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Transportation Research Procedia 45 (2020) 890–897

Transportation Research Procedia

www.elsevier.com/locate/procedia

AIIT 2nd International Congress on Transport Infrastructure and Systems in a changing world (TIS ROMA 2019), 23rd-24th September 2019, Rome, Italy

A Simulation-Optimization Method for Signal Synchronization with Bus Priority and Driver Speed Advisory to Connected Vehicles

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Abstract

The paper introduces a model-based optimization procedure for the design of a control system with signal synchronization, real-time bus priority and green light speed advisory to car drivers. The traffic model simulates car traffic as platoons and bus movements individually. An optimization routine simulates the effect of different bus priority rules, which can be actuated online through bus identification devices and applies a metaheuristic algorithm to optimize signal settings. The macroscopic model and the design method have been applied and also tested in microsimulation on a principal street in Rome with a tram line on a reserved lane. Results obtained show that offline signal optimization and online signal priority can significantly reduce both travel times of bus riders and delays for total traffic. Similarly, speed advisory to drivers, if considered in signal optimization, can improve not only drivers' delays but even transit passengers' delays because it allows more efficient use of the road.

Keywords: Signal Synchronization; Transit Priority; Green Light Optimal Speed Advisory; Traffic Simulation; Connected Vehicles

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1. Introduction

Recent advances in communication technologies that support connected vehicles open new perspectives for traffic control. They introduce additional knowledge of all connected vehicle positions and allow to provide drivers with recommended speeds through in-vehicle messages. Signal synchronization usually seeks to optimize travel times based on traffic flow measures, while transit priority control system adapts signal settings to only current bus positions. In

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10.1016/j.trpro.2020.02.079

the presence of connected vehicles, traffic control includes guided adaptations of car drivers who comply with optimal speed advice and optimizes signal settings taking into account predicted arrivals of all connected vehicles.

Beside the well-established literature on traffic signal control (see for example Fusco et al. 2017 for a review), a more recent research stream is growing that considers the additional functions enabled by Connected Vehicle technology for Green Light Speed Advisory (GLOSA) systems (Katsaros et al., 2011; Wan, 2016; Stebbins, 2017; Stahlmann et al., 2018; Edwards et a., 2018) and for enhanced transit priority strategies through bus-signal coordination (Hu et al., 2016).

In this paper, we introduce a simulation-based optimization method, called SINTAC, conceived as a design tool for near-optimal pre-timed traffic signal coordination of road arteries with actuated bus priority control and driver speed advisory. This method generalizes the platoon progression model by Colombaroni et al. (2009) in order to simulate movements and stops of individual buses and assess different transit priority control policies. With respect to the existing literature, this method solves the bus priority problem with an optimization method similar to Stevanovic *et al.* (2008) but applies an original macroscopic platoon-based model instead of a commercial micro-simulation package. With reference to the specific literature on GLOSA applications (Seredynski et al., 2015; Hu et al. 2016; and Laskaris et al., 2018, among others), it introduces the simulation of GLOSA in the same optimization-simulation procedure.

This integrated framework opens new perspectives for the assessment of technology advances in ICT applications to connected vehicles and for the design of integrated control systems that optimize signal regulation depending on real-time locations of both private and public vehicles.

2. Traffic Model

Traffic model provides queue lengths and average delays at signals of platoons traveling along an urban artery. The delay at nodes is defined as the excess of travel time relative to travel at the synchronization constant speed. So, the transient phases are all included in the effective red time. The delay at nodes depends on the arrival time and the length of the platoon as well as on the starting and the time length of the red at the signal. Three different cases may occur.

Case A: Platoon p arrives at node i during the time interval necessary to clear the queue (if any) at the end of red time. In this case, the whole platoon is delayed (front-delayed platoon, illustrated in Fig.1, left) and the total delay is given by equation (1), whose term between parentheses represents the average delay per vehicle.

$$D_{i,p} = q(v_s)l_{i,p}\left[\vartheta_i + \frac{r_i}{2} + \tau_i - t_{i,p}\right]; \quad \vartheta_i - \frac{r_i}{2} \leq t_{i,p} < \vartheta_i + \frac{r_i}{2} + \tau_i \tag{1}$$

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

Case B: Platoon p arrives at node i after the queue (if any) at the end of red time has been cleared and ends after the start of red time at the next cycle C, so that the rear of the platoon, denoted by ζ in Figure 1, right, is delayed.

