



SIGNAL SETTINGS SYNCHRONIZATION AND DYNAMIC TRAFFIC MODELLING

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Abstract.

The object of the paper is to investigate the effect of signal synchronization on the traffic flow patterns on the network and validate results of synchronization problem in signal setting design. A platoon based traffic model is applied to solve both one-way and two-way synchronization problems in under-saturated conditions. Assessment of results through dynamic traffic assignment model shows that solution found is rather robust and, if more traffic is attracted by the improved arterial performance, larger benefits can be achieved on the whole network. A specific analysis has been conducted to point out the representation of queue propagation and the gridlock phenomenon.

Keywords: Road traffic network models, Traffic signal synchronization, Dynamic traffic assignment

1. Introduction

The paper aims at dealing with some relevant issues arising in design of the road network signal settings; namely, the interaction between signal synchronization and drivers behavior and the possible need for validating results of synchronization problem through dynamic traffic assignment models.

This problem is interesting by both a theoretical and an application point of view, since several mathematical studies and experimental results have shown that usual signal setting policies, which simply adjust signal parameters according to the measured traffic, may lead to system unstable solutions and deteriorate network performances.

At core of the problem is the difference between a user equilibrium flow pattern, where individuals choose their paths in order to minimize their own travel time, and a system optimizing flow that minimizes total delay of all users. The problem is object of an intensive research activity by the scientific community by many years. Valuable literature reviews are reported in Cantarella et al. (1991) and Taale and Van Zuylen (2001). More recent contributions have been provided, among others, by Cascetta et al.

(2006), who introduced a clear distinction between local and global approaches to signal optimization, and by Chiou (2011), who introduced an algorithm based on a quasi-Newton subgradient projection and contraction method, and Adacher and Cipriani (2010), who proposed a surrogate algorithm.

The global optimal signal settings on a road network aims at optimizing traffic signals by imposing a consistent pattern of traffic flows. This is a complex problem that involves traffic dynamics, users' route choice and application of suitable control strategies. With several noticeable exceptions (Ghali and Smith, 1995; Smith and Ghali, 1990; Abdelfatah and Mahmassani, 1998; Abdelghani et al., 1999), the problem is usually tackled by following an equilibrium approach, that is, by searching for a possibly optimal configuration of mutually consistent traffic flows and signal variables. The equilibrium approach assumes, but does not reproduce, the existence of a process where drivers correct their route choice day-to-day, according to the modified network performances, until no further improvement could be achieved. The traffic flow is modeled by a stationary relationship between link travel time and link flow. In this case, although the delay at node approaches can be taken into account as it may be added to the link cost, neither a realistic modeling of traffic congestion on a road network or an explicit representation of real-time traffic control is possible. A different approach consisting of formulating the day-to-day route choice process explicitly has been recently followed by Cantarella et al. (2012), who individuated stability conditions for simple O-D networks.

Although the combined problem of signal settings and traffic assignment is a well known non convex problem, a systematic analysis of the objective function of the global optimization signal setting problem highlighted in several examples large quasi-convex intervals for even different levels and patterns of traffic demand (Cipriani and Fusco, 2004). So, benefits of signal synchronization (as computed by assuming traffic flows as given) may be either nullified by redistribution of traffic or even amplified (at network level) if synchronization allows the artery accommodate more traffic without vehicle delays increasing. Thus, it is useful to examine the effectiveness of the signal setting solution and validate it by applying a traffic assignment model.

The question is worth of investigation also because of the different models usually applied for signal settings and for traffic assignment.

When signal settings include synchronization, the time-independent equilibrium assumption introduced in traffic assignment is inadequate to appreciate the effect of signal offsets and a dynamic traffic assignment approach is required.

In the paper we discuss these issues and examine them through numerical examples on real-size road networks.

In section 2 we describe a platoon progression model that extends a simpler delay model for synchronized arteries (Papola and Fusco, 2000) by introducing different hypotheses of driving behavior along the artery. The extended model was recently implemented in a software program, which applies a mixed genetic-hill climbing algorithm to optimize signal synchronization with active bus priority strategies at signals (Colombaroni et al. 2009; Fusco et al., 2010).

Different signal setting strategies are then tested for both one-way and two-way synchronization problems in section 3.

In section 4, we assess the consistency of these macroscopic models with dynamic traffic assignment models based on the so-called mesoscopic approach that reproduces the longitudinal interaction between vehicles at an aggregate level and simulates individual behavior at nodes, including route choice. The analysis is supported by numerical experiments on a wide study area located in Rome, Italy.

2. Traffic model

2.1. Hypotheses

Several different hypotheses about drivers' behavior can be considered.

If there is no information about the synchronization speed, it is usual assuming that the vehicle speed on each link depends on the average link traffic density.

However, if one envisions that an information system advises drivers about the synchronization speed, it is possible to consider several alternative hypotheses, depending if we allow drivers accelerating to gain possible available space produced by exiting and entering maneuvers or not. In each hypothesis we assume to include the transient phase of motion into the effective red time.

Three reasonable hypotheses are:

- 1) all drivers travel at the synchronization speed v_s ;
- 2) the leading vehicle of each platoon tends to travel at the synchronization speed, v_s , while the following vehicles of the same platoon tend to travel at least at v_s (that is, at the steady-state, if there are no empty spaces inside of the platoon, all vehicles travel at speed v_s ; otherwise, if vehicles exiting the artery leave available some spaces inside of the platoon, following vehicles accelerate in order to refill the empty space, "compressing" then the platoon);
- 3) the first vehicle passed during the green time travels at the synchronization speed v_s , while all following vehicles along the artery, including the leading vehicles of successive platoons, tend to travel at least at v_s (that is, each following driver that has available space in front of him or her will accelerate at a given acceleration rate until he or she reaches the previous vehicle, if the link is long enough).

The hypotheses above provide different possible platoon patterns along the artery: in case 1) each platoon will have a constant length while progressing along the artery (that is, it will occupy the same time interval, even if the number of vehicles changes passing from one arc to another), until it is stopped at a node (if it does); in case 2) platoons will have a time length $l_{p,j} = n_{p,j}/q(v_s)$, where $n_{p,j}$ is the number of vehicles of platoon p on the arc j , and $q(v_s)$ is the flow corresponding to the synchronization speed v_s ; in case 3) there will be just one platoon arriving at each node.

Moreover, we assume that the synchronization speed is not far from the critical speed (i.e., the speed corresponding to saturation flow); we also hypothesize that at every intersection there is enough green time to accommodate all arriving vehicles traveling at the synchronization speed, that is:

$$\sum_{i=1}^m n_{i,j} \leq q(v_s) g_j \quad (1)$$

where $q(v_s)$ is the flow at the synchronization speed v_s , g_j is the green time for the coordinated route at intersection j and $n_{i,j}$ is the number of vehicles belonging to the i -th platoon (over a total number of m platoons) arriving during the cycle length at intersection j .

2.2. Node delay model

Delay at nodes on coordinated routes is defined as the time lost with respect to a travel at constant speed v_s .

We assume that on each link all vehicles can actually reach the synchronization speed v_s , even if they are stopped at a node. Thus, both upstream and downstream there are steady state traffic condition, where all vehicles travel at speed v_s and at a time interval $1/q(v_s)$ each other. Figure 1 depicts vehicle trajectories assumed in the model for node delay and describes: the delay of first vehicle d_1 ; the delay of the last vehicle of the platoon d_n ; the lost time at start k_a ; the lost time in the stopping phase k_j ; the time length of the platoon at steady-state conditions, $n/q(v_s)$.

It follows from the figure that, if all vehicles can accelerate up to the synchronization speed v_s and no vehicle enters or exits the artery at intersection j , delays d_1 and d_n are equal, as well as those of all vehicles belonging to this platoon.

With respect to traditional formulations of node delay, which consider only upstream delay, we include both upstream and downstream delay (Newell, 1989). Moreover, we obtain in such a way a simpler linear expression of total delay.

As shown in Figure 1, we exclude the transient phase of vehicle progression and we refer only to steady-state condition. So, the link model becomes trivial, while the main issue is represented by platoon re-combination at nodes, as explained in section 2.3.

