STRATEGIES FOR SIGNAL SETTINGS AND DYNAMIC TRAFFIC MODELLING

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1. Introduction

The paper describes the objectives, the methodology and the preliminary results of the research project "Interaction between signal settings and traffic flow patterns on road networks", granted by the Italian Ministry of University and Research with the Fund for Investments on Basic Research (FIRB). The project joins three research units, belonging respectively to the University of Rome "La Sapienza", the University "Roma Tre" and the Institute for Information System Analysis (IASI) of the Italian National Council of Research.

The object of the research is to develop a general procedure to study, model and solve the problem of optimal road network signal settings, by taking into account the interaction between signal control systems and traffic flow patterns. 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 (*Cfr.* [3] and [19]).

The global optimal signal settings on a road network is a complex problem that involves dynamic traffic patterns, users' route choice and real-time application of suitable control strategies. With several noticeable exceptions (*Cfr.* [13], [18], [1] and [2]), 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 (*Cfr.* [5]).

In order to investigate real-time applications, the research project aims at extending the static modeling framework usually adopted in the scientific literature to apply dynamic traffic assignment models and deal with both coordinated arteries and traffic-flow responsive signal settings.

The study is being developed focusing on the following topics:

- Modelling of traffic flow along coordinated traffic networks and real-time applications of synchronization strategies;
- Advanced models and methods for signal settings and traffic control.

2. A macroscopic model for the estimation of queues at signalized intersection based on traffic counts

Traffic control based on logic programming has recently appeared. The method adopted in this paper, described in [9], [10] and [11], is one of the first models and applications of this type. It is an adaptive method actuated by vehicles that adopts logic programming to model and solve the decision problems associated with traffic control. Such a method can be applied with success to urban intersections with high levels of traffic where many different and unpredictable events contribute to large fluctuations in the number of vehicles that use the intersection.

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The logic programming methods based on vehicle counts make it possible to design the traffic control strategies with a high degree of simplicity and flexibility. The system makes use of a very efficient logic programming solver, the Leibniz System [20], that is capable of generating fast solution algorithms for the decision problems associated with traffic signal setting.

A very effective input for the above logic controller would be the queue lengths at each approach of the intersection. However, the only available data are often the measures of flows and occupancies at given road sections obtained with loop detectors; in this case, it would be desirable to pre-process these data in order to obtain queue lengths. This can be achieved by means of mathematical traffic flow models; in particular, a suitable macroscopic model based on the simplified theory of kinematic waves by Newell [14] was developed to estimate the queue length of each stream at a given intersection, as a function of vehicles counts taken at an upstream section. Queue lengths at each instant, in turn, are fed into the logic programming model in order to apply the control strategy.

The model presented here is conceived for a real time estimation of the vehicle queue at each approach of signalized road intersections. The queue is estimated based on the signal settings and on vehicle counts taken on a give upstream section of each approach; thus, the model requires input data easily available from traditional loop detectors. The model adopts a macroscopic representation of traffic and it is described in the following.

The generic approach of a given intersection is represented by a homogeneous flow channel, named segment, with initial section corresponding to the loop detector, and final section corresponding to the stop line at the intersection. The following notation is adopted:

- $F(\tau)$ cumulative inflow at time τ, that is the number of vehicles that entered the segment from the beginning of the analysis period until τ;
- $\eta(\tau)$ maximum cumulative outflow at time τ, that is the maximum number of vehicles that could exit the segment from the beginning of the analysis period until τ, if no signal was present at the end of the segment;
- $E(\tau)$ actual cumulative outflow at time τ, that is the actual number of vehicles that exit the segment from the beginning of the analysis period until τ, taking into account the signal at the end of the segment;
- $e(\tau)$ actual outflow at time τ; by definition, $e(\tau) = \mathrm{d}E(\tau)/\mathrm{d}\tau$;
- L length of the segment;
- V free-flow speed on the segment;
- W speed of the kinematic wave propagating hypercritic flow states;
- Q physical capacity of the segment;
- K_J maximum vehicular density of the segment;
- $g(\tau)$ signal state at time τ with the respect to the segment ($g(\tau) = 0$ or 1, namely: red or green).

