four different levels of intersection demands, three road axis distribution and three different arm allocations (fig 6). So a total of 36 scenarios were performed. The demand is codified in matrices of origin and destination of 15-minutes each. The total time of simulation is two hours and fifteen minutes. These scenarios were tested for three different cases (Table 1).

| Total Traffic Demand | Road Axis | Arm Allocation | Demand Profile in matrices of 15min |
|----------------------|-----------|----------------|-----------------------------------|
| Demand (veh/h)       | assignment|                | 00:00-00:15 00:15-00:30 00:30-00:45 00:45-01:00 01:00-01:15 01:15-01:30 01:30-01:45 01:45-02:00 02:00-02:15 |
| 500                  | 1 2 3    | 1 2 3          | 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 |
| 1000                 | 1 2 3    | 2->3 3->2      | 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 |
| 1500                 | 1 2 3    | 3 2 1          | 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 |
| 2000                 | 1 2 3    | 3 2 1          | 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 |

Webster method (1957) calculates signal timing for the entire demand and the maximum green time duration of each stage is add in traffic simulator.

A three-stage traffic signal plan was defined for case (1) and sets on as initial simulation interval of cases (2) and (3). The simulation interval is defined in 300s each one.

4.2. Results and discussion

After the successful implementation of the algorithm through the API in Aimsun, we conducted comparison tests between the network featuring a full-actuated traffic control, case (1), and the same network featuring traffic lights.
controlled by the implemented algorithm (API), case (2) and (3). We run scenario ten times. All possible configurations for traffic signal plan design found out by algorithm and the simulation results are listed in fig. 7.

Traffic signal plan design is divided in maximum conflict degree of 0 or 1. Each graph of simulation results has a different total traffic demand in intersection where nine demand profiles are represented (x-axis) for the three test cases (series).

The simulation results show that the system controlled by our algorithm with maximum conflict degree of 1 (case 2) has a superior performance in total delay than the other two cases. For low total demand, of 500 and 1000 veh/h, both case (1) and (3) have similar total delay values. But for high demands, of 1500 and 2000veh/h, case (3) has an inferior performance.

As a consequence of the result analysis, it is possible to conclude that the proposed algorithm with fixed operation reduces the total delay if maximum degree of conflict is 1 (case 2) comparing with a control with vehicle-actuated operation and a fixed traffic signal plan design with conflict degree of 0. So the autonomy of changing the traffic signal plan design, respecting the maximum conflict degree of 1, and the green time duration in each simulation interval, offers superior performance than a traditional vehicle-actuated traffic signal control. However if the maximum conflict degree is 0, a traditional vehicle-actuated traffic signal control gives superior performance. The difference of traffic signal control with plan design autonomy between a maximum conflict degree of 1 (case 2) and 0 (case 3) is in average 40% more total delay. Comparing total delay of cases (2) and (3) with case (1), in average decreases 40% and increases 14% respectively.

5. Conclusion and Future works

The paper contributes to develop an integrated traffic signal control where signal plan design and signal timing calculation are optimized simultaneously in response to recurrent traffic flow fluctuation at an intersection. The traffic signal plan is determined in every simulation interval according with the demand in the last interval. The novel signal timing and plan design control algorithm is implemented in the microscopic traffic simulator Aimsun, using TraSMAPI and the Aimsun API module for communication with the simulator.

The simulated network encompassed a simple fictitious intersection with three-arms and only road traffic. The algorithm employed allowed us to find new signal groups and new orders of the signal groups as well as new green time duration for each signal group in order to handle recurrent demand fluctuations. The comparison study in the simulated system permitted us to conclude that the proposed control method gives a better performance when the...
maximum conflict degree is 1 (case 2). However if the maximum conflict degree is 0 the traditional vehicle-actuated traffic signal control has better performance for higher traffic demands. The difference of a maximum conflict degree of 1 (case 2) and 0 (case 3) in traffic signal plan design results in average 40% more total delay.

This paper develops a simple adaptive signal control model that can be easily applied to an existing fixed signal control system with traffic monitoring in order to improve the performance.

In the future, the traffic signal setting control algorithm will be revised in order to include vehicle-actuated operation and ability to make arrival predictions. The algorithm will also be enhanced in order to consider different decision criteria for traffic signal plan selection beyond delay minimization. The algorithm should be tested in more complex intersection to explore in depth the algorithm results. Finally, the algorithm should be tested in other simulators taking advantage of the simulator-independent nature of TraSMAPI, which allows a solution once designed to be tested in different platforms with no need for recoding.

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