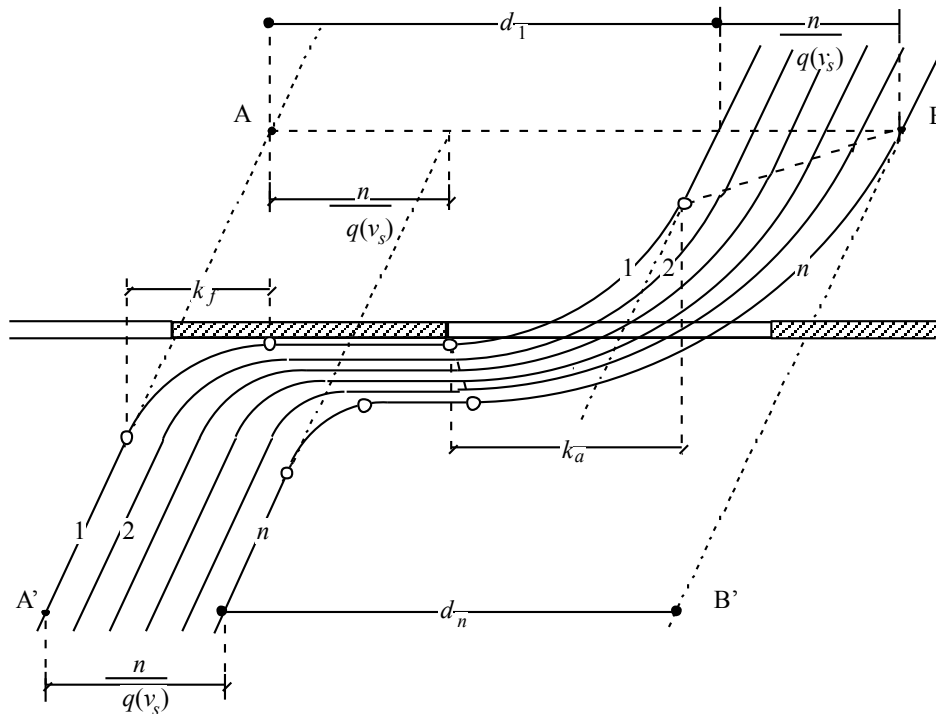


Figure 1. Vehicle trajectories assumed in the model for the delay at one node of a synchronized route.

Since we include the transient phases of motion in the effective red time, we obtain the following linear formulae for the delay at nodes, whose expressions depend on the arrival time and the time length of the platoon, the offset and red time of the signal, as well as the time needed to clear a queue, if any, at the end of red.

Case A: Platoon p arrives at node i after the start of red and before the queue (if any) at the end of red time has been cleared (*front-delayed platoon*, illustrated in Figure 2):

$$\mathcal{G}_i - \frac{r_i}{2} \leq t_{i,p} < \mathcal{G}_i + \frac{r_i}{2} + \tau_i \quad (2)$$

$$D_{i,p} = q(v_s)l_{i,p} \left(\mathcal{G}_i + \frac{r_i}{2} + \tau_i - t_{i,p} \right) \quad (3)$$

$$z_{i,p} = q(v_s)l_{i,p} \quad (4)$$

where:

\mathcal{G}_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 $q(v_s)$;

$q(v_s)$ is the traffic flow at the synchronization speed;

$t_{i,p}$ and $l_{i,p}$ are, respectively, the arrival time and the time length of platoon p at node i ;

$D_{i,p}$ and $z_{i,p}$ are, respectively, the total delay and the number of vehicles of platoon p stopped at node i .

The term between parentheses in the definition of the total delay represents the average delay per vehicle, d .

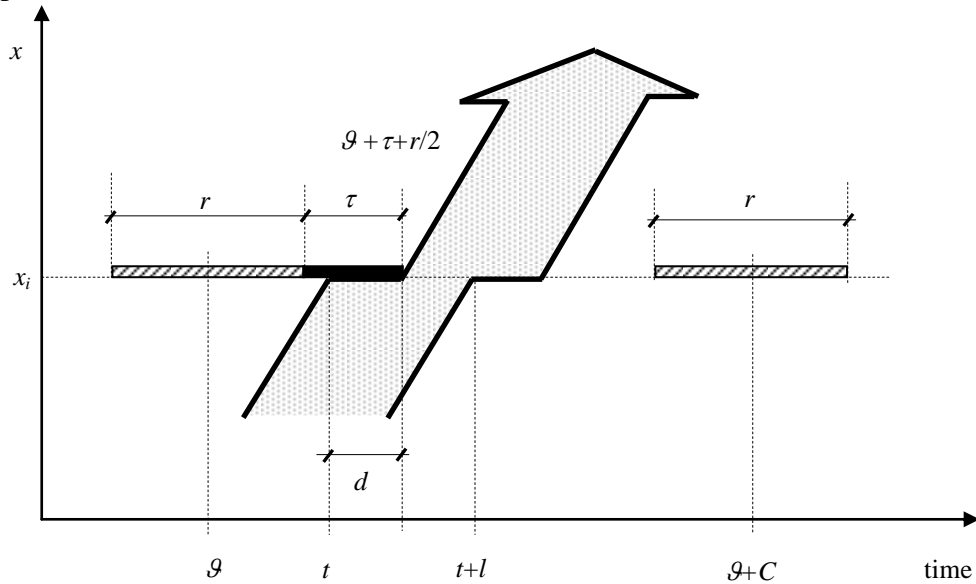


Figure 2. Delay d at one node for a front-delayed platoon (case A).

The condition that platoon p ends during the green time:

$$t_{i,p} + l_{i,p} < \mathcal{G}_i - \frac{r_i}{2} + C \quad (5)$$

is an obvious consequence of capacity condition, so it is not needed if we write capacity conditions explicitly.

The case of no queue at the end of red time at node i is a particular one, which belongs to case A: it is then $\tau=0$ and the condition is that platoon p arrives before the end of the red time.

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 (*rear-delayed platoon*, illustrated in Figure 3):

$$\mathcal{G}_i + \frac{r_i}{2} + \tau_i \leq t_{i,p} < \mathcal{G}_i + C - \frac{r_i}{2} \quad (6)$$

$$D_{i,p} = q(v_s) \left(t_{i,p} + l_{i,p} - \mathcal{G}_i - C + \frac{r_i}{2} \right) r_i \quad (7)$$

$$z_{i,p} = q(v_s) \left(t_{i,p} + l_{i,p} - \mathcal{G}_i - C + \frac{r_i}{2} \right) \quad (8)$$

where C is the cycle length at node i .

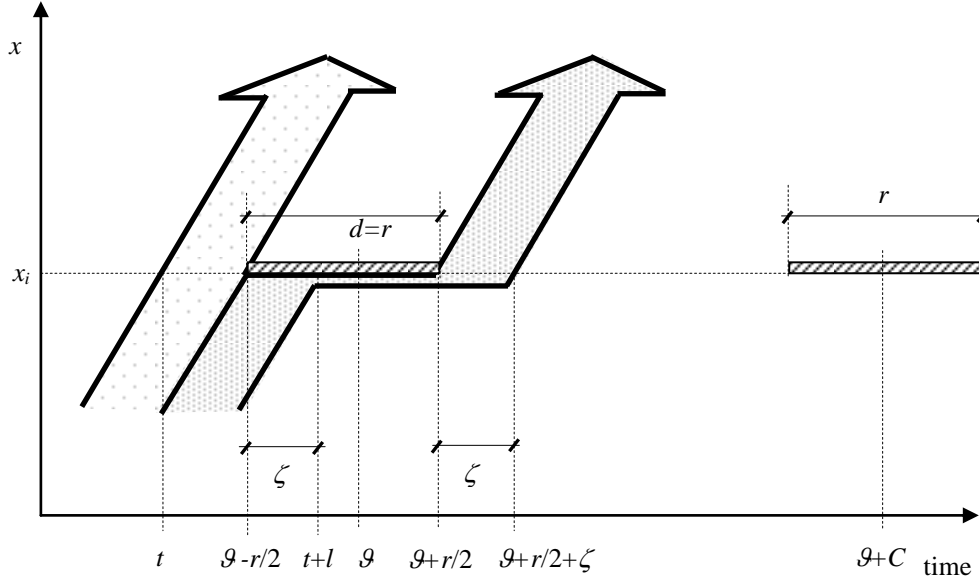


Figure 3. Delay d at one node and time interval ζ which stopped vehicles belong to for a rear-delayed platoon (case B).

The condition that platoon p ends before the queue clearance time τ is an obvious consequence of capacity condition, so it is not necessary:

$$\mathcal{G}_i + C - \frac{r_i}{2} < t_{i,p} + l_{i,p} \leq \mathcal{G}_i + C + \frac{r_i}{2} \quad (9)$$

Again, the case of no queue at node i at the end of red time is a particular case belonging to the condition above: in such a case it is $\tau_i = 0$ and the condition is that platoon p arrives after the end of the red time and ends during the red time.