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

Case C: Platoon p arrives at node i after the queue (if any) at the end of red time has been cleared and ends before the start of red time, so that it is not delayed.

$$D_{i,p} = 0; \quad \vartheta_i + \frac{r_i}{2} + \tau_i \leq t_{i,p} < \vartheta_i + C - \frac{r_i}{2} - l_{i,p} \tag{3}$$

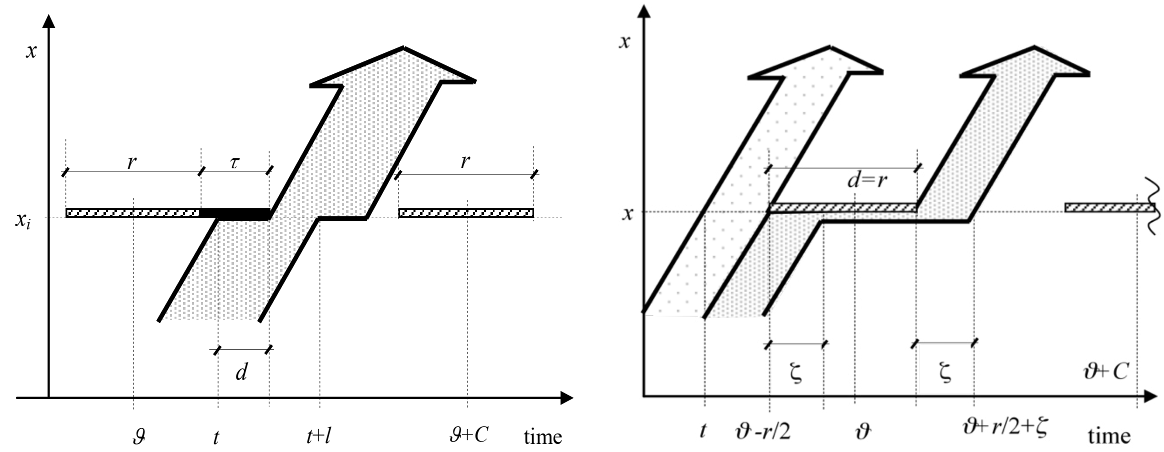

Fig. 1. Node delay for a front-delayed platoon (on the left) and for a rear-delayed platoon (on the right).

The traffic model performs the platoon classification at nodes, which is needed to determine the average delay and the number of stopped vehicles, and the platoon recombination at nodes and links, which are needed to determine the departure time and the length of platoons.

The mechanism of platoon recombination at nodes is exemplified in Figure 2 (left), where two platoons, A-type and B-type (denoted as 1 and 2, respectively, in the figure), arrive at the node *i* and a third platoon of vehicles (denoted as 3) entering the artery from side streets starts at the beginning of the effective red time for the artery (i.e., at the beginning of the effective green time for side streets). Since A-type platoon is split into 2 sub-platoons (1' and 1" in the figure) and platoon 2 arrives before the queue has been cleared, it joins platoon 1". Departures at the node are then composed by platoon 1', whose starting time coincides with its arrival time; by platoon 2, which starts at the end of the effective red time, and by platoon 3, entering the artery from side streets.

Platoon progression and recombination along the links are illustrated by the example in Figure 2 (Right). The link module computes the arrival times and the time length of platoons at the downstream intersection. The arrival time is determined by applying either the synchronization speed or an acceleration rate if drivers are advised to accelerate with the goal of arriving at the next intersection during the green. The first vehicle of platoon 1 travels at the synchronization speed v_S. Drivers of following vehicles may change their speed spontaneously if some preceding vehicle exited from the arterial and formed gaps ahead within the platoon, or if they received any recommendation from GLOSA system. These two cases are represented in the figure by speeds *v'* and *v"*, respectively.

