Book Section:
De Luca, S, Di Pace, R, Memoli, S et al. (1 more author) (2016) Comparing Signal Setting Design Methods through emissions and fuel consumption performance indicators. In: Świątek, J and Tomczak, JM, (eds.) Advances in Systems Science: Proceedings of the International Conference on Systems Science 2016 (ICSS 2016). Advances in Intelligent Systems and Computing, 539 (539). Springer International Publishing , Cham, Switzerland , pp. 200-209. ISBN 978-3-319-48943-8

https://doi.org/10.1007/978-3-319-48944-5_19

Comparing Signal Setting Design Methods through emissions and fuel consumption performance indicators

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Abstract In order to address the Signal Setting Design at urban level two main approaches may be pursued: the coordination and the synchronisation approaches depending on the steps considered for the optimisation of decision variables (two steps vs one step). Furthermore, in terms of objective functions mono-criterion or multi-criteria may be adopted. In this paper the coordination approach is implemented considering the multi-criteria optimisation at single junctions and mono-criterion optimisation at network level whereas the synchronisation is implemented considering the mono-criterion optimisation.
The main purpose of the paper is the evaluation of the performances of two strategies not only considering indicators such as the total delay, the queue length etc. but also considering other indicators such as the emissions and the fuel consumption. The methodological framework is composed by three stages: i) the decision variables (green timings and offsets) computation through optimisation methods; ii) the implementation of optimal signal settings in a microscopic traffic flow simulator (Simulation of Urban MObility"- SUMO); iii) the estimation of emissions and fuel consumption indicators.

Keywords: network signal setting design; macroscopic traffic flow model; microscopic traffic flow model; sustainable transportation.

1 Introduction and motivation

This paper aims to compare the results of two different Network Signal Setting Design methods not only by considering the usually adopted indicators such as the capacity factor (computed at network level), the total delay etc. but also considering other indicators such the total emissions and the fuel consumption.

The mitigation of environmental impact due to the traffic congestion is still a difficult challenge to be pursued; the considered strategies usually refer to the Intelligent Transportation Systems ([1],[2]) and in particular to the enhanced eco-driving technologies [6] or on the application of transport policies (demand or supply).

As regards the supply strategies some researchers investigated the significance of the correlation between signalised junctions and emissions/fuel consumption ([9]) whilst others ([12]; [18]; [11]; [13]) developed multi-criteria optimisation frameworks using these indicators as alternative criteria.

In fact even though optimisation strategies are usually based on total delay minimisation, or on the combination of total delay minimisation and capacity factor maximisation, none of these objective functions are strictly related to the emission/consumption evaluation; in particular these indicators are usually represented by the number of stops. Summing up the optimisation problem considering the trade-off between the network performances and the air pollution indicators estimation might be represented through multi-criteria method. Based on previous considerations, the paper aims to preliminarily investigate the effectiveness of two control strategies in terms of emission and fuel consumption indicators. The main contribution with respect to the current literature is on the enhanced traffic control strategies.

The research is organised in three sections as in following described in more details.

In the first section the results achieved through two optimisation strategies, coordination and synchronisation are shown and discussed; in particular, in case of coordination method the multi-criteria optimisation at a single junction (green timings are the decision variables) is adopted (capacity factor maximisation an delay minimisation, are the considered criteria) and mono-criterion optimisation is applied at network level (offsets are the decision variables), whilst in case of synchronisation method the mono-criterion optimisation (green timings and offsets are optimised together) is adopted (the total delay is the considered objective function); in terms of algorithms some meta-heuristic algorithms are adopted in both cases and in particular the Genetic Algorithms [4] (to get optimal green times at each single junction) and the Hill Climbing (to get optimal offsets) are combined for the coordination approach [7], whereas the Simulated Annealing is adopted for mono-criterion optimisation in the synchronisation approach. In both strategies the adopted traffic flow model is based on macroscopic approach.

In the second section the considered network and the given values of input variables computed through the optimisation strategies, are implemented in a microscopic simulator (Simulation of Urban MObility"- SUMO).

Finally, in the third stage the total emissions and the fuel consumption are computed through HBEFA model ([4]) embedded in SUMO.

The reminder of this paper is organised as follows: section 2 provides a description of the optimisation strategies focusing on decision variables, constraints and objective functions description and on the presentation of the macroscopic traffic flow model used for total delay computation; in section 3 the emissions and fuel consumption estimations through SUMO is briefly discussed; the results of the numerical application are shown in section 4; finally conclusions and further perspectives are presented in section 5.

2 Optimisation strategies

In this section the basic notations, the constraints and the objective functions are described. Furthermore, the considered traffic flow model is described.