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 (no-delayed platoon):

$$\mathcal{G}_i + \frac{r_i}{2} + \tau_i \leq t_{i,p} < \mathcal{G}_i + C - \frac{r_i}{2} \quad (10)$$

$$t_{i,p} + l_{i,p} \leq \mathcal{G}_i + C - \frac{r_i}{2} \quad (11)$$

$$D_{i,p} = 0 \quad (12)$$

$$z_{i,p} = 0 \quad (13)$$

Case C can also be obtained from both A and B cases, by adding the condition that delay is always non-negative.

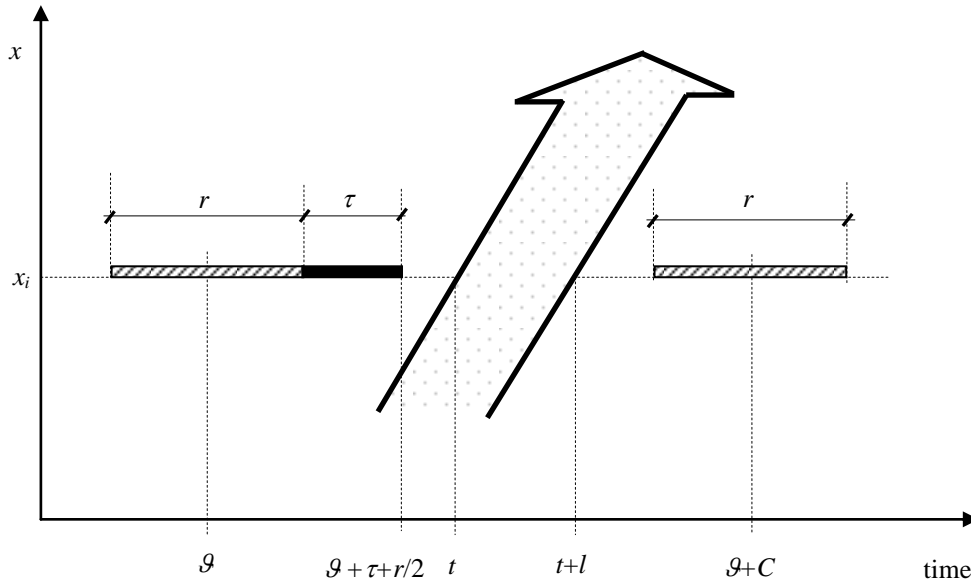


Figure 4. No-delayed platoon (case C).

Remark: The classification of one platoon is not independent to the arrival times of other platoons, which determine the queue clearance time, τ_i . Thus, delay at node i is a function of signal settings and traffic patterns at nodes $1, 2, \dots, i$.

2.3. Arterial delay model

The delay model has been developed specifically to assess synchronization strategies along signalized arteries. The logic of the algorithm is depicted in the flow chart in Figure 5.

Platoon classification explained in Section 2.2 is at the core of the arterial model, as it is needed not only to determine the average delay and the number of stopped vehicles, but also to determine the departure time and the time length of platoons, by taking into account as they combine together at nodes.

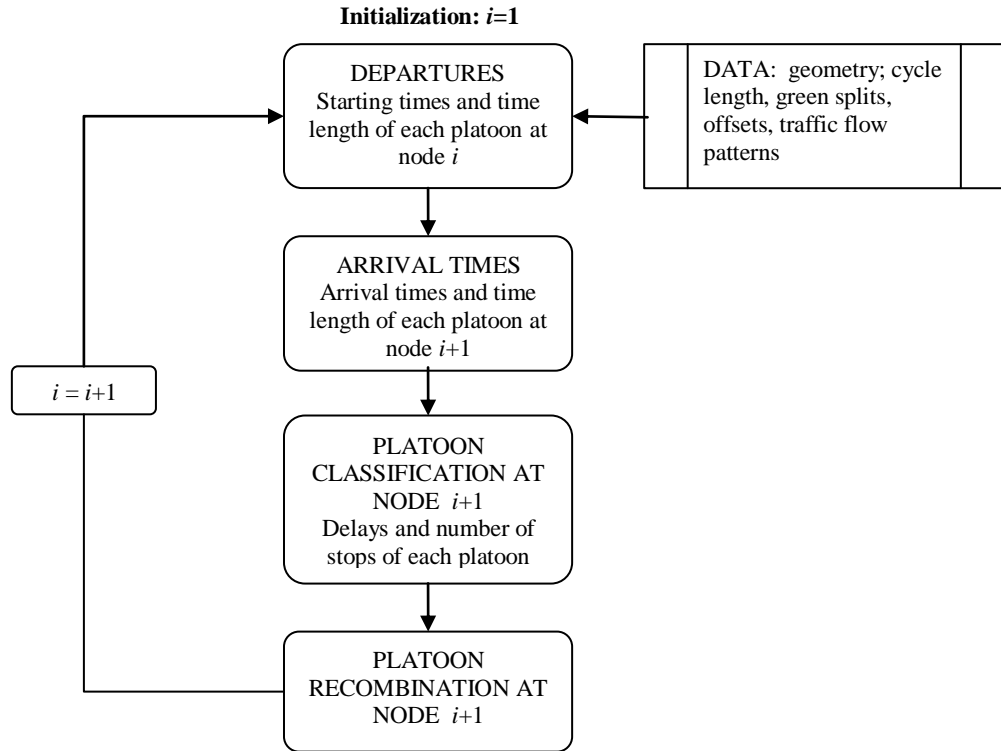


Figure 5. Flow chart of the algorithm applied to compute delay model at nodes of synchronized arteries.

The mechanism of platoon recombination at nodes is exemplified in Figure 6, where two platoons, A-type and B-type, arrive at the node i . The figure depicts also a third platoon of vehicles 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).

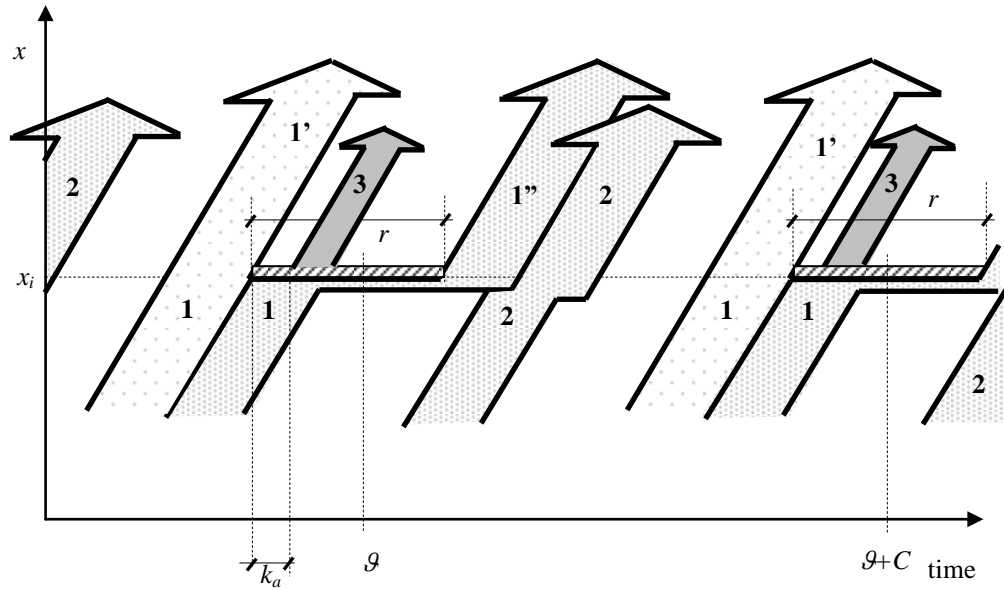


Figure 6. Example of platoon recombination at node i .

Since A-type platoon (denoted as 1 in the figure) 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.

The link module computes the arrival times and the time length of platoons at downstream intersection. The arrival time is determined by applying either the synchronization speed or an acceleration rate, accordingly to the assumptions introduced in section 2.1, and verifying if following platoons can catch up the preceding one. The time length is computed by subtracting the vehicles that exit the artery at the upstream node and assuming that all vehicles belonging to the platoon can accelerate, compressing then the platoon. Platoon progression and recombination along the links is illustrated by the example in Figure 7.

The first vehicle of platoon 1 travels at the synchronization speed v_s . Dashed line represents the trajectory of the last vehicle if no vehicle had got the artery and it had traveled at the synchronization speed; however, due to exiting vehicles, all vehicles within the platoon can travel at a higher speed, as indicated by the solid line for the last vehicle traveling at v'' . All vehicles of the entering platoon (numbered as 2 in the figure) travel at a speed $v' > v_s$ and may catch up the preceding platoon, depending on the link length and the value of v'' . This is the case of platoon 2 in figure. However, platoon 3 starts at the end of effective red time, travels at speed v' and the leading vehicle can not catch up the tail of platoon 2. Successive vehicles within the platoon can accelerate in order to refill the empty spaces left by exiting vehicles and such a condition is applied to compute the time length of the platoon at node $i+1$.