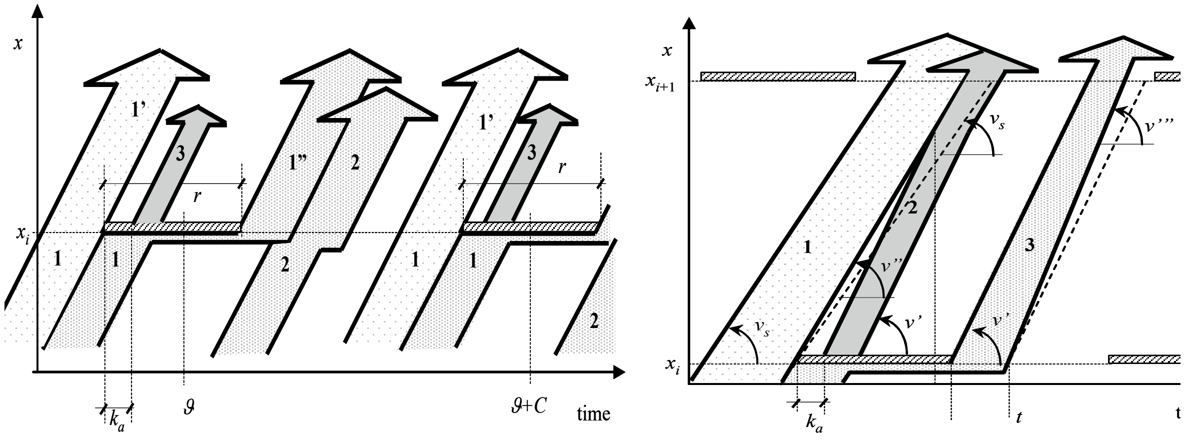

Fig. 2. Examples of platoon recombination at a node i (on the left) and of platoon progression and recombination along a link (on the right).

Dashed line represents the trajectory of the last vehicle if no vehicle of the platoon had left the artery or if, in any case, it had traveled at the synchronization speed; however, due to exiting vehicles, all vehicles within the platoon can accelerate and travel at a higher speed, as indicated for the last one, whose speed is indicated as *v*”. The time length is computed by subtracting the vehicles that leave the artery at the upstream node and assuming that all vehicles belonging to the platoon can accelerate, compressing then the platoon.

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

2.1. Bus Priority Model

Bus priority model is designed to simulate pre-timed signal settings (passive bus priority, applied as reference timing plan) and to take into account also different actuated bus priority strategies. It simulates buses individually and computes the number of passengers, the dwell time and the vehicle position in the queue, if any, for each bus at each bus stop. Buses arriving during the same signal cycle are moved as platoons along the downstream link. It is so possible to assess time-varying traffic signal performances during the simulation and evaluate new priority rules that consider several components like bus schedule adherence, the number of passengers on the bus, traffic flow on cross streets, green split, predicted headway between two following priority requests. In order to avoid excessive disadvantages to general traffic, a limit is set to the number of consecutive cycles where buses can have priority.

Figure 3 depicts the flow chart of the whole process for bus priority acknowledgment rule and simulation. Given the transit data as routes, stops, and number of passengers, the model computes bus departures, bus arrivals at stops and predicted arrival at nodes. These are computed independently from the traffic model as buses are assumed running on reserved lanes so that interactions with car traffic occur only at nodes. At each iteration –that is, for each signal cycle– and at each node *i*, predicted arrival times at nodes are input for the Priority acknowledgment module. Then, the model simulates and evaluates the priority acknowledgment rule; in this step, it computes bus delay at node *i*+1 and alters the signal timings; then the traffic model is applied to compute cars delay. As the priority rule is selected, the “Priority action” module chooses the most suitable action, depending on the current state of signals and sends the relative information to the traffic model, in order to update the “Platoon classification at node *i*+1” module.

Priority actions consist in either anticipating the start of green or extending the end of the green. The choice of the most suitable action depends on the predicted arrival time of the bus at the stop line.

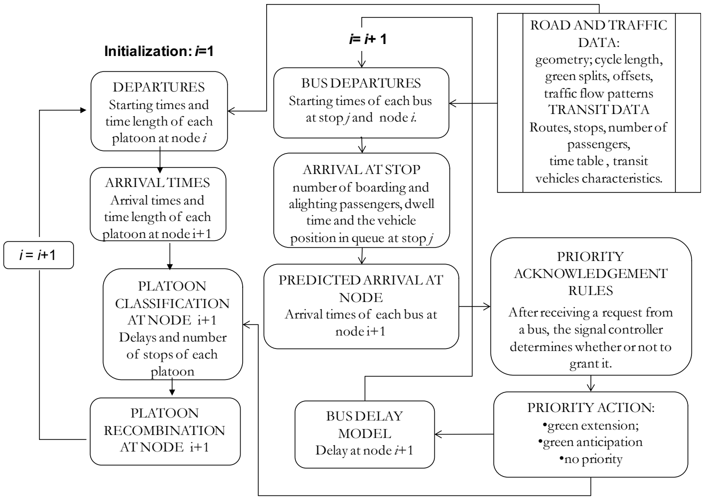

Fig. 3. Simulation model of car traffic and bus priority.

