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Network signal setting design with stage sequence optimisation

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ABSTRACT

One of the most straightforward short term policies to mitigate urban traffic congestion is control through traffic lights at a single junction or network level. Existing approaches for *single junction Signal Setting Design* (SSD) can be grouped into two classes: Stage-based or Phase-based methods. Both these approaches take the lane marking layouts as exogenous inputs, but lane-based optimisation method may be found in literature, even though for isolated signal-controlled junctions only. The *Network Signal Setting Design* (NSSD) requires that offsets are introduced; a traffic flow model is also needed to compute total delay. All existing methods for NSSD follow a stage-based approach; these methods do not allow for stage matrix optimisation: it is shown that explicit enumeration of stage sequences is only practicable for very small networks.

This paper focuses on Network Signal Setting Design introducing the so-called *scheduled synchronisation* that includes green scheduling, green timing and coordination into one optimisation problem. The paper proposes a stage-based method to solve such a problem, as an extension of the synchronisation method and the traffic flow model proposed in Cantarella et al. (2015): first a set of candidate stages is defined for each junction, then the stage sequences, the stage lengths and the offsets are optimised all together. To the authors' knowledge, no other one-step optimisation method is available in literature for scheduled synchronisation. Results of the proposed method to a small network were compared with those from explicit enumeration of all stage sequences; results for a larger network are also discussed.

1. Introduction and contribution

In order to mitigate urban traffic congestion, several policies can be adopted and may be applied in the short or long time horizon. With regard to the short term policies, one of the most straightforward is control through traffic lights at a single junction or network level (Gayah and Daganzo, 2012; Gu et al., 2014).

With respect to this aim, existing approaches for *single junction Signal Setting Design* (SSD) – in off-line or planning applications – can be grouped into two classes:

- Stage-based (e.g. Webster, 1958; Allsop, 1971, 1975; Burrow, 1987) methods,
- Phase-based (e.g. Improta and Cantarella, 1984; Gallivan and Heydecker 1998; Silcock, 1997; Wong, 1996, 1997; Wong et al., 2002) methods.

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Stage-based signal setting methods divide the cycle into stages, each one being a time interval during which some mutually compatible approaches have green. Stage composition (say which approaches have green in each stage), and their sequence are traditionally represented through the so-called stage matrix. Once the stage matrix is given for each junction, the stage lengths (and possibly the cycle length) can be optimised with respect to several objective functions, such as minimization of total delay or maximisation of capacity (well-known methods of this kind are SIGSET and SIGCAP).

Phase-based methods address the signal setting as a periodic scheduling problem: the cycle length, the start and the length of the green period for each approach, and a binary variable for each pair of incompatible approaches are considered as optimisation variables see for instance the Binary Mixed Linear Program proposed by Improta and Cantarella (1984). In this case, the stage composition and sequence may easily be obtained from optimisation variables, thus, the stage matrix is a post-process result of the procedure. Some commercial software codes following this methodology are available, for instance OscadyPro®TRL (Burrow, 1987).

It is worth noting that all the above referred papers, both for the stage-based and the phase-based approaches, take the lane marking layouts as exogenous inputs, thus not included within the optimisation procedures proposed in this paper. On the other hand, developments on the lane-based optimisation method, for isolated signal-controlled junctions only, may be found in literature, from Lam et al. (1997) to more recently Wong et al. (2000), Wong and Wong (2003), Zhou and Zhuang (2014), Sun et al. (2015) and Yu et al. (2016).

The *Network Signal Setting Design* (NSSD) requires that further variables are introduced: the offsets that define when the signal setting plan of each junction starts with respect to a given clock reference. A traffic flow model is also required to compute total delay.

All existing methods for NSSD follow a stage-based approach. These methods do not allow for stage matrix optimisation thus, the effects of stage composition and sequence on network performance are not considered. It is worth noting that explicit enumeration of stage sequences is only practicable for very small networks (as shown in Section 3).

For instance, TRANSYT15®TRL and TRANSYT-7F®FHWA allow to compute the cycle length, the green times and the offsets by combining a traffic flow model and a signal setting optimiser. In particular, TRANSYT15® generates several, but not all, significant stage sequences to be tested but the optimal solution is not endogenously generated, while TRANSYT-7F® is able to optimise the stage sequence for each single junction starting from the ring and barrier NEMA (i.e. National Electrical Manufacturers Association) phases. Still, these methods do not allow for complete stage matrix optimisation; moreover, the effects of stage composition and sequence on network performance are not analysed.

Other analyses may be also found in Hadi and Wallace (1993; 1994) which studied the possibility of introducing a phase sequence optimisation capability to TRANSYT-7F® using Genetic algorithms and the Cauchy simulated annealing. Moreover, with respect to the stage sequence optimisation Park et al. (2000) developed a simulation framework made up of a mesoscopic flow simulator and Genetic Algorithm optimiser, and showed that the simulator provided better results than those obtained using the software TRANSYT-7F®.

More recent contributions based on binary variables have been proposed by Friesz et al. (2013), Liu and Smith (2015) and Smith et al. (2015) for switch-on / switch-off signals in the case of within-day dynamic traffic assignment; some authors have introduced the continuum signalised junction model (Han et al., 2014; Han and Gayah, 2015) to avoid discrete variables.

The existing phase-based methods are available for single junctions only. Currently, in practical applications, once the green timing and scheduling have been carried out for each junction through a phase-based method, offsets can be optimised (coordination) using the stage matrices and greens obtained from single junction optimisation or using the stage matrices only to optimise both greens and offsets (synchronisation), through a stage-based method, as those above described.

This paper focuses on Network Signal Setting Design (NSSD) introducing the so-called *scheduled synchronisation* that includes green scheduling, green timing and coordination into one optimisation problem. The paper proposes a stage-based method to solve such a problem (see Section 2.). In this method, first a set of candidate stages is defined for each junction, then the stage sequences, the stage lengths and the offsets are optimised all together. To the authors' knowledge, no other one-step optimisation method is available in literature for scheduled synchronisation

The proposed method, called CENEO (ComplEte NEtwork Optimisation), is an extension of the synchronisation method and the traffic flow model proposed in Cantarella et al. (2015) that requires the stage sequence as input data and optimises stage lengths and offsets only (called ENEO in the rest of the paper for easy reference).

As already said, existing phase-based methods are not available for networks of junctions. These methods might be formally extended to specify one-step methods for NSSD (offsets are quickly obtained the start and the length of the green period of each approach). Nonetheless, the resulting Mixed Optimization Program is hard to solve since several equivalent local optima exist; this condition may quite easily be dealt with for a single junction, but it is still unclear how it can effectively be circumvented for a network (with loops). So far stage-based methods for single junctions can more simply be extended to scheduled synchronisation by explicitly including the stage sequencing within the optimisation method, after the stage generation step, as said above. Resulting methods are simpler to specify than those derived from phase-based methods. These reasons and others discussed in Section 2.4 support the stage-based approach pursued in this paper.

The paper is organised as follows: Section 2 describes the proposed method CENEO, and some consideration about advantages with respect to phase-based methods are also discussed; in Section 3 the results of the numerical applications for two toy networks carried out through CENEO are shown; in Section 4 the final conclusions are discussed. A list of notations is included at the end of the paper.