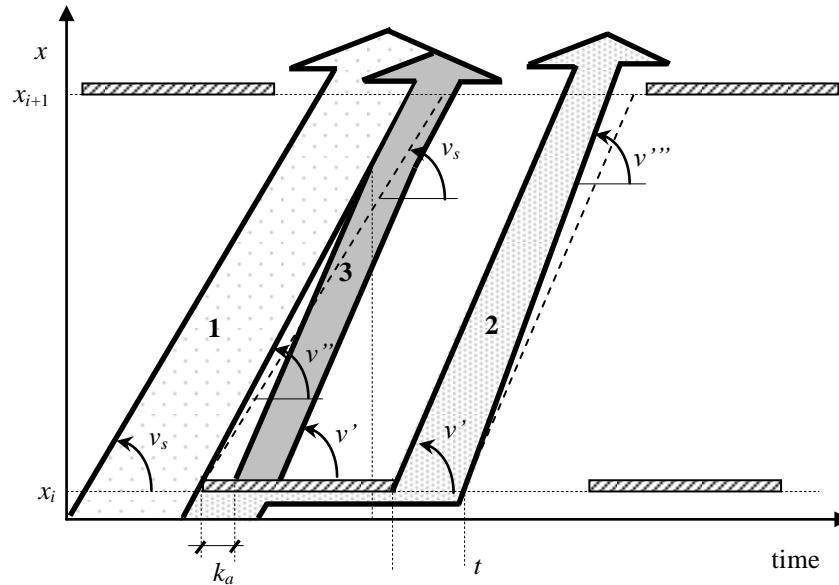


Figure 7. Example of platoon progression and recombination along a link.

The node delay module 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 can not be determined before all platoons have been analyzed, the delay computation requires an iterative procedure that classifies the different platoons progressively. It is worth noting that such a procedure involves few iterations, because the platoons can both catch up each other along the links and recombine together at nodes, when more platoons arrive during the red phase.

3. Signal synchronization strategies

The traditional approach to signal control assumes traffic pattern as given and signal parameters (cycle length, green splits and offsets) as design variables. Signal synchronization of two-way arteries can be applied by following two different approaches -maximal bandwidth and minimum delay-, although a solution procedure that applies the former problem to search for the solution of the latter one has been developed (Papola and Fusco, 1998). Specifically, it is well known that, given the synchronization speed and the vector of distances between nodes, the offsets that maximize the green bandwidth are univocally determined by the cycle length of the artery. Such a property of the maximal bandwidth problem has been exploited to facilitate the search for a sub-optimal solution of the minimum delay problem. Thus, a linear search of the sub-optimal cycle length is first carried out starting from the minimum cycle length for the artery and then a local search is performed starting from the offset vector corresponding to that cycle length.

If demand does not exceed capacity, the platoon progression model described in section 2 makes it possible a quick evaluation of the artery delay without involving any simulation. Nevertheless, the performances of the solutions obtained by applying the platoon progression model will be further assessed by dynamic traffic assignment.

Two-way synchronization as a complex non-convex problem usually requires heuristic procedures to compute the signal solution that minimize delays. The simple platoon model introduced here allows implementing instead a systematic investigation

of the space of design variables in order to individuate the relationship between signal settings and traffic flow.

In case of one-way synchronization, simple strategies can be envisioned for offset optimization.

Both one-way and two-way synchronization problems are illustrated in the following with reference to a real 6-node 2.6km long artery, composed by the streets Viale Regina Margherita and Viale Liegi, in the city of Rome.

3.1. *One-way synchronization*

We first tackle the one-way synchronization problem. One could expect that the average delay for one-way synchronized arteries should be quite nil, if offsets are adjusted accordingly to the travel time of the first vehicle of the platoon. However, due to entering and exiting vehicles, the platoon pattern might vary significantly along the artery and the strategy that synchronizes signals with the trajectory of the first vehicle may be even far from the optimum. Accordingly to the phenomenon of platoon recombination explained in section 2.3, we introduce two different strategies for one-way signal synchronization that aim at exploiting the platoon computation carried out by the platoon progression model. The simplest, Strategy A, consists of starting the red of each node just after the end of the primary platoon (that is, the platoon with the most number of vehicles). In the second strategy, Strategy B, the red is checked to start after the end of every platoon and the position giving the least delay is then selected.

Numerical tests were conducted by carrying out a systematic analysis of the optimal offsets on the abovementioned artery by assuming a one-way circulation in direction Viale Regina Margherita-Viale Liegi. The average traffic flow was taken as independent variable, ranging from 0.01 to 0.20 veh/s/lane. For each value of the average flow, ten different experiments have been performed by taking, in each of them, a different random vector of entering and exiting traffic. Green splits have been assumed as given, while 5 different values of the cycle length have been considered. Both strategies A and B have been applied in each case and corresponding average delays are reported in Figures 8 and 9, respectively. For low traffic volumes (0.1veh/s/lane), average delays range from 5s/veh to 10s/veh for strategy A and from 1s to 2s when adopting strategy B. For medium traffic volumes (0.20 veh/s/lane), strategy A provides delays ranging from 20s/veh to about 50s/veh, while strategy B can reduce delays as 3.5-6s/veh. Thus, the latter strategy, B, outperforms the former one, and the difference is striking, especially for large traffic flows. Such an occurrence highlights that the performances of the artery are heavily affected by the complex process of platoon re-combination at nodes, so that the strategy that favors the main platoon can be ineffective if it is stopped later, while secondary platoons can run without being delayed.

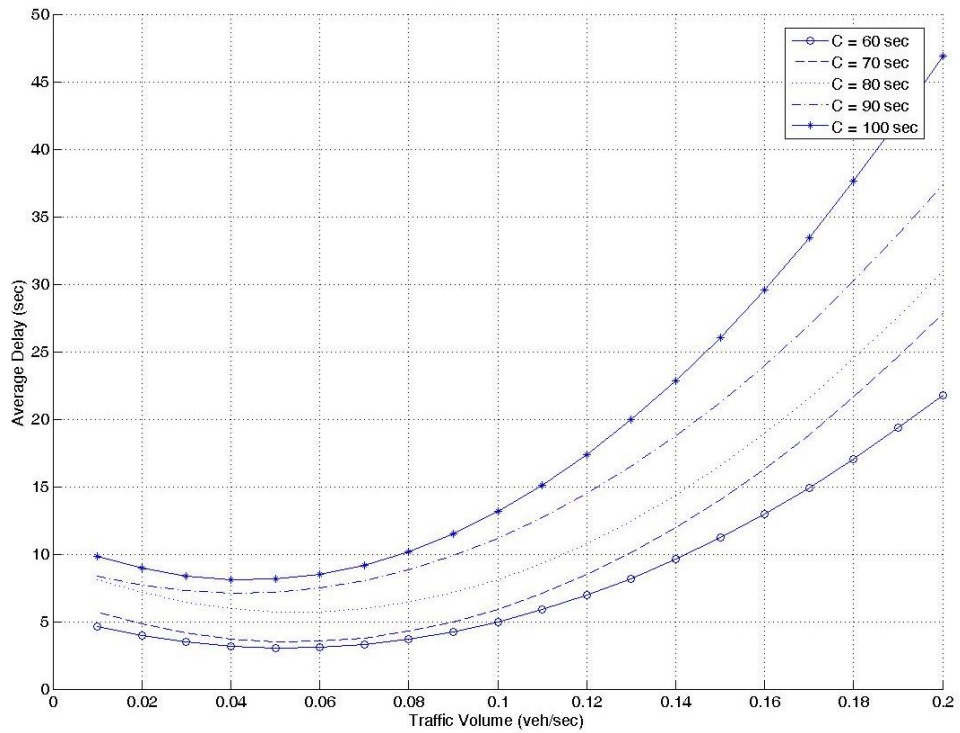


Figure 8. Relationship between average delay and traffic volume on Viale Regina Margherita-Viale Liegi by assuming one-way circulation for different cycle length and synchronization Strategy A: at each node the red starts just after the end of the primary platoon.

