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Scheduled Synchronisation based on a mesoscopic flow model with speed dispersion

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Abstract

This paper proposes a method for netwok signal setting design, based on enhacements of an existing coordination method aiming: 1) to extend the existing approach in order to address the Traffic Control through Scheduled Synchronisation (i.e 'one step' optimisation of stage matrix, green timings, and node offsets); 2) to extend the considered Mesoscopic Traffic Flow model (TRAFFMED) to the vehicle platoon speed dispersion; 3) to build up a solution method suitable for both off-line and on-line applications. The proposed optimisation method is an application of the Simulated Annealing meta-heuristic. Some numerical applications are proposed, specifically analysing 'two step' optimisation (synchronisation), and'one step' optimisation (scheduled synchronisation), for off-line (pre-timed strategy) and on-line applications (on-line computation strategy). A grid network was considered as case study and the effectiveness of the proposed strategies were evaluated by comparing the obtained results with those computed through commercial (benchmark) and in-house codes.

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Keywords:Network Signal Setting Design; Meta-heuristics; Mesoscopic Traffic Flow Model; Platoon Dispersion model; ScheduledSynchronisation; Stage Based method.

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1. Introduction and motivation

In this paper the flow based Network Signal Setting Design is addressed through a new method, which is also compared with others already in literature.

Network Signal Setting Design methods can be grouped into three main classes depending on the optimisation variables: i) the three step optimisation (also called coordination), if the stage matrix for each single junction is an input data and green times and offsets are optimised in two separate steps; ii) the two step optimisation which may be further divided in two approaches: the synchronisation, when the stage matrix for each junction is an input data and green timings and offsets are simultaneously optimised; the green timing and scheduling (e.g. Memoli et al., 2017), when first the stage sequence and green times are optimised together for each single junction then the offsets are optimised for the whole network (coordination); iii) the one step optimisation (also called scheduled synchronisation)in which stage sequence, green times and offsets are simultaneously optimised.

Flow-based methods have most often been applied according to a fixed time strategy (possibly distinguishing several periods within a day), in this case the main drawback relies on the use of historical traffic data instead of more reliable (filtered) real-time data, needed for traffic responsive strategies. Among traffic responsive strategies the most relevant are the actuated control (Li et al., 2011) and the adaptive control (see SCOOT - Hunt et al., 1981, Bretherton et al., 1998, Stevanovic et al., 2009; OPAC - Gartner, 1983, PRODYN - Henry et al., 1983).

Based on previous considerations the paper proposes a solution approach suitable for traffic responsive applications, too; the method is a further developing of those proposed in Memoli et al. (2017) and Di Gangi et al. (2016). In particular, Memoli et al. (2017) tested the suitability of a method for scheduled synchronisation for off-line applications, whereas the extension of a coordination method to on-line applications was tested in Di Gangi et al. (2016). Moreover, it should be observed that the only application founded in the literature for stage sequence optimisation refers to the flexibility of the most modern traffic actuated controllers able to pairing nonconflicting phases (i.e. NEMA; National Electrical Manufacturers Association).
The main contributions of the paper are:

- A.1) to extend the coordination method proposed in Di Gangi et al. (2016) to address the Synchronisation and the Scheduled Synchronisation (as methods ENEO and CENEO respectively in Memoli et al., 2017) through a mesoscopic flow model;
- A.2) to extend the Mesoscopic Traffic Flow model (TRAFFMED) in Di Gangi et al. (2016) embedding a representation of the speed dispersion phenomenon (see Robertson, 1969);
- A.3) to propose a solution method suitable for both fixed time and traffic responsive applications.

Regarding to point A.2, even though most available tools for single junction signal setting are analytical based, in case of urban network traffic control a crucial role is played by traffic flow modelling, then the optimisation procedure is usually simulation based. As a matter of fact the traffic flow phenomena, such as flow dispersion, queue propagations and spillbacks significantly affect network signal setting design. At this aim the simulation of traffic flow speed dispersion represents a crucial issue, and is has been embeded into the mesoscopic traffic flow modelling TRAFFMED (TRaffic Analysis and Flow Forecasting MEsoscopic Dynamic) in Di Gangi et al. (2016).

In order to support the theoretical results four case studies are discussed: two scenarios refer to the implementation of the synchronisation in off-line and on-line contexts whilst other two scenarios refer to the implementation of the scheduled synchronisation still in off-line and on-line contexts.

The remainder of this paper is organised as follows: in section 2 the model formulation is described; in section 3 the results of the performed numerical applications are shown and compared with those of other benchmarks or in-house tools; in section 4 some conclusions are discussed.