3. Optimization Algorithm

3.1. Objective Function

In this study, an algorithm has been developed to optimize the signal synchronization by taking into account the delay of both public and private traffic. The algorithm combines the search for a global minimum by a genetic algorithm and a local refinement procedure with predefined steps around the tentative solution point. The objective function is defined as a linear combination of different components of total delays on the artery, calculated as follows.

$$f = w_1 \sum_{i=1}^{n} D_i^{(1)} + (1 - w_1) \sum_{i=1}^{n} D_i^{(2)} + w_l \sum_{i=1}^{n} \sum_{h=1}^{H(i)} D_{i,h}^{(l)} + w_b \sum_{i=1}^{n} \sum_{b=1}^{B(i)} D_i^{(b)} \tag{4}$$

with the following definition of symbols:

- $D^{(1)}{}_i$ the total car passenger delay at node i in direction 1
- $D^{(2)}{}_i$ the total car passenger delay at node i in direction 2
- $D^{(l)}{}_{h,i}$ the total car passenger delay of queue $h \in H$ in lateral approach l at node i
- $D^{(b)}{}_{b,i}$ the total delay at node i for passengers in bus $b \in B$
- w_1 the weight of delay in direction 1, with $0 \leq w_1 \leq 1$
- w_l the weight of delay in lateral approaches l, with $w_l \in \Re^+$
- w_b the weight of delay for passengers on buses, with $w_b \in \Re^+$

3.2. Genetic Algorithm

The Genetic Algorithm (GA) represents each possible signal setting solution for the artery through a genome whose elements symbolize the cycle length, the green split in each of the 2 directions and the offset of each signal.

The evolutionary process of GA starts from an initial population of individuals that correspond to possible solutions, each of them characterized by a different genome patrimony. Since the quality of the initial population affects the algorithm convergence significantly, a subset of the initial solutions has been designed by applying simple but reliable criteria that are usually good practice in traffic engineering, while the remaining have been chosen by random. More specifically, the following special designed solutions have been considered:

- the actual signal settings;
- a maximal green bandwidth solution corresponding to the maximal of the actual cycle lengths of the artery and the actual green splits, computed by applying the algorithm developed by Papola and Fusco (1998a);
- a good practice solution obtained by applying the following simple rules, that is: either Webster's optimum cycle length for medium-low saturation degree or minimum cycle length for high saturation degree; green splits according to either equisaturation criterion or a priority criterion that assigns all the available green to the artery; offset set according to the maximum bandwidth criterion.

In addition, all the solutions must fulfill a set of constraints on the minimum and maximum values for the cycle length, the green splits and green time for pedestrian crossing.

At each generation, the optimization algorithm computes the fitness of each individual of the population by simulating the road artery under the pre-timed signal setting corresponding to the genome of that individual and implementing a given priority strategy (or a combination of them with given weights), which modifies the pre-timed signal plan according to the bus arrival at intersections.

Then, GA uses the roulette wheel method to apply the well-known genetic operators of crossover and mutation. The probability of mutation, in the absence of improvements in the objective function, varies linearly from γ_{min} to γ_{max} in a given number of iterations. This strategy is used to avoid a deadlock into a local minimum. The GA also uses the feature of elitism to keep a quota η of the solutions ordered according to their fitness.

The genetic algorithm stops after a given number of iterations. Then, a local adjustment algorithm applies a strategy similar to the Hill-Climbing method used by Transyt. It performs a series of trials sequentially to increase and then decrease the design variables: cycle length, green rate splits and offsets. The algorithm tries variable perturbations by applying three step lengths $s_1 > s_2 > s_3 > 0$ for each of them. It keeps each variable change that improved the objective function and continues to try changes until no more improvements are obtained.