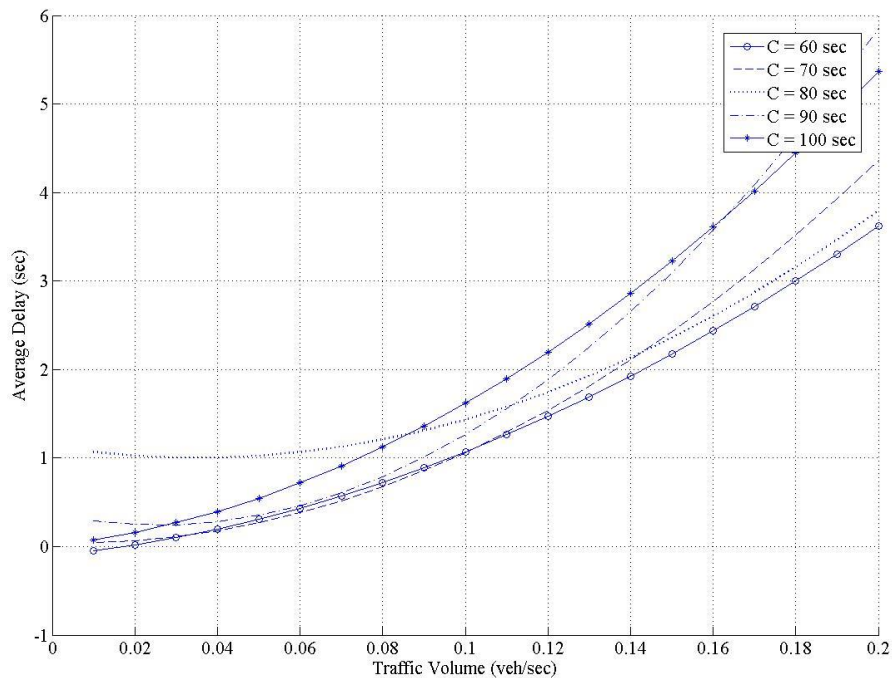


Figure 9. Relationship between average delay and traffic volume on Viale Regina Margherita-Viale Liegi by assuming one-way circulation for different cycle length and synchronization Strategy B: at each node the red can start just after the end of any platoon and the most suitable is selected.

3.2. Two-way synchronization

Then, we deal with the more general two-way synchronization problem. Analogous numerical experiments concerning the application of the platoon progression model have been carried out on the same artery considering both traffic directions.

Results of the synchronization method are illustrated in Fig.10, where the average delay is shown for 20 different random extractions of entering and exiting traffic.

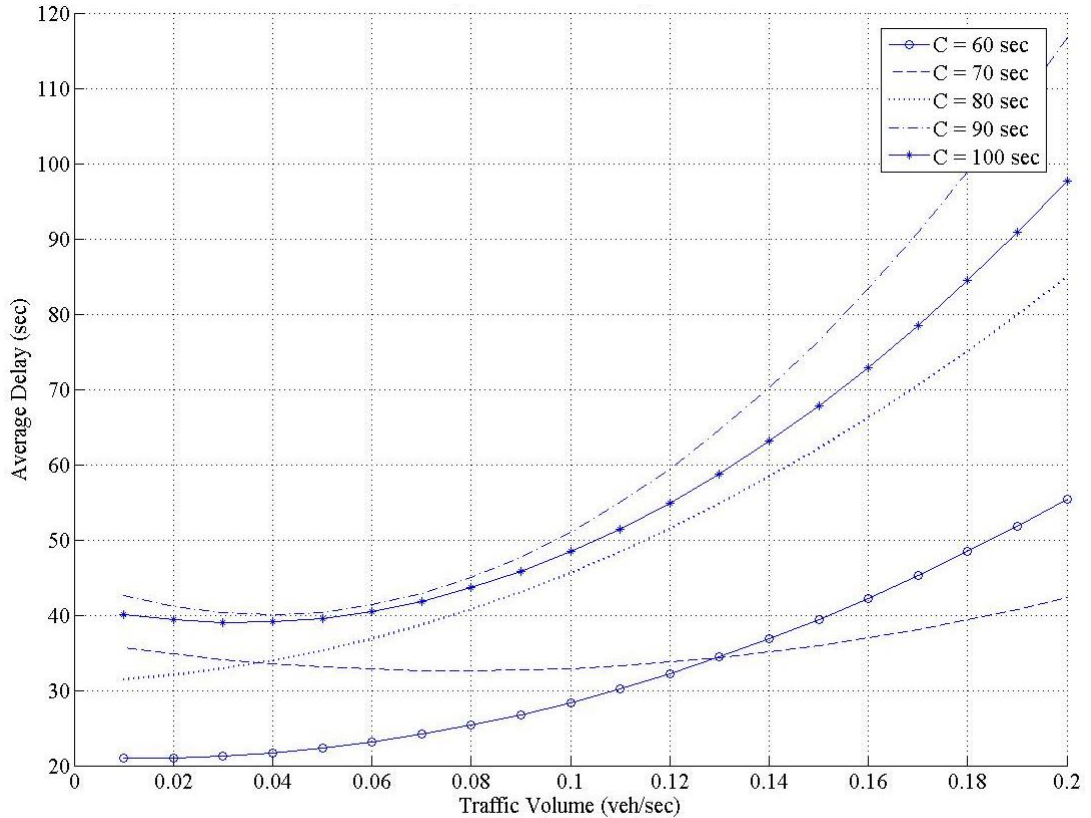


Figure 10. Relationship between average delay and traffic volume on the two-way artery Viale Regina Margherita-Viale Liegi for different values of cycle length.

For any given value of the cycle length, the average arterial delay is a continuous convex function of traffic flow. However, it is not a convex function with respect to cycle length: for higher values of flow (for example, 0.18veh/s), the lowest average delay is provided when $C=70$ s; higher values would be obtained if the cycle length were decreased at 60s as well as if it were increased at 80s or at 90s. However, if the cycle length were increased at 100s, the delay would decrease again, giving rise so to a third inversion of the sign of the function derivative. It is worth noticing also that, if the most appropriate cycle length is used for different values of flow, the synchronization solution is rather robust with respect to variations of flow. In fact, when the flow increases from 0.01veh/s to 0.20 veh/s the average delay increases only from 20s to 42s.

Further analyses concern the relationship between the objective function and the design variables for given traffic flows, as it occurs in usual signal setting problems. On this regard, actual traffic volumes observed in the peak-off period are considered.

In a first experiment, the common cycle length of the artery has been set equal to the maximal cycle length of the junctions. The green times have been adjusted consequently to keep the green splits unchanged. Thus, the offsets are the only control vector. In a

second experiment, also the cycle length has been varied from the minimum cycle for the most critical junction of the artery (namely, 32s) to its current value (108.5s). As before, the objective functions of the two problems are the maximal bandwidth and the minimum delay for the artery.

The corresponding values of maximum bandwidth and sub-optimal minimum delay offsets are reported in Table 1 and Table 2, respectively.

Table 1. Offsets of maximum bandwidth [s] for different values of cycle length.

Node N.	Cycle [s]								
	32	42	52	62	72	82	92	102	108.5
1	0	0	0	0	0	0	0	0	0
2	14.9	19.5	24.2	28.8	33.5	38.1	42.8	47.4	104.7
3	14.9	40.5	50.2	59.8	33.5	38.1	42.8	47.4	50.4
4	30.9	19.5	50.2	59.8	69.5	79.1	88.8	47.4	50.4
5	15.5	20.4	9.2	61.1	34.9	39.8	44.6	100.5	52.6
6	17.7	23.3	2.9	3.4	40.0	45.5	51.1	5.6	6.5

Table 2. Offsets of minimum delay [s] for different values of cycle length.

Node N.	Offset of minimum delay [s]								
	Cycle [s]								
	32	42	52	62	72	82	92	102	108.5
1	0	0	0	0	0	0	0	0	0
2	31.9	39.5	45.2	10.8	12.5	64.1	76.8	94.4	1.7
3	15.9	5.5	45.2	59.8	4.5	38.1	42.8	47.4	47.5
4	28.9	19.5	26.2	37.8	12.5	59.1	64.8	47.4	50.5
5	18.5	41.4	27.2	61.1	35.0	39.8	44.6	84.5	85.1
6	19.7	32.3	4.9	3.4	43.0	54.5	63.1	7.6	5.9

Figure 11 plots the value of delay at nodes along the artery for different values of the cycle length and the corresponding sub-optimal offsets, by assuming acceleration capabilities of vehicles and then allowing a platoon catching up the preceding one.

As expected, the delay function is non convex. The lowest value is obtained for a cycle length of 42s, while other local minima are obtained for the cycle lengths of 72s and 102s.