2. Modelling framework

2.1. Network Signal Setting Design

The proposed method for Network Signal Setting Design is an enhancement of the network synchronisation and scheduled synchronisation methods in (Memoli et al.2017) to include the mesoscopic traffic flow model in Di Gangi et al. (2016), further extended as described in the next sub-section 2.2. As already stated, decision variables in case of synchronisation are green times and offsets (once given the stage matrix at each junction) whilst in case of scheduled synchronisation stage sequences, green times, and node offsets and are simultaneously optimised. Solution algorithms aiming at total delay (TD) minimisation are based on Simulated Annealing (SA) meta-heuristic. For the sake of brevity the synchronisation and the scheduled synchronisation are not herein discussed in detail; in the following just a brief description of the considered assumptions for the scheduled synchronisation is provided. In particular four requirements have to be satisfied:

(referring to the stage composition)

- *the compatibility requirement,* ensuring that all the approaches in a stage must be mutually compatible;
- *the completeness requirement,* meaning that no further approach may be added to a stage without violating the compatibility requirement;

(referring to the stage sequence)

- *the feasibility requirement,* requiring thateach approach belongs to at least one stage in the sequence.
- *the consecutiveness requirement,* ensuringthat each approach has green in consecutive stages;

Once all stages consistent with the compatibility and the completeness requirements have been generated (throught the Bron & Kerbosh algorithm), let us define *compulsory* a candidate stage that contains an approach not included in any other stage; otherwise it is called *optional*. When the number of optional stages is null, then the number of feasible sequences is given by the number of permutations of the n compulsory stages (i.e. n!); actually, any periodic rotation of a sequence does not affect optimal green times and performance indicators, while optimal offsets change in an easily predictable way, thus a periodic rotation does not affect the optimal solution. This way, if n is the number of available stages, n! is the number of feasible sequences and (n - 1)! is the number of equivalent classes containing all stage sequences leading to the same optima solutions (e.g. if four stages are available six equivalent classes exist).

Besides, if there is at least one optional stage, the stages can be grouped into 2^{no} sub-sets, each including all the number of compulsory stages and some (or none at all) of the n_o optional stages; for instance let consider as example a case where 4 stages are available, three are compulsory and one is optional. Thus in this case eight equivalent classes exists: 2 classes are composed by sequences of three compulsory stages and 6 classes are composed by sequences of three compulsory plus one optional stages.

2.2. EVD-TRAFFMED:
Embedded Vehicle Dispersion – TRaffic Analysis and Flow Forecasting MEsoscopic Dynamic

In terms of traffic flow simulation the adopted model is an enhanced version of that proposed in Di Gangi et al. (2016). In particular, the extension of the model takes explicilty into account of the vehicle speed dispersion. This dispersion can effectively be represented by the Platoon Dispersion Model (PDM) presented by Robertson in 1969. Even though during the last five decades different methods have been proposed in literature to predict traffic flow profiles in order to derive the link delay/offset relation (kinematic theory, diffusion theory etc.), one of the most straightforward is still the PDM, widely adopted in a number of practical applications and a number of tools including TRANSYT (Robertson, 1969) and SCOOT (Hunt et al., 1981).

The Robertson's model represents the vehicles dispersion as in follows:

$$q_d(j) = \sum_{i=1}^{j-t} q_0(i)\, F(1-F)^{j-t-i} = F\, q_0(j-t) + (1-F)\, q_d(j-1) \qquad (1)$$

$$F = (1 + \alpha\beta T)^{-1} \quad (2)$$

where: T = mean link travel time;α = 0.5 and β = 0.8; $q_d(j)$= flow rate over a time step Δt arriving at downstream signal at time interval j; $q_0(i)$= discharging flow over time step Δt observed at upstream signal at time interval i;
Δt = time step duration, usually assumed as 1 second; F= smoothing factor; α and β = dimensionless model parameters.

With reference to the EVD-TRAFFMED model, let us consider an interval j of length Δt and a generic time instant $0<\tau<\Delta t$ within the interval j. At time interval j, the density k(j), the link speed v(j) and the travel time T(j), derived from the previous time interval j-1, are assumed known. The speed can be obtained by any speed - density relationship (fundamental diagram – stable regime); in this paper the BPR-like function was adopted assuming suitable parameters for urban links.

Let consider the number of vehicles *n(τ)* which have reached the link *a* during the interval j until the time instant τ; the entry flow at link *a* could be obtained as:

$$q(\tau) = n(\tau)/\tau \quad (3)$$

Assuming that within the generic interval j steady state conditions hold, the equation of the fundamental diagram could be rewritten as:

$$k(j)v(j) = q_d(j) \quad (4)$$

then the speed of the vehicle reaching the link *a* at time instant τ within the interval j, will be expressed as:

$$v(j) = q_d(j)/k(j) \quad (5)$$

3. Numerical applications

In this section, the numerical results obtained through the proposed methods and the benchmark tool, TRANSYT, are compared.The proposed methods were implemented in a Python code (according to the JetBrains PyCharm Community Edition 3.0.2 framework) and run on a server machine which has an Intel(R) Xeon(R) CPU E5-1620 v3, clocked at 3.50GHz and with 8GB of RAM.