4. Experimental Application

The procedure described in the previous sections was applied to simulate the road traffic and the above-mentioned bus priority strategies and drivers' speed advisory on a suitably selected stretch of via Prenestina, a main street located in the Eastern area of Rome hosting a tram corridor. The road segment considered, depicted in Figure 4, is a 2km-long, 2-lane urban street, which contains 6 signalized intersections and is served by 3 tram lines operated with 33m long vehicles having a capacity of 270 passengers and running on separated transit lanes. Two tram lines have a frequency of 7 vehicle/hour, the remaining of 5 vehicle/hour so that the total frequency is 19 vehicle/hour. Traffic flows in the a.m. peak hour were surveyed on the field and simulated by the model. Saturation flows used by the traffic optimization program were estimated by applying the well-known standard HCM (2010) method.

To test the performances of our simulation-optimization method, the road artery was studied by applying the microsimulation software SUMO with TRACI interface for traffic signal control simulation (Wegener et al., 2008).

The goal of the microsimulation is twofold: compare the platoon-based traffic model with a microsimulation model and then assess the results of the design method by using a different model from that used to compute the optimization. Consistently with the objective function definition, total delays were computed separately for the arterial, lateral streets, and transit. It is just worth mentioning that flows are invariant in different scenarios so that total person delay or average delay per person differ only for a scale factor.

Intersection positions, hourly vehicular flows, current signal settings and the corresponding average delays at the intersections, computed by the platoon-based model, are reported in Table 1.

Fig. 4. Stretch of the road arterial (via Prenestina in Rome) with the signalized intersections under study.

Table 1. Abscissae, vehicular flows, current signal settings and average vehicle delays (*s*) at the intersections on the artery.

Intersection	x	q_{EB}	q_{WB}	q_{NB}	q_{SB}	C	g_E	g_W	d_E	d_W	d_L	$d_{T,E}$	$d_{T,W}$
Giovenale	0	1188	1324	0	0	108	0.61	0.61	18	17	0	0	37
Fieramosca	683	1188	1210	0	693	120	0.5	0.5	8	19	22	3	2
C. Casilina	734	962	1166	412	0	120	0.37	0.83	57	3	51	17	1
Dep.ATAC	864	962	1191	0	0	90	0.73	0.73	11	8	0	0	2
P.Labicano	1633	0	1191	1634	0	122	0.5	0.5	0	22	24	9	7
P.Maggiore	2064	604	0	0	2370	153	0.29	n.a.	45	0	11	0	2

Legend: x: Intersection abscissa (*m*); q_{EB}, q_{WB}, q_{NB}, q_{SB}: Eastbound, Westbound, Northbound and Southbound traffic flows (*veh*/*h*); C: Cycle length (*s*); g_E, g_W: Eastbound and Westbound green splits for the artery (adimensional); d_E, d_W, d_L: Average delay for cars Eastbound, Westbound directions and Lateral streets (*s*); $d_{T,E}$: Eastbound delay for Transit; $d_{T,E}$: Westbound delay for Transit (*s*).

With reference to the first goal, in order to have a wider test case for model comparison, a longer stretch 5km long of the same road artery with 19 intersections was considered, which also includes the segment to optimize.

A model in SUMO was built and calibrated against observed flows at each intersection with the aim of properly reproducing intersection capacity and vehicle progression. To have a simpler but standard term of comparison, also the HCM (2010) method was applied to compute delays at every intersection. The average delays for the whole arterial and the segment under study were calculated as a weighted average of individual delays with traffic flows.

Results of the comparison are reported in Fig.5a. The average delays along the arterial computed with the platoon-based model are very similar to those obtained in microsimulation SUMO (2% for the whole arterial and 7% for the segment). The differences with the values computed with HCM (2010) method are more significant (26% and 23%, respectively) as it can be expected considering the different nature of the HCM method, which assumes isolated junctions and applies the coordinate transformation method to take into account randomness of arrivals and possible oversaturation.

Then, the study focused on the simulation of different control scenarios with and without transit priority (with FIFO policy) and with GLOSA on the road segment described in Fig.4. The following scenarios were analyzed:

- no project;
- vehicle delay minimisation (synchronization) without bus priority;
- person delay minimisation (optimization) with bus priority;
- person delay minimisation with bus priority (optimization) and green light speed advisory (GLOSA) with an allowed speed increase of 11 km/h for all drivers along the arterial.