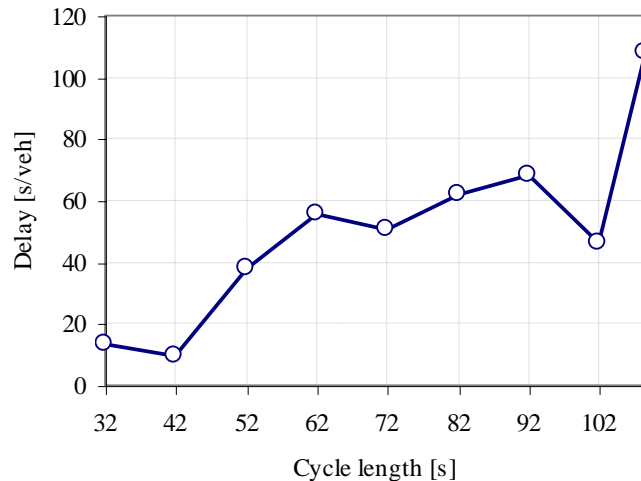


Figure 11. Estimation of node delay along the artery by the platoon progression model for different values of the cycle length.

4. Experiments on signal control strategies by applying different traffic models

4.1. Signal control and dynamic assignment problems

Dynamic traffic assignment models are the advanced modeling framework suited to simulate traffic patterns in congested urban networks, as they can both simulate the flow progression along links and reproduce the complex interaction between traffic flow and route choice behavior of users. In order to validate the results of the synchronization solution provided by the platoon model, a dynamic traffic assignment model is applied with a twofold goal. The first concerns the consistency between the platoon model and the mesoscopic models implemented in dynamic traffic assignment models; the second the impact that synchronization would induce on drivers' route choice and then on traffic patterns.

Several software packages for solving dynamic traffic assignment are now available. Two of the most popular and advanced (Dynasmart, 2004 and Dynameq, 2005) have been taken into consideration in this research and have been object of a systematic comparison.

Both have been applied to a selected area of the road network of Rome, having 51 centroids, 300 nodes, 870 links, 70 signalized junctions (18 under control), including the artery Viale Regina Margherita-Viale Liegi. Figure 12 shows the study network as displayed by the two software packages.

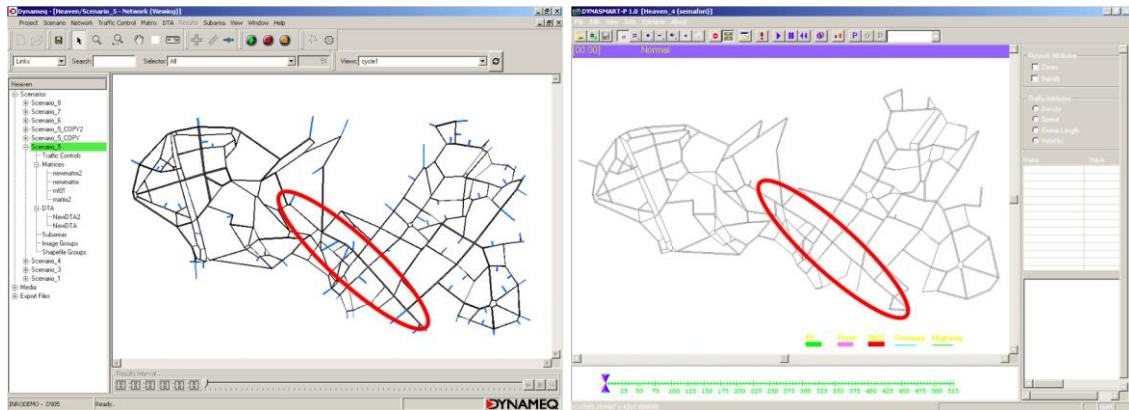


Figure 12. The study network in Dynameq (on the left) and Dynasmart (on the right). The red ellipse indicates the synchronized artery Viale Regina Margherita-Viale Liegi.

Both models require a time dependent origin – destination demand matrix which can be estimated using network observations such link flow counts, measured speeds (see Bera and Rao, 2011 for a review; Cipriani et al., 2011 for a dynamic model). Despite both procedures are simulation based, they differ on several points: the modeling approach of traffic flow (Dynameq assumes a fundamental triangular diagram, Dynasmart a modified Greenshield model); the route choice (two phases for Dynameq: a path generation phase, in which one new path at each iteration is added until the maximum predefined number of paths is reached, and a convergence phase in which no new paths are added; one phase for Dynasmart, which does not introduce any distinction between the generation phase and the convergence phase); the simulation process (Dynameq uses an event based procedure, Dynasmart a macroparticle simulation model); the convergence criterion (time based for Dynameq, flow based for Dynasmart).

Dynameq model exploits variants of gradient like directions and the method of successive averages (MSA) to determine pre-trip dynamic equilibrium path choices.

The path choices are modelled as decision variables governed by a user optimal principle where each driver seeks to minimize the used path travel time. All drivers have perfect access to information, which consists of the travel times on all paths (used and unused). The solution algorithm takes the form of an iterative procedure designed to converge to these conditions and consists of two main components:

1. A method to determine a new set of time-dependent path input flows, given the experienced path travel times at the previous iteration.
2. A method to determine the actual link flows and travel times that result from a given set of path inflow rates. This is referred to as the network loading component, which is carried out using an efficient event-based traffic simulation model. The model explicitly represents the operation of traffic signals and realistically captures traffic congestion phenomena such as the upstream spill-back of congestion from link to link.

Thus, Dynameq aims especially at providing a detailed representation of traffic flow by following a microsimulation approach. It reproduces the traffic behavior at junction approaches by an explicit lane changing model and resolves conflicts at nodes by applying a gap acceptance rule. It simulates pre-timed signal traffic control and ramp metering.

On the other hand, Dynasmart provides a simpler framework to model the traffic flow and aims rather at allowing simulating the impact of real-time strategies of traffic control and information systems (like actuated traffic signal, ramp metering, variable message signs and vehicle route guidance) on users' behavior.

Comparison of link traffic flows between a static assignment model (Emme/2) and dynamic assignment models shows not very dissimilar results ($R^2=0.69$), but, as expected, the static model provides higher values of link traffic flows. In fact the static model assumes that the whole trip demand is assigned within a steady-state simulation period, while dynamic models simulate the whole charging and discharging process of the network by complying with capacity constraint.

In a first experiment Dynameq was applied to simulate the artery by assuming a cycle length of 108.5 seconds (which better fits the current conditions) and the corresponding suboptimal offset vector (last column of Table 2).

Two issues are dealt with: one concerns the effectiveness of synchronization, taking into account the interaction between traffic control and drivers' route choice to the solution found; the other one regards the capability of such a simple model to estimate the average travel time along the artery.

As for the first issue, results reported in Table 3 show a significant reduction of delay on the artery (about 13%), which is even more important if we consider that, due to its improved performances, the artery attracts 13.8% more traffic. The total travel time on the whole network decreases as about 2%, although the study area is much wider than the influence area of the artery and, more important, the objective function of the synchronization algorithm accounts only the travel time of the artery.

Table 3. Offsets Comparison of arterial and network results pre and post synchronization.

	Current scenario	Synchronization	Difference
Average arterial travel time [s]	176.5	154.0	-12.7%
Average total arterial traveled distance [veh·km]*	41.4	47.1	+13.8%
Average total network travel time [veh·h]*	87.6	85.5	-2.4%

* Values referred to 5 minutes time intervals

As for the second issue, since signals have been set by assuming the traffic flows as given and the dynamic traffic assignment provided the equilibrium traffic flows corresponding to these signals, to validate the platoon progression model, the latter has been applied again by taking these equilibrium traffic flows as input.

Although the platoon progression model is based on a much simpler theory that assumes stationary and homogeneous traffic flow, the two models provide very similar results. As far as the two assumptions considered in the platoon progression model, namely the possibility or not that platoons can always catch-up each other, indicated as hypotheses b) and c) in section 2.1, the former assumption provided a better correspondence with the microsimulation performed by Dynameq, as shown in Figures 13 and 14 for the two directions, respectively.