As already introduced above four case studies are discussed:

- case studies A, based on a two-step optimisation strategy (synchronisation) looking for total delay minimisation; the proposed method was tested in two cases: (A_1) fixed time (pre-timed timing plan), and (A2) traffic responsive (timing plan computation);
- case studies B, based on the scheduled synchronisation (which belongs to the one step strategies; the proposed method was tested in two cases: (B_1) fixed time (pre-timed timing plan), and (B_2) traffic responsive (timing plan computation).

In order to compare the results the grid network in Di Gangi et al. (2016), shown in Figure 1, was considered; it is characterised by 4 e-e pairs (e-e pair flows are displayed in Table 1), 9 nodes and 12 bidirectional links (totaling 32 links including connectors), each one with one lane for each direction, thus there is only one access at the end of each link. The saturation flow of each lane is assumed equal to 1800 PCU/h. The length of the links connecting node 5 with other nodes (2-5, 5-6; 5-8) is 400 m, whilst the length of the other links is 800 m.

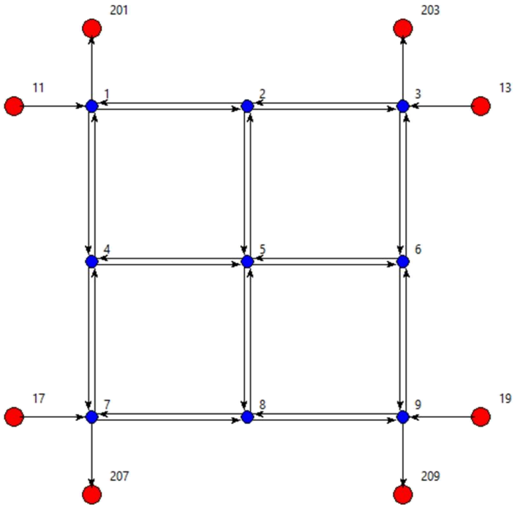

Fig. 1. Layout of the toy network

Table 1. entry-exit matrix.

	Exit [PCU/h]			
Entry [veih/h]	**201**	**203**	**207**	**209**
11	#	480	384	336
13	432	#	288	384
17	480	624	#	423
19	336	576	432	#

3.1. Synchronisation

Case Study A_1:

This case study aims at validating the proposed synchronisation strategy with the traffic flow represented through the enhanced version of the mesoscopic model, ENEO – EVD - TRAFFMED – SA. The proposed strategy was compared with the benchmark tool (TRANSYT – PDM – SA), and the cross analysis was made considering two indicators: the total delay (TD) and the degree of saturation (DOS). In general results may be considered comparable, in particular the proposed EVD – TRAFFMED - SA slightly outperforms TRANSYT - PDM – SA (see table 2).

Table 2. Case study B1 (two steps optimisation, synchronisation) - Performance indicators

Performance indicator	TRANSYT - PDM- SA	ENEO – EVD - TRAFFMED- SA
TD[PCU-h/h]	60.44	57.32
DOS[%]	73	67

The obtained results can be anticipated since the proposed mesoscopic model is able to redistribute the queues over the available paths differently from other models, for instance the CTM (Daganzo, 1995), that allows vehicles to be held at the upstream cells rather than advancing forward to the available-capacity downstream cells; thus CTM induces the queue lenghts overestimation whilst the mesoscopic model leads for more realistic queue representation comparable to the obtained results through PDM in which the queue propagation is not properly reproduced.

Case Study A_2:

The synchronisation method applied to the fixed time plan computation (ENEO - EVD_TRAFFMED - SA 2steps), and was further implemented for the traffic responsive scenario (case study A_2). Table 3 makes it clear the comparison between results performed through the proposed ENEO - EVD_TRAFFMED - SA 2steps and those computed through TRANSYT - PDM - SA2steps; in both cases the same optimisation strategy (synchronisation) is adopted in order to analyse only the effect of the traffic flow model (EVD - TRAFFMED vs. PDM). The traffic signals were updated every 15 minutes (control interval) by implementing the optimisation procedure on the basis of the flows measured at the previous control interval; the traffic flow model acts both as a forecasting model for predicting traffic flows, and as simulation model for computing total delay.