2.1 Variables and constraints

Assuming that the green scheduling is described by the stage matrix (i.e. the stage matrix composition and sequence), let

c be the cycle length, assumed known or as a decision variable (common to all junctions);

for each junction (not explicitly indicated)

t_j be the duration of stage j as a decision variable;

t_{ar}, be the so-called all red period at the end of each stage to allow the safe clearance of the junction, assumed known (and constant for simplicity's sake);

Δ be the approach-stage incidence matrix (or stage matrix for short), with entries δ_{kj} =1 if approach k receives green during stage j and 0 otherwise, assumed known;

l_k be the lost time for approach k, assumed known;

$g_k = \Sigma_j \delta_{kj} t_j - t_{ar} - l_k$ be the effective green for approach k;

$r_k = c - g_k$ be the effective red for approach k;

y_k be the arrival flow for approach k, assumed known;

s_k be the saturation flow for approach k, assumed known;

$(s_k \cdot g_k) / (c \cdot y_k)$ be the capacity factor for approach k;

and for each junction in the network

ϕ_i be the offset as the time shift between the start of the plan for the junction i and the start of the reference plan, say the plan of the junction number 1, $\phi_1 = 0$.

Some constraints were introduced in order to guarantee:

stage durations being non-negative

$$t_j \geq 0 \qquad \forall j$$

effective green being non-negative

$g_k \geq 0 \qquad \forall\, k$

this constraint is usually guaranteed by the non-negative stage duration, but for a too short cycle length with regard to the values of all-red period length and lost times, say

$\Sigma_j\, MAX_k\, (\delta_{kj}\, l_k + t_{ar}) \geq c$

consistency among the stage durations and the cycle length

$\Sigma_j\, t_j = C$

the minimum value of the effective green timing

$g_k \geq g_{min} \qquad \forall k$

A further constraint was included in order to guarantee that the capacity factor must be greater than 1 (or any other value)

$((s_k \cdot g_k) / (c \cdot y_k) - 1) \geq 0 \qquad \forall k$

Such a constraint may be added only after having checked that the maximum junction capacity factor for each approach k in the junction i is greater than 1, otherwise a solution may not exist whatever the objective function is.
Finally let assume

$c \geq \phi_i \geq 0.$

2.2 Objective functions

At a single junction, the objective functions in the optimisation problems were:

- the junction capacity factor computed as

$$CF = MAX_k\, (s_k \cdot g_k) / (c \cdot y_k)$$

- the total delay computed
- for non-interacting approaches (isolated or external junctions) by the two terms Webster's formula ([17]) as

$$TD = \Sigma_k\, y_k \cdot (0.45 \cdot c \cdot (1 - g_k /c)^2 / (1 - y_k / s_k)$$
$$+ y_k \cdot 0.45 / (s_k \cdot g_k / c) \cdot ((g_k / c) \cdot (s_k / y_k) - 1)))$$

- for the interacting approaches by evaluating vehicles queuing interval by interval and considering input as the flow obtained by cyclic flow profiles. A more detailed expression consistent with the traffic flow modelling will be described in subsection 2.3.

Further objective functions could be considered such as the queue length, the number of stops etc.

2.3 Traffic Flow Model

One of the considered objective functions is the total delay, as described in more details above; to compute total delay at single junction different analytical formulations may be applied (e.g. [16]) whereas at network level to represent total delay traffic flow modelling is required. With reference to the literature traffic flows may be described through

- microscopic models, modelling both the space-time behaviour of the systems' elements (i.e. vehicles and drivers) as well as their interactions;
- mesoscopic models, modelling traffic by groups of vehicles possibly small, the activities and interactions of which are described at a low detail level;
- macroscopic flow models, modelling traffic at a high level of aggregation as a flow without distinguishing its parts (i.e. the traffic stream is represented in an aggregate manner using characteristics as flow-rate, density, and speed).

In this paper traffic flow is modelled through macroscopic model and in particular the Cell Transmission Model (CTM; [8]) is implemented. Moreover, since CTM assumes the same speed for all the vehicles on a road, it cannot fully predict realistic traffic flow behaviour as the platoons keep the same density when moving from the upstream stop-line section to the downstream section, and all vehicles travel at the same free flow speed. The CTM includes the horizontal queuing at the cost of not considering the platoon dispersion then to overcame this limitation the CTM&PDM (see [3]) allowing horizontal queues and platoon dispersion modelling was adopted.