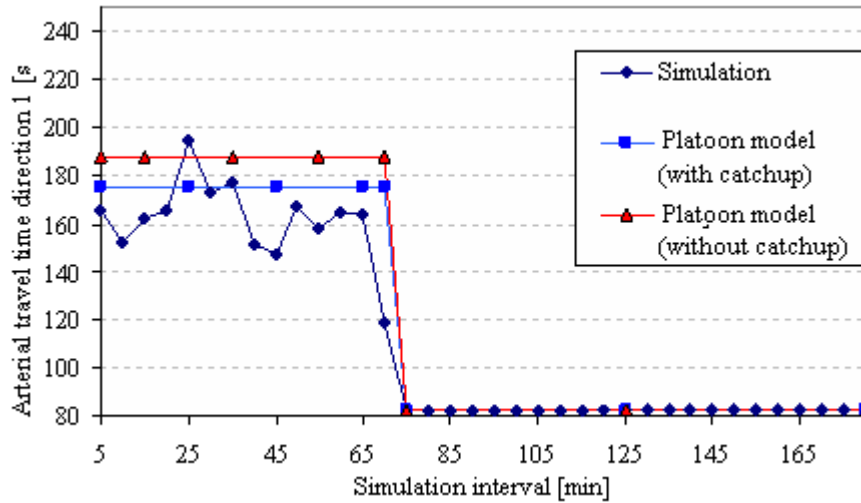


Figure 13. Comparison between simulation and platoon progression model (Arterial direction 1, Cycle length 108.5 s).

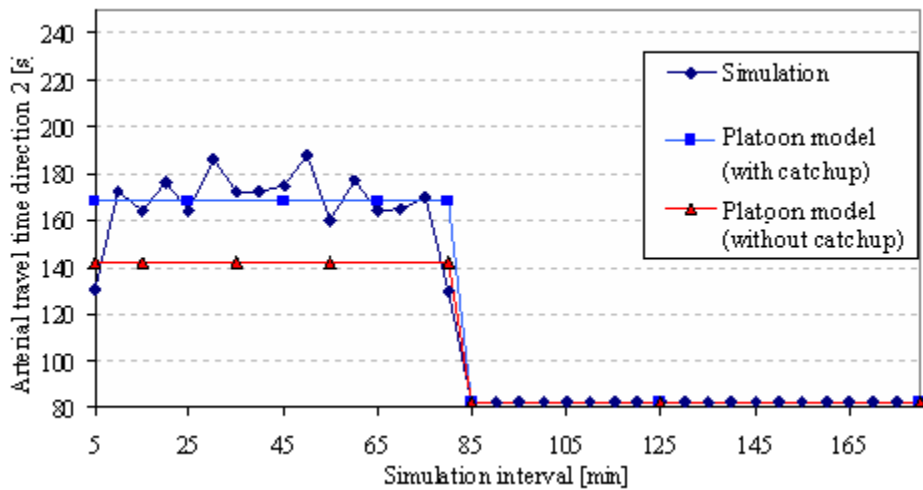


Figure 14. Comparison between simulation and platoon progression model (Arterial direction 2, Cycle length 108.5 s).

Then, experiments have been repeated by assuming the two local minima values for the cycle length that had been computed by applying the platoon progression model (namely, 42 s and 72 s).

Table 4. Comparison of arterial and network results pre and post synchronization (C=42s).

	Current scenario	Synchronization	Difference
Average arterial travel time [s]	176.5	153.8	-12.9%
Average total arterial traveled distance [veh·km]	41.4	59.9	+44.7%
Average total network travel time [veh·h]	87.6	100.1	+14.3%

Table 5. Comparison of arterial and network results pre and post synchronization (C=72s).

	Current scenario	Synchronization	Difference
Average arterial travel time [s]	176.5	148.8	-15.7%
Average total arterial traveled distance [veh·km]	41.4	52.6	+27.1%
Average total network travel time [veh·h]	87.6	88.6	+1.1%

Results, summarized in Tables 4 and 5, show similar values of delay reduction on the artery (about 13% and 16% for C=42s and C=72s, respectively), with an even higher increase of traffic with respect to the previous experiment.

However, a slight worsening affects the total network travel time, which increases as 14.3% for a cycle length of 42s and 1.1% for a cycle length of 72s (Table 4).

Thus, synchronization is very effective to improve the performances of the artery. Moreover, traffic patterns are very sensitive to improved signal settings, so that the artery attracts much higher traffic volumes. As signal settings affect also performances of transversal roads, arterial improvements do not imply a reduction of total network travel time. This is as more evident as closer the cycle length is to the minimum value that satisfies the capacity conditions. In this case, in fact, even small perturbations of traffic can heavily affect the average delay, especially on transversal roads.

The validation of platoon progression model for different values of cycle length (Figure 15) shows that the differences between the two models become larger when shorter values of cycle are used. In such cases, the green is long just enough to allow the traffic flow being served and even a small random increase of traffic produces a temporary over-saturation and a relevant increase of delay, which can not be predicted by a stationary model.

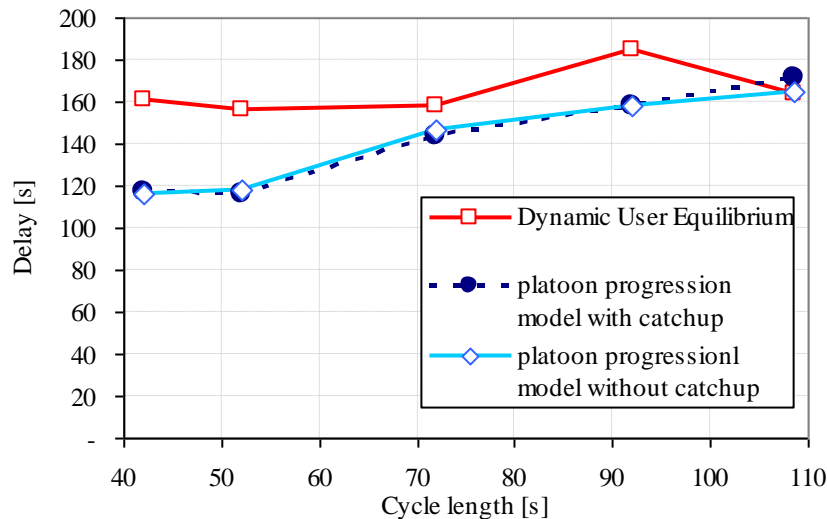


Figure 15. Delay on the arterial computed by different models for different values of cycle length

4.2. Some remarks on queue simulation in dynamic traffic assignment in over-saturated conditions

In traffic network simulation, modeling of queue progression and clearance is crucial to ensure a realistic and accurate simulation of the traffic congestion. As a matter of fact, spill back of queues at nodes may reduce the capacity of upstream intersections and may so provide even a large increase of the overall delay. Moreover, simulation of high congested networks by dynamic traffic models can often lead to gridlock conditions that block the simulation. Because of the relevance of gridlock on the dynamic assignment problem, it has been object of a more detailed study, addressed to analyze its starting point and its propagation across the network.

For this purpose, peak-hour conditions having a total hourly demand of about 31,000 trips with a time-varying profile have been simulated by applying both dynamic user equilibrium assignment models introduced in Section 4.1.

It has been observed that gridlock starts when a queue at one node blocks the traffic flow on a transversal link. The total block of traffic characterizing a gridlock condition occurs when all the links belonging to a circuit are saturated by a queue: in this case, dynamic network traffic models predict that the outflow is zero, so that, all links belonging to a circuit, each of them blocks the flow from the upstream link and the queue can not be dissipated.

To focus on a specific critical condition for gridlock starting, we analyze in detail the queue spilling back along one of the main arteries of the study area in direction of the city center (Via Nomentana, in Figure 16) in the time interval between the 20th and the 80th minute of simulation.

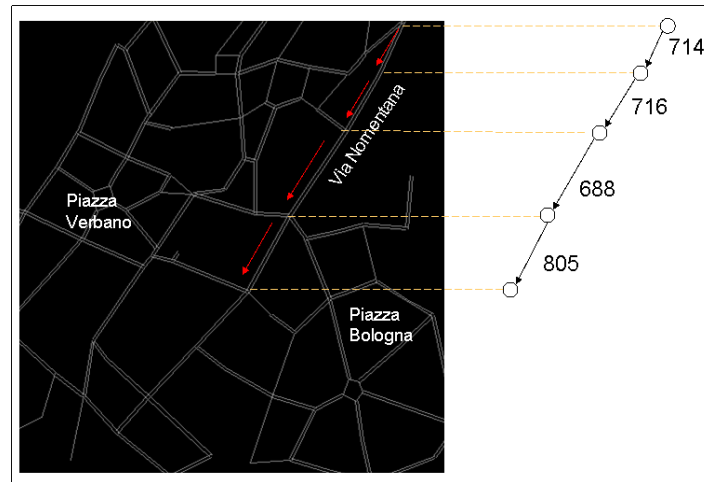


Figure 16. Links of Via Nomentana.

