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Signal setting optimization on urban road transport networks: The case of emergency evacuation

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A B S T R A C T

Traffic signal setting is an important element in traffic planning of urban road networks in ordinary conditions and/or in emergency conditions. As traffic signal setting affects user behaviour mainly at the path choice dimension, this dependence has to be studied by means of assignment models. We thus present a system of models and procedures for signal setting optimization with assignment of travel demand to a congested road transport network. Two interacting procedures are developed to solve the system of models: (i) an optimization procedure to obtain an optimal configuration of signal setting parameters and (ii) an assignment procedure, incorporating a path choice model with explicit path enumeration and a flow propagation model, to capture the effects of signal setting configuration on user path choice behaviour.

The system of models and procedures is applied and validated on a real test site, where the transport system is in dynamic conditions due to the time-varying road network and travel demand. The test site is a portion of a small-size town where the population needs to be evacuated due to an imminent calamitous event. The results show considerable reductions in total delays on the network and evacuation times in the case of optimized signal setting parameters.

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1. Introduction

Signalized junctions represent critical points of urban transportation networks and their traffic signal setting affects overall network performance. Since road congestion usually takes place at or close to junction areas, an improvement in signal settings contributes to improving travel times, driver comfort, fuel consumption efficiency and safety. In other words, traffic signal setting is an important element in traffic planning in urban areas in ordinary conditions (e.g. recurrent traffic congestion) and/or in emergency conditions (e.g. non-recurrent traffic congestion caused by unexpected events).

This study focuses on problems concerning the delay minimization (or the allocation of existing capacity) of urban junctions of road transportation networks (the topology is given) in order to handle travel demand. In ordinary conditions, the problem may concern the signal settings design to minimize travel time (or maximize the capacities junction factor) of users on the road network in different time periods of a day. In emergency conditions, the problem concerns the signal settings design to minimize travel time of users of road network that evacuate from an area where a calamitous event

is approaching in a small, but significant, time period (e.g. hours). Both in ordinary and in emergency conditions, it is crucial to estimate how users adapt their behaviour, in terms of path choice on the road network, to signal settings configurations defined in a planning (or policy) scenario. In order to support the definition of reliable solutions to the above problem, it is necessary, according to us, to overcome the classical static approaches and to introduce dynamics both in signal setting and path choice models.

There is a large body of scientific literature dealing with signal setting models, which include two main research lines of transportation field: (i) the network design (optimization) models and algorithms for network layout and junction control, and (ii) the assignment (simulation) models and algorithms.

As far as concern the network design models and algorithms, the Network Design Problem (NDP) consists of finding the optimal layout and/or the optimal signal setting parameters of a road transport network, according to a set of criteria (e.g. total delay, pollution minimization). The first studies on NDP were finalized to solve the layout design. Billheimer and Gray (1973) proposed a solution algorithm for uncongested transport networks; later the problem has been extended to congested transport networks (Chen and Alfa, 1991). Gao et al. (2005), Poorzahedy and Abulghasemi (2005) proposed methods for adding new lanes and infrastructures in a road network. The NDP for signal setting design

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is studied with un-elastic or elastic path choice for the users (see next section for a detailed state-of the-art).

Algorithms to solve the network design models belong to two classes: exact and heuristics. Several exact algorithms to find the optimal solution are present in literature (e.g. Dantzig–Wolfe), but they can be applied only in small size systems. Heuristic algorithms are used when the exact solution is not possible to obtain in a reasonable computation time. Among the heuristic algorithms proposed in literature (e.g. tabu search; simulated annealing; ant colony optimization; . . .), an interesting class is given by the Genetic Algorithms (GA). They belong to the class of bio-inspired and soft computing procedures for solving optimization problems (Goldberg, 1989). A general review of GA is proposed in Nicklow et al. (2010), developed in the field on evolutionary computation in environmental and water resources engineering.