3 Total Emissions and Fuel consumption estimation

Different models have been developed in the literature for emissions and fuel consumptions estimation; among them some are based on traffic conditions such as stop-and-go or free- flow driving other on the estimation of emissions/consumptions produced via engine (e.g. HBEFA, Handbook of Emission Factors; [5]; Road Model, [15]) or are vehicle operating models thus various driving cycle variables are required as input (e.g. PHEM; Passenger car and Heavy Emission Model, [10]; CMEM; Comprehensive Modal Emissions Model; [14]).

In this paper emissions and fuel consumption have been estimated through TraCI4Matlab which is an implementation of the TraCI (Traffic Control Interface) protocol; through this protocol user is able to interact with SUMO (Simulation of Urban Mobility) in a client (Matlab)-server (SUMO).

4 Numerical application

In this section it is shown an application to a network with four interacting signalised junctions forming a loop (shown in Fig. 1 as a square for simplicity's sake). Two design strategies were considered:

A coordination: once fixed a master junction in the network, say the junction 1, this consists in optimising the node offsets, say the time distance among the start of the signal plan of the other junctions in the network and the start of the signal plan of junction 1. The green times at each junction were previously computed through a multi-criteria Genetic Algorithm which optimises simultaneously the junction total delay (to minimise) and capacity factor (to maximise);

B synchronisation: offsets and green times were simultaneously optimised considering the minimisation of network total delay.

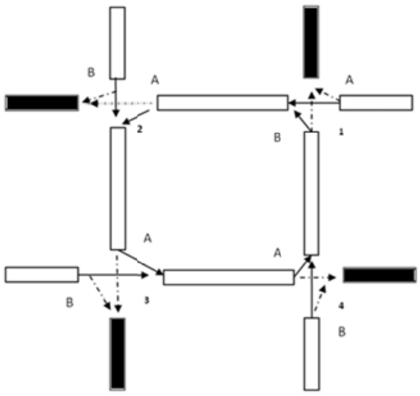

Fig.1. junction layout; stage matrix; characteristics of the junction

All information related to the network, in terms of flow and saturation flow for each approach, are summarised in Table 1. With regards to the links length L1= 500m, L2=200m; L3=600m and L4=200m.

Table 1. flow and saturation flow for each approach

Junction	Stage	$y_{k\ [veic/h]}$	$s_{k\ [veic/h}$
1	A	400	1750
	B	245	
2	A	390	
	B	227	
3	A	422	
	B	286	
4	A	375	
	B	191	

Strategy A:

In this case two optimisation steps are identified: first the green times of each junction were optimised considering the trade-off effect between two criteria (Total Delay, TD and Capacity Factor, CF); as expected, any solution was not dominant with respect to both criteria at the same time (see Table 2); then starting from the timings obtained by the multi-criteria single junction signal setting design the network total delay, the degree of saturation (DOS) and the link offsets between the signal plans of the interacting junctions were carried out (see Table 3).

Table 2. Total Delay, Capacity Factor and effective greens of each approach

Junction	Stream	TD [PCU-hr/hr]	CF	Effective green
1	A	1.27	1.66	31
	B	2.35	2.15	49
2	A	1.75	2.32	40
	B	1.91	2.47	40
3	A	1.49	1.88	33
	B	2.30	2.68	47
4	A	1.53	2.38	40
	B	1.79	2.44	40

Table 3. Offsets, TD and DOS

Coordination Results					
Offset 1-2* [sec]	**Offset 2-3* [sec]**	**Offset 3-4* [sec]**	**Offset 4-1* [sec]**	**TD [PCU-hr/hr]**	**DOS [%]**
54	31	58	37	8.48	60

Offset i-j refers to the time distance between the start of signal plan of junction j with respect to the start of signal plan of junction i.

Strategy B:

In this case the green times at each junction (see Table 4) and the offsets (see Table 5) are simultaneously optimised considering the minimisation of network total delay (as described in section 2).

Table 4. Synchronisation results: effective greens

Synchronisation Results		
Junction	Stream	Effective green
1	A	38
	B	42
2	A	45
	B	35
3	A	43
	B	37
4	A	46
	B	34

The network parameters (i.e. the input flows and the link lengths) were fixed as equal to those adopted in previous implementations. Results shown in Table 5 make it clear that there is a greater efficiency in terms of level of service function by using a synchronisation strategy with respect to a coordination strategy; in fact $TD_{Coordination}$ = 8.48 PCU-hr/hr whereas $TD_{Synchronisation}$ = 6.71 PCU-hr/hr and $DOS_{Coordination}$ = 60% whereas $DOS_{Synchronisation}$ = 49%.