Values of occupancy in Figure 17 display how the queue starts around the 25-th minute from downstream link (identified by number 805 in figure) and then spills back to upstream links, reaching the last one (identified by number 714 in figure) after 10 minutes. At the 70-th minute, all blocked vehicles on the downstream link starts to move and the queue is partially cleared at the end of simulation.

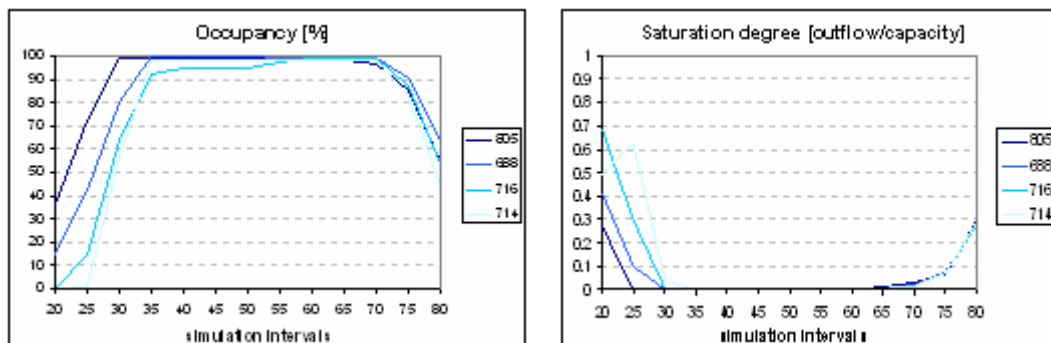


Figure 17. Occupancy of links of Via Nomentana as computed by Dynasmart.

Unlike in static traffic assignment, link saturation does not depend only on the flow entering the link, which is indeed only 25% of its saturation flow, but depends on the intersection at the end of the downstream link (picture on the left in Figure 17). Spill back and dissipation of queues across the network is displayed in Figure 18. It highlights that the queue on Via Nomentana is induced by the queue on the transversal link (Viale Gorizia), which blocks the outflow from Via Nomentana (picture on the left in the Figure).



Figure 18. Queue movement across the network as computed by Dynasmart in three different consecutive time instants (from left to right).

Similar conditions occur on the parallel artery directed to the city center (Corso Trieste), as well as on another transversal artery (Via di Santa Costanza), which connects Corso Trieste and Via Nomentana. Such a situation is critical for a gridlock condition (picture at the center of Figure 18).

Anyway, in the example shown, the queue on Corso Trieste does not spill back up to Via Nomentana, so that the gridlock condition is not attained and the queue can finally be cleared.

Picture on the right of Figure 18 illustrates also a definite gridlock condition occurring in Piazza Verbano, where the links component of the roundabout are not long enough to allocate the queues fed by the upstream roads. After the gridlock is reached, queues can not be cleared and vehicles involved in it cannot reach their destination at the end of the simulation.

Accurate calibration of the most important parameters of the model, as link storage capacity and critical speed, is then required to properly simulate usual recurrent congestion conditions when temporary over-saturation occurs and even long and multi-branched queues spill back across the network but are always dissipated as the demand flow decreases.

Actually, dynamic traffic models are conceived to simulate the congestion mechanism and can reproduce stopping and queuing phenomena, but cannot reproduce the subsequent phase of traffic re-starting after downstream conditioning has been removed. This is true for all dynamic traffic models, starting from the well-known car following model (Rothery, 1998) that reproduces drivers behavior along a link, to the most advanced dynamic network models analyzed here.

To reproduce the phenomenon of slow queue movement and allow outflow from saturated links, a minimum speed corresponding to jam density has been introduced in Dynasmart.

However, Dynameq applies an adaptive gridlock prevention algorithm that permits to stop the vehicles on a link when they are going to feed a potential gridlock situation. In the case under study, the link 805 is recognized as a potential source for gridlock conditions, as it reaches a critical value of the occupancy rate. Thus, the outflow from the upstream link (indicated as 688) is reduced and is controlled until critical conditions are definitely disappeared (picture on the left in Figure 19). Picture on the right shows how the occupancy of link 688 is still high until the risk of a gridlock decreases (after the 65th minute).

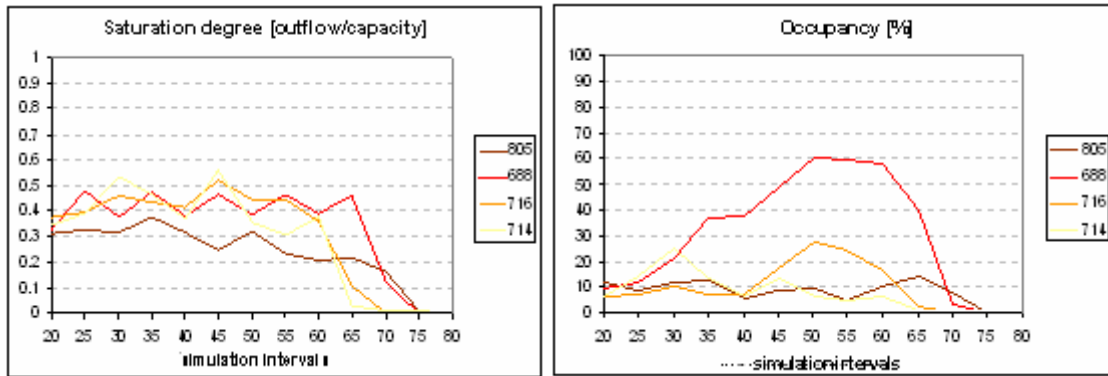


Figure 19. Outflow and occupancy of different links of Via Nomentana as computed by Dynameq.

The analyses conducted confirm that dynamic traffic assignment models can capture the spreading and clearance of congestion on road networks, as confirmed also by Figure 20, which highlights the good correspondence between simulated and observed saturation degrees on links 805 and 688.

The main problems experienced in practical applications to real networks arise from calibration and, more specifically, from the need of a fine tuning of link jam density and saturation flow to properly reproduce the gridlock phenomenon. This is especially true on narrow mesh road networks, as in many European historical towns.

However, to authors' knowledge, no model has yet been developed to describe the behavioral mechanism behind the dissipation of multi-branching queues on a road network.

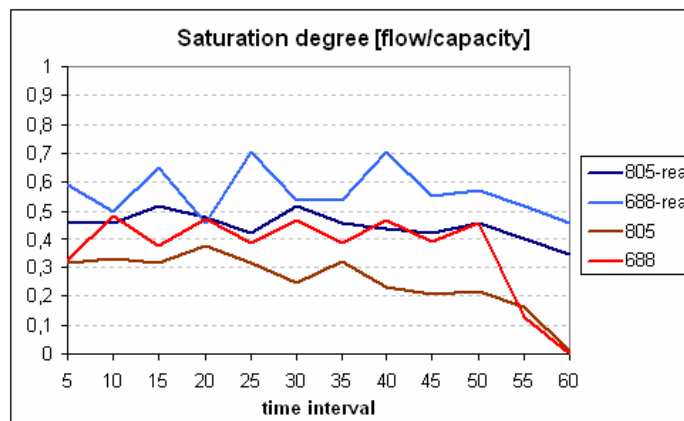


Figure 20. Observed and simulated degree of saturation of different links of Via Nomentana as computed by Dynameq.

5. Conclusions and further developments

Main results of a research project on interaction between signal settings and traffic flow patterns on road networks have been presented.

Different approaches to model traffic flow have been introduced and compared: the platoon progression model on a synchronized artery; a generalization of the cell

transmission model; a microsimulation queuing model; two dynamic traffic assignment models.

In numerical applications to a real-size artery, we observed a good correspondence between the platoon progression model and dynamic traffic simulation models, if signals are far from saturation. Non-convexity of the minimum delay synchronization problem does not guarantee obtaining the global optimal solution; nevertheless, the objective function seems to be rather robust with respect to flow changes, so that travel time improvement provided by signal synchronization on a main artery may induce more drivers to use it without any significant increase of delay on it and, on the contrary, with a decrease of delay on other roads of the network.

Numerical tests on a real-size network highlighted that the gridlock phenomenon is very relevant to simulate the road network under heavy congested conditions. Hence, more research efforts should be undertaken to develop a model that properly reproduce the dissipation of multi-branched queues on the network.

As far as signal control, we introduced a synchronization algorithm based on the platoon progression model, which revealed to be very effective in reducing arterial travel times. Current research on signal control is focusing on both arterial synchronization and real-time distributed control. The dynamic traffic control concerns a Linear-Quadratic regulator designed to keep signals settings and traffic flows stably near a desired state, namely the solution of the global optimization of signal settings problem.

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