The flow states along the segment are determined on the basis of the simplified theory of kinematic waves, assuming the concave fundamental diagram depicted in Figure 1, expressing the relation between the vehicular flow $q(x,\tau)$, density $k(x,\tau)$ and speed $v(x,\tau)$ at a given section x of the segment and instant τ.

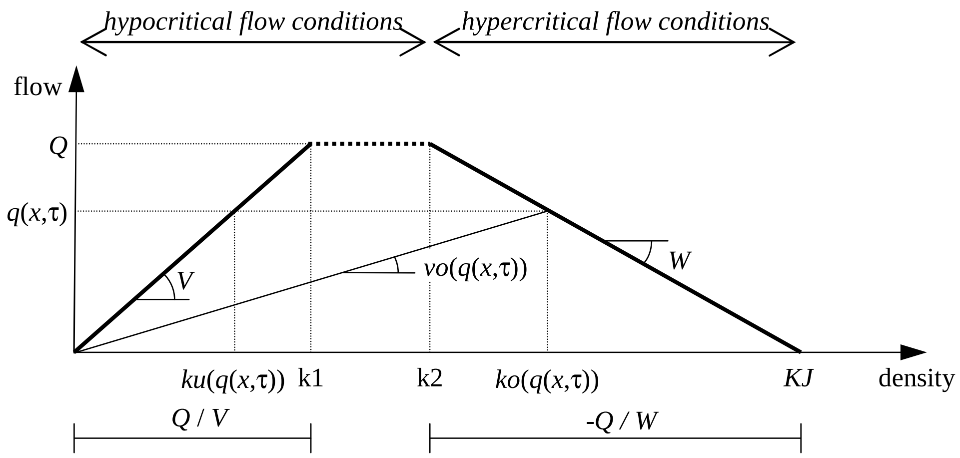

Figure 1. The adopted fundamental diagram, expressing the relation among vehicular flow, speed and density along the segment.

With reference to Figure 1, it is assumed that $k_2 \geq k_1$, implying the following relation among the above parameters:

$$KJ \geq Q \cdot \left(\frac{1}{V} - \frac{1}{W} \right)$$

Based on the fundamental diagram, it is possible to identify two families of flow states:

- *hypocritical flow conditions*, corresponding to uncongested or slightly congested traffic; under this conditions, if vehicular density increases, then the vehicular flow increases also;
- *hypercritical flow conditions*, corresponding to heavy congested traffic, where queues and "stop and go" phenomena occur; under this conditions, if vehicular density increases, then the vehicular flow decreases;

Then, $k_o(q(x,\tau))$ and $v_o(q(x,\tau))$ express the density and the speed as functions of the flow in presence of hypercritical flow conditions, while $k_u(q(x,\tau))$ and $v_u(q(x,\tau))$ express the density and the speed as functions of the flow in presence of hypocritical flow conditions. To be noticed that, in this particular case, $v_u(q(x,\tau)) = V$.

It is assumed that the period of analysis $(0, T]$ is divided into I time intervals identified by the sequence of instants $\boldsymbol{\tau} = \{\tau^0, \dots, \tau^i, \dots, \tau^I\}$, with $\tau^i < \tau^j$ for any $0 \leq i < j \leq I$, $\tau^0 = 0$, $\tau^I = T$. The segment at time τ^0 is assumed to be empty.
In the following, the generic temporal profile $x(\tau)$ of the cumulative flows and of the signal state introduced above are approximated, respectively, through a piecewise linear and a piecewise constant function, defined by the values $x^i = x(\tau^i)$ taken at each instant $\tau^i \in \boldsymbol{\tau}$. Under this assumption, for $\tau \in (\tau^{i-1}, \tau^i]$, with $0 < i \leq \mathrm{I}$, in the two cases we have, respectively:

$$x(\tau) = x^{i-1} + (\tau - \tau^{i-1}) \cdot (x^i - x^{i-1}) / (\tau^i - \tau^{i-1}), \qquad (1)$$

$$x(\tau) = x^i. \qquad (2)$$

The model is structured as follows:
For each time interval $\tau^i \in \boldsymbol{\tau}$:

1. Determine F^i as the number of users that crossed the magnetic loop from the beginning of the analysis period until τ^i;
2. Calculate η^i. From the First in First Out rule [4], it is equal to the number of users that entered the segment at a previous instant; the latter is determined by the hypocritical travel time, which, for the fundamental diagram adopted, is constant and equal to the free-flow travel time. Then, we have:

$$\eta^i = F(\tau^i - L / V) \,, \tag{3}$$

where the cumulative inflow a time $\tau^i - L / V$ can be easily determined based on (1).