As far as concern assignment models, they are subdivided into Static (SA) and Dynamic (DA) models. SA models generally simulate the so-called user equilibrium condition, where link (or path) flows and travel costs are mutually consistent. This condition, if reached, will persist as long as the network and the travel demand do not change, because the single user has no incentive to change his path. Although it is an abstract concept, equilibrium ensures a reasonable approximation of user behaviour and mathematical properties (e.g., existence and uniqueness of equilibrium). In DA models, the dynamics could involve two kinds of variations. A day-to-day variation involves vehicular flow pattern over successive reference time periods (e.g. days) (see Horowitz, 1984; Cantarella and Cascetta, 1995; Cantarella, 2009). A within-day variation is related to vehicular flow pattern inside the reference time period. Within-day DA models simulate the interaction between travel demand flows and the road transport network in order to estimate time-varying travel times and vehicular flows on a network inside (within) a reference time period (see, for a general overview Peeta and Ziliaskopoulos, 2001; Di Gangi et al., 2003; Cascetta, 2009). By removing the assumption of steady-state traffic conditions of SA models, DA models allow transport system evolution to be represented when travel demand peaks, temporary capacity variations, queue formation and dispersion occur (as it is in the case of evacuation conditions). The concept of equilibrium can be extended, or not, to the dynamic context, according to the treatment of travel time (see Huang and Lam, 2002).

Our research contribution concerns the integration of a signal setting design model and a within-day DA model into a single framework. In particular, our work aims to:

- develop a signal setting design model able to provide a solution which takes into account the dynamics of vehicular arrival flow profiles at the junctions of a congested road network;
- improve the quality of the simulation of user path choice behaviour, developing a path choice model (as part of the DA model), able to explicitly simulate, through behavioural rules, the sequence of users' decisions concerning choice set generation and the choice of alternatives, with a specification on the evacuation case;
- introduce dynamics into the supply model in order to capture the propagation of vehicle flow along each link, developing a dispersion model to estimate the vehicular flow profiles.

The framework is validated with data from a real test site where the transport system is in within-day dynamic conditions due to time-varying road network and travel demand. The test site is part of a small-size town where the population needs to be evacuated due to an imminent calamitous event. Considerable reductions are achieved in terms of total delay on the network and evacuation time in the case of optimized signal setting parameters, accentuated by the small network size with few path alternatives.

The remaining part of the paper is structured into five sections. Section two presents a review of existing signal setting models and the research road map. Section three presents the proposed signal setting model, which optimizes signal setting parameters according to an objective function and a set of constraints. The behavioural constrain, obtained by means of a dynamic assignment model, is presented in detail. In section four the procedures for the implementation of the proposed signal setting model are illustrated and described in each individual component. Section five describes the test of the proposed system of models and procedures on a real experimental site. The last section is devoted to conclusions and research perspectives.

2. Literature review on signal setting models and research road map

In the behalf of the research lines about network design and assignment models, this section reviews signal setting models existing in literature in order to define the road map from current knowledge to the new issues of our research on signal setting models.

Signal setting models may be classified according to the path choice that can be: (i) inelastic or (ii) elastic.

2.1. Inelastic path choice

In signal setting models with inelastic path choice, say optimization of signal timings, the path flow pattern is considered known. Several methods have been proposed for signal setting (see Papageorgiou, 1991; HCM, 2000; Wong and Wong, 2002, 2003), as briefly presented below. These methods can be classified according to the optimization of single or (a network of) interacting junctions.

Methods for single junctions fail to take account of the interaction between adjacent junctions, considering each of them isolated. They follow one of two approaches in relation to: the green timing optimization given the cycle time and the stage structure (e.g. Webster, 1958; Webster and Cobbe, 1966; Allsop, 1971, 1974); the green timing and scheduling optimization (e.g. Cantarella and Improta, 1988; Heydecker, 1992).

Methods for (a network of) interacting junctions explicitly allow for the effects of offsets on interaction between adjacent junctions, especially on delays. Such methods follow one of two approaches:

- coordination, given the green timing of each junction, which means optimization of the offsets for total delay minimization (e.g. NETCO in Cantarella et al. (1991)),
- synchronization, given the stage structure of each junction, which means optimization of the green times and the offsets for total delay minimization (e.g. TRANSYT in Robertson (1969)).

Signal setting models with inelastic path choice generally allow explicit simulation of time-dependent vehicle arrival flow profiles at the junction, which are cyclic (see Robertson, 1969), as flow path patterns between origin–destination pairs (or turning percentages) are exogenous. Hence they are not affected by path costs.

2.2. Elastic path choice

In signal setting models with elastic path choice, path flow pattern is affected by user path choice behaviour, since in urban networks signal setting affects delays at junctions, and hence transportation costs. Interaction between user path choice behaviour and level of service provided by the transportation network