In the scenarios without GLOSA, it was assumed that drivers spontaneously try to fill the gap within the platoon by increasing their speed of 3.6 km/h. In both synchronization and optimization scenarios, the metaheuristic algorithm described in Section 3 is applied by assuming a population composed of 50 individuals, which evolves for 20 generations. Although the optimization process is conducted offline and real-time actions are only simulated, the repetition of different cycles with different occurrences for the whole time period demonstrated to be sufficient to achieve consistent reductions of overall delays. The following considerations can be made from their observation:

- in the current condition (No Project), even if vehicular delays for trams are relatively low (as shown in Table 1) and lower than those of cars thanks to the reserved transit lanes, the total personal delays (102 person·h) are significantly higher than those of car drivers on the same artery (56 person·h);
- synchronization with respect to only car traffic reduces drivers' delays along the artery from 56 to 48 person·h and lateral delays from 30 to 23 person·h; however, it increases tram users' delays from 102 to 223 person·h;
- optimization with respect to all users reduces every single component of the total delay and achieves an overall reduction from 188 to 105 person·h (–44%);
- optimization with GLOSA allows reducing delays on the main artery not only for car drivers, who are served by the advisory but even for tram users, although delays at cross streets increase slightly.

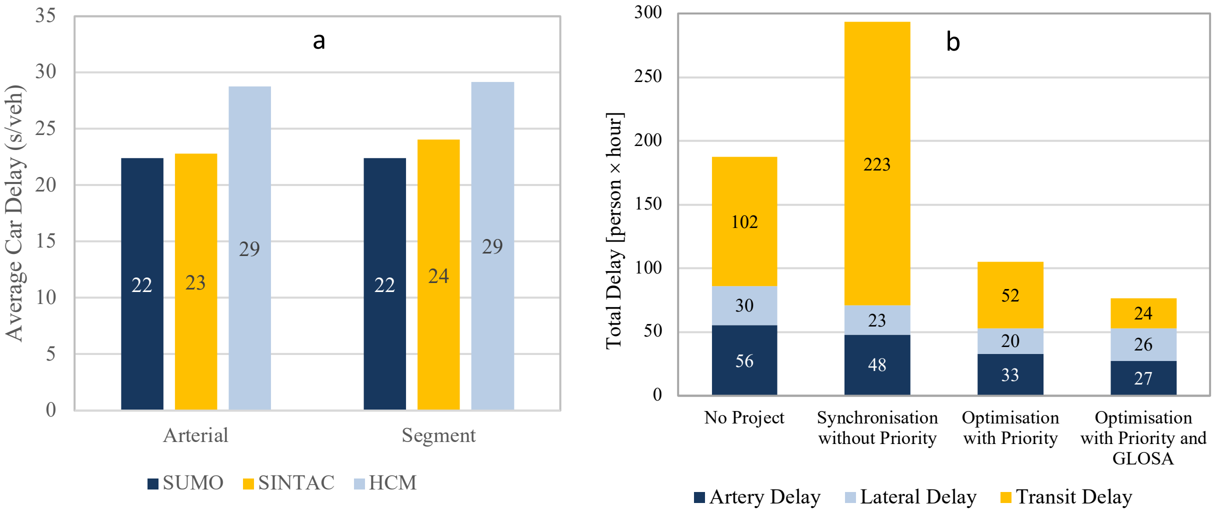

Fig. 5. (a) Average No Project delays at the 19-intersection whole arterial and at the 6-intersection segment under study computed by SUMO, the proposed model (SINTAC) and HCM 2010. (b) Total person delays at signals for different control scenarios computed by the proposed model.

The last observation is worthy of further analysis because the positive impact of GLOSA on transit delays is not intuitive. Indeed, GLOSA advises drivers to accelerate if it is convenient to pass the signal at the end of the green. Thus, it makes the vehicle platoons shorter and allows to reduce spacings that occur along the artery because of vehicles that exited the artery at previous junctions. Drivers tend to do this spontaneously (in fact, a catch-up speed of 3.6 km/h has been considered in the model even if drivers are provided with no advice); however, the GLOSA system does this systematically when useful and with a suitable speed value. Shorter car platoons need shorter green times: this condition is highly beneficial for tram cars that do not need long durations of greens and are disadvantaged by long red times.

4. Conclusions

The paper introduced a model and an algorithm for simulating car traffic, bus priority and Green Light Advisory Speed along urban arteries. Different bus priority rules were tested to solve conflicting priority requests. Numerical tests on a 6-node artery in Rome highlighted the potential effectiveness of the optimization procedure that includes active transit priority at signals and speed advisory.