3. Calculate E^i, which is less or equal than η^i due to the presence of the signal. In fact, during the red phase, the outflow is null, thus the cumulative outflow remains constant and equal to the value at the beginning of the red phase, while a queue of vehicles grows on the segment; during the green phase, the outflow is equal to the segment physical capacity until the queue vanishes, and is equal to the flow arriving at the intersection afterwards; then, Based on the "Newell-Luke minimum principle" ([6]; [14]) – stating that, when more than one kinematic wave reaches a point at a same time, the flow state yielding the minimum cumulative flow dominates the others – the actual cumulative outflow is determined as:

   $$E^i = \min\{ \eta^i \,;\, E^{i-1} + Q \cdot g^i \cdot (\tau^i - \tau^{i-1})\}$$

4. Calculate the outflow $e(\tau)$ during time interval $(\tau^{i-1}, \tau^i]$, which, based on its definition and on (1), it is piece-wise constant over the values $e^i = e(\tau^i)$ taken at each instant $\tau^i \in \boldsymbol{\tau}$, where:

   $$e^i = (E^i - E^{i-1}) / (\tau^i - \tau^{i-1})$$

5. Calculate, the effect that the queue generated on the final section produces on the initial section. Based on the simplified theory of kinematic waves specified for the adopted fundamental diagram, we have:

   $$u(\tau^i) = \tau^i - L / W$$

   $$G(u(\tau^i)) = E^i + L \cdot e^i \cdot K_J \,,$$

   where $u(t^i)$ is the time when a queue generated on the final section at time τ^i may reach its initial section, while $G(u(\tau^i))$ is the maximum number of vehicles that could actually enter the segment until time $u(\tau^i)$ respecting its storage capacity. Note that $u(\tau^i) > \tau^i$, because W is always negative.

6. Calculate the number N^i of vehicles on the segment at time τ^i:

   $$N^i = F(\tau^i) - E(\tau^i)$$

7. Check if at time τ^i the queue reached the initial section, which is true if $G(u^i)) \leq F(u^i)$, and calculate the approximate queue length QL^i at time τ^i, which is:

   $$QL^i = \begin{cases} (F^i - E^i)/(G(\tau^i) - E^i) \cdot L & \text{if } E^i < \eta^i \\ 0 & \text{if } E^i = \eta^i \end{cases}$$

The macroscopic queuing model has been tested on a real intersection in the town of Rome and the results showed a very good match between observed and predicted values of queue length.

2. Modeling of traffic flow along coordinated traffic networks and real-time applications of synchronization strategies

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 [15]. 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.

A different approach has been introduced by [16] and generalized by [17], who proposed an analytical model that relates maximal bandwidth solutions and delays at nodes. The great advantage of this model is that it makes it provides a closed form expression of delay along coordinated arteries, which is rigorous in the case of uniform platoon and minimum cycle length and approximate in more general cases. Thus, starting from the maximal bandwidth solution, it is possible to apply the analytical model to assess different possible synchronization strategies very quickly without involving any simulation.

The model is here extended to apply different hypotheses of drivers' behavior. Such hypotheses concern the capability of drivers to accelerate and catch up the tail of a preceding platoon, if any. Specifically, the following assumptions have been introduced: a) all vehicles follow the same trajectory and, after having been stopped at a signal, accelerate at a given rate until they reach a given cruise speed; b) all vehicles can accelerate along a link and catch up the previous platoon; c) all vehicles can accelerate up to a given maximal acceleration rate, so that they catch up the previous platoon only if the link is long enough.

As the analytical model assumes steady-state uniform and homogeneous traffic conditions, it provides only a rough approximation of real traffic performances when dynamic conditions become relevant. On this regard, we also extend the static synchronization method to a dynamic context by applying a modified formulation of the well-known cell transmission model [6], by introducing the following changes:

- in less than critical conditions, vehicles can move forwards by a generic quantity, dependent on the traffic density on the link;
- capability of simulating even complex signalized intersections;
- apply dynamic shortest paths and follow different OD pairs in the network loading process.