Table 3. Case study A2 (two steps optimisation traffic responsive, synchronisation) - Performance indicators

	ENEO – EVD - TRAFFMED- SA2steps**			**TRANSYT - PDM- SA2steps**		
Interval	**MMQ [PCU]**	**TD^N[PCU-h/h]**	**CF**	**MMQ [PCU]**	**TD^N[PCU-h/h]**	**CF**
1	*123.59*	*63.24*	*1.12*	*91.42*	*41.32*	*1.10*
2	108.32	57.48	<1*	133.76	74.53	<1*
3	144.28	70.52	<1*	139.12	80.88	<1*
4	101.22	32.15	1.61	126.38	63.33	<1*

**oversaturation*

Results point out that TRANSYT - PDM - SA 2steps is outperformed by ENEO - EVD_TRAFFMED - SA 2steps. This result is presumably due to the possibility, in TRAFFMED, of distributing queues over the network links and imposing alternative paths (the traffic model is embedded in a dynamic network loading in which the path choice is properly addressed).

3.2. The Scheduled Synchronisation

Case Study B_1:

Further analyses refer to the scheduled synchronisation for fixed time application (off-line CENEO - EVD_TRAFFMED - SA 1step). In this case we may expect a large dispersion of solutions due to the random nature of the SA with respect to case A. Then the stability of the method was analysed by comparing the differences (deltas) of total delays at each of 24 runs, with respect to the best solution (see Table 4). Comparing with case study A_1 it should be noted that significant improvements in the performance indicators are observed; in fact TD in A_1 scenario was equal to 60.44 [PCU-h/h] whilst in this case it was equal to to 32.19 [PCU-h/h].

Table 4. Case study B_1 – optimal total delays (TD) of each simulation run; error percentage w.r.t. best solution achieved

Sim.run	TD [PCU-h/h]	Delta to best[%]
		Internal dispersion
1	33.82	+5.06
2	34.21	+6.28
3	33.9	+5.31
4	35.31	+9.69
5	34.01	+5.65
6	33.83	+5.09
7	33.34	+3.57
8	34.44	+6.99
9	34.15	+6.09
10	33.98	+5.56
11	33.44	+3.88

12	33.01	+2.55
13	34.29	+6.52
14	**32.19**	**0.00**
15	35.34	+9.79
16	34.67	+7.70
17	33.52	+4.13
18	33.44	+3.88
19	34.18	+6.18
20	35.00	+8.73
21	34.20	+6.24
22	33.07	+2.73
23	33.04	+2.64
24	34.23	+6.34

Case Study B_2:

Latest analyses refer to the scheduled synchronisation for on line application (on-line off-line CENEO - EVD_TRAFFMED - SA 1step). Results (see Table 5) were compared with those carried out through two steps optimisation. As expected the scheduled synchronisation get a significant improvement not only in terms of total delay but also with respect to the capacity factor, even though the computational time significantly increases.

Table 5. Case study B_2 – (one step optimisation traffic responsive, scheduled synchronisation) - Performance indicators

	CENEO – EVD - TRAFFMED- SA 1step					**ENEO – EVD - TRAFFMED- SA 2steps**			
Interval	**Number of sim run [#]**	**Running time [min]**	**MMQ [PCU]**	**TD^N [PCU-h/h]**	**CF**	**Running time [min]**	**MMQ [PCU]**	**TD^N [PCU-h/h]**	**CF**
1	*12*	*12*	*87.44*	*30.28*	*1.95*	*4*	*123.59*	*63.24*	*1.12*
2	17	15	102.56	38.23	1.59	5	108.32	57.48	<1*
3	28	24	121.12	42.65	1.45	6	144.28	70.52	<1*
4	22	18	91.22	31.03	1.83	6	101.22	32.15	1.61

4. Conclusions

This paper focuses on the Network Signal Setting Design. The main purposes are: i) to extend the coordination approach proposed in Di Gangi et al. (2016) in order to address the Synchronisation and the Scheduled Synchronisation through mesoscopic flow model, ii) to enhance the mesoscopic traffic flow model, TRAFFMED, still presented in Di Gangi et al. (2016) embedding the flow speed dispersion (see Robertson, 1969), and iii) to propose a solution method suitable for both fixed time and traffic responsive applications.

some numerical applications were carried out on a nine nodes grid network to show performances of the propsoed methods.

For off-line synchronisation results obtained through the proposed method may be considered comparable with respect to results achieved through a benchmark tool (TRANSYT) whilst the on-line application of the same method, points out that the proposed method may significantly outperform the benchmark tool; this is presumably due to the enhanced traffic flow modelling which is able to distribute the queues over the network links.

With reference to the Scheduled Synchronisation, off-line application may significantly outperform the application both of off-line and online Synchronisation, moreover, the on-line Scheduled Synchronisation get a further significant improvements mainly in terms of capacity factor optimisation, even though the computational time significantly increases.

Most relevant topics worthy of further research are: i) the integration of the proposed on-line methods with a better flow forecasting model; ii) the extension of the proposed framework to store and a forward strategy (Gazis and Potts, 1963); iii) the application of the strategy to a real case study.

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