Real-time bus priority at signals, if correctly included in a general optimization framework, does not disadvantage general traffic, but, on the contrary, can improve delays for both cars and bus passengers.

Similarly, information to car drivers on optimal speed to catch the green before the red starts can improve delays even for tram passengers if this behavior is considered in the optimization method because more efficient use of the road allows shortening long red durations that heavily affect tram delays.

Moreover, an integrated system of information and control that optimizes signal settings and GLOSA actions can take whole advantage by both mutual adaptations of drivers’ behaviors and dynamic signal settings.

Future work is addressed to generalize signal control strategies and consider transit fleet management that delays earlier buses at signals in order to improve adherence to schedule. Moreover, advances in V2X communication and their use by private cars provide new opportunities to apply Transit Signal Priority not only to reserved transit lanes but also to shared lanes where transit vehicles run in mixed traffic. In fact, if a not negligible fraction of cars are connected, the length of the queue at signals can be estimated (Shahrbabaki et al., 2018) and the corresponding green extension can be accurately computed.

References

Colombaroni, C., Fusco, G., Gemma, A. (2009). Optimization of Traffic Signals on Urban Arteries through a Platoon-Based Simulation Model, Proceedings of 11th WSEAS International Conference on Automatic Control, Modeling and Simulation, Istanbul, Turkey, May 30 - June 1.

Edwards, S., Hill, G., Goodman, P., Blythe, P., Mitchell, P., Huebner, Y. (2018). Quantifying the impact of a real world cooperative-ITS deployment across multiple cities. Transportation Research Part A: Policy and Practice, 115, 102-113.

Fusco, G., Gentile, G., Meschini, P. (2017). Urban traffic signal optimisation. In: “Intelligent transport systems (ITS): Past, present and future directions”, Fusco, G. (Ed.). Nova Science Publisher, New York. 161-200.

HCM (2010). Highway Capacity Manual 2010. Transportation Research Board, National Research Council, Washington, DC.

Hu, J., Park, B. B., Lee, Y. J. (2016). Transit signal priority accommodating conflicting requests under Connected Vehicles technology. Transportation Research Part C: Emerging Technologies, 69, 173-192.

Katsaros, K., Kernchen, R., Dianati, M., Rieck, D. (2011). Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform. 7th Intern. Wireless Communications and Mobile Computing Conference, 918-923.

Laskaris, G., Seredynski, M., Viti, F. (2018). Improving Public Transport Service Regularity using Cooperative Driver Advisory Systems. 2nd Symposium on Management of Future motorway and urban Traffic Systems. Ispra, June 11-12, 2018.

Papola, N., Fusco, G. (1998). Maximal bandwidth problems: a new algorithm based on the properties of periodicity of the system. Transportation Research Part B, 32(4), 277-288.

Seredynski, M., Khadraoui, D., Viti, F. (2015). Signal phase and timing (SPaT) for cooperative public transport priority measures. Proceedings of 22nd ITS World Congress.

Shahrbabaki, M. R., Safavi, A. A., Papageorgiou, M., Papamichail, I. (2018). A data fusion approach for real-time traffic state estimation in urban signalized links. Transportation Research Part C: Emerging Technologies, 92, 525-548.

Stahlmann, R., Möller, M., Brauer, A., German, R., Eckhoff, D. (2018). Exploring GLOSA systems in the field: Technical evaluation and results. Computer Communications, 120, 112-124.

Stebbins, S., Hickman, M., Kim, J., Vu, H. L. (2017). Characterising green light optimal speed advisory trajectories for platoon-based optimisation. Transportation Research Part C: Emerging Technologies, 82, 43-62.

Stevanovic, J., Stevanovic, A., Martin, P.T, Bauer, T. (2008). Stochastic Optimization of Traffic Control and Transit Priority Settings in VISSIM, Transportation Research Part C, 16, 332–349.

Wan, N., Vahidi, A., Luckow, A. (2016). Optimal speed advisory for connected vehicles in arterial roads and the impact on mixed traffic. Transportation Research Part C: Emerging Technologies, 69, 548-563.

Wegener, A., Piórkowski, M., Raya, M., Hellbrück, H., Fischer, S., Hubaux, J. (2008). TraCI: An interface for coupling road traffic and network simulators. Proc. of 11th Communications and Networking Simulation Symposium, CNS'08, 155-163. doi:10.1145/1400713.1400740.