The great advantage of the application of cell transmission model is in its capability to evaluate the spatial progression of queues, which is not considered by the analytical model, as it only computes the queue clearance time. If traffic demand significantly changes in time, the progression of queues at signals becomes a crucial issue and requires quick modifications of traffic plans.

Preliminary tests on a real traffic artery in Roma confirmed the expectations that the two models provide consistent results, when similar assumptions on stationary demand are introduced, as they are both based on the macroscopic traffic flow approach (*Cfr.* [12]).

Moreover, different synchronization schemes have been tested and simulated by applying two different dynamic traffic assignments (namely, Dynasmart [8] and Dynameq [7]) in order to verify the travel time estimates of the analytical model as well as to assess the impact of the arterial synchronization on users' route choice.

Two relevant issues have been highlighted.

Firstly, a proper synchronization scheme can improve not only the travel time along a synchronized artery, but can also exploit the arterial capacity better than uncoordinated signal settings. Thus, it can attract traffic from alternative routes and improve so the overall network performances. In some experiments based on real traffic data, we simulated a specific area of the road network of Roma, having 51 centroids, 300 nodes, 870 links, and 70 signalized junctions. Within this area, a 6-node artery was synchronized by applying the method provided by [24]. Results obtained show (see Table 1) a significant reduction of the travel time along the artery (about -13%), which is even more important if we consider that, due to its improved performances, the artery attracts about 14% 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 1. Effects of signal synchronization on arterial and network performances.

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

Secondly, a critical issue in dynamic modeling of heavily congested networks is the spillback of queues, which may produce the gridlock of the network. If this occurs, the outflow decays toward an irreversible jam state. In the reality, temporary oversaturation of heavy congested networks is usually observed. Anyway, the gridlock is never irreversible, as drivers modify their usual behavior by acting in cooperative way or even violating any circulation rule, in order to restart the traffic. Thus, additional models should be introduced in dynamic traffic modeling to simulate drivers' behavior in such gridlock conditions. The lack of empirical observations does not allow designing realistic models and it is now possible only to introduce corrective algorithms that, with the aim of preventing the gridlock, apply fictitious control measures that temporary reduce the outflow of links upstream of potential gridlocks. It is observed that the cell transmission model, being a deterministic macroscopic model, is less sensitive to risks of gridlock than simulation based dynamic assignment models. Moreover, the computation time required by the cell transmission models is so short that it is compatible with on line applications.

Therefore, we aim at extending our off-line experiments to a quasi-dynamic control for signal synchronization. In this envisioned framework, the analytical model is applied to generate medium-term synchronization schemes on the basis of steady-state assumptions. The cell transmission model receives data from traffic detectors and is applied to simulate the performances of the synchronization scheme in a rolling horizon approach. Simulation results are then exploited to apply simple decision rules to both determine the optimal updating of signal schemes and to provide local adjustments of traffic plans to better accommodate traffic progression. Such a local real-time adjustment of signal settings becomes crucial when the queue at a signal is going to saturate the link storage capacity and then reduce the capacity of upstream links. As the extended cell transmission model is specifically devised to quickly estimate queue progression along the network, it can be effectively applied on-line.

3. Conclusions

In the paper we present the results of an ongoing research on the interaction between signal settings and traffic flow patterns on road networks. The main focus of the paper is on dynamic modeling requirements for on-line signal network control. As far as the local control, a macroscopic queue model for the estimation of queues at signalized intersection based on traffic counts is introduced and tested on two signalized intersections in Roma, by obtaining a very good match between observed and estimated values. As far as network control, a minimum delay synchronization strategy based on approximate travel time estimates provided by an analytical delay model is introduced and applied to a real road network in Roma. Performances are assessed by different dynamic traffic assignment models (Dynasmart and Dynameq) as well as by a specific extension of the well-known cell transmission model developed in the research project. Results provided by the cell transmission model are consistent with those predicted by the analytical model. We aim at extending our off-line experiments to and apply the two models on-line. In fact, the cell transmission model easily and quickly supplies dynamic estimates of queue progression and allows real time signal settings adjustments in order to avoid spillback of queues, which demonstrated to be the most critical issue affecting traffic performances.

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