Table 5. Synchronisation results: offsets

Offset 1-2* [sec]	**Offset 2-3* [sec]**	**Offset 3-4* [sec]**	**Offset 4-1* [sec]**	**TD [PCU-hr/hr]**	**DOS [%]**
54	13	72	41	6.71	49

*Offset i-j refers to the time distance between the start of signal plan of junction j with respect to the start of signal plan of junction i.

The signal settings obtained through Strategy A and Strategy B have been then implemented in the microscopic simulator SUMO (see Figure 2), in order to get further indicators which were related to emissions and fuel consumption.
Results shown in Table 6 makes it clear, as expected, that the Synchronisation approach allows to improve the network performances also in terms of air pollution indicators. As a matter of fast such results highlight relevant insights into optimal traffic signal strategy for fuel consumption and emissions minimisation.

Table 6. Emissions and Fuel Consumption

		Coordination	**Synchronisation**
[ton/year]	CO2	52.822	50.695
	CO	0.575	0.455
	HC	0.024	0.014
	Nox	0.200	0.098
	PMx	0.008	0.004
	FuelConsumed	22.660	20.211

5 Conclusions and research perspectives

The main focus of the paper is on the comparison of the results performed through two different optimisation strategies for Network Signal Setting Design.

With reference two the decision variables (green timings and offsets) the considered optimisation strategies were the coordination and the synchronisation; the first one was carried out in two steps where during the first step the optimal values of the green timings at single junction were computed whereas in the second step the optimal values of the offsets were carried out; the second strategy was computed in only one step thus all decision variables were optimised at the same time.

In case of coordination multi-criteria optimisation was adopted at single junction whilst mono-criterion optimisation was adopted at network level; in case of synchronisation only mono-criterion optimisation was considered. Furthermore, in terms of algorithms, due to the nature of the optimisation problem, meta-heuristics algorithms were adopted; in particular in coordination approach Genetic Algorithms and Hill Climbing where respectively considered at single junction and at network level, whereas in synchronisation approach the Simulated Annealing was adopted.

Moreover, the objective functions considered in the optimisation procedure were: i) in case of coordination, the capacity factor and the total delay at a single junction and the total delay at network level; ii) in case of synchronisation the total delay.

The paper deals with the preliminary investigation of the effect of two optimisation strategies on alternative indicators in order to evaluate the significance of the introduction of other objective functions such as the emissions (to be minimised) and the fuel consumption (to be minimised).

To this aim, in order to compare the effectiveness of two strategies were considered common indicators such as the total delay and the degree of saturation, and were also introduced the emissions and the fuel consumption indicators.

The results point out the relevant effect of synchronisation with respect to the coordination thus highlighting the possibility to introduce in multi-criteria optimisation of further criteria based on emissions and fuel consumption. Furthermore it is expected that increasing the degree of complexity of the network the effect of two strategies in terms not only of performance indicators but also in terms of air pollution indicators, could be more significant and then relevant.

In future works researchers

- will investigate the relevance on air pollution indicators of optimisation strategies by increasing the traffic flows;
- will evaluate the effectiveness of the strategies for bigger grid network;
- will develop a multi-criteria optimisation based on performance criteria and air pollution indicators.

Acknowledgements. The research has been supported by the University of Salerno, Italy, EU under local grant n. ORSA151059 financial year 2015 and by ‘APPS4SAFETY – PON03PE_00159_3’.

References

[1] Bifulco, G. N., Cantarella, G. E., Simonelli, F. (2014) *Design of Signal Setting and Advanced Traveler Information Systems.* Journal of Intelligent Transportation Systems: Technology, Planning and Operations 18(1), 30-40.

[2] Bifulco, G. N., Cantarella, G. E., Simonelli, F., & Velonà, P. (2016). *Advanced traveller information systems under recurrent traffic conditions: Network equilibrium and stability*. Transportation Research Part B: Methodological. doi:10.1016/j.trb.2015.12.008

[3] Cantarella, G. E., de Luca, S., Di Pace, R., & Memoli, S., (2015). *Network Signal Setting Design: Meta-heuristic optimisation methods.* Transportation Research Part C: Emerging Technologies.
[4] Cantarella, G. E., de Luca, S., Di Pace, R., & Memoli, S. (2014). *Signal setting design at a single junction through the application of genetic algorithms.* In Computer-based Modelling and Optimization in Transportation, pp. 321-331.
[5] Colberg, C.A., Tona, B., Stahel, W.A., Meier, M., and Staehelin, J. (2005) *Comparison of a road traffic emission model (HBEFA) with emissions derived from measurements in the Gubrist road tunnel (Switzerland)* Atmospheric Environment, 39, 4703-4714.
[6] de Luca, S., Di Pace, R., & Marano, V. (2015). *Modelling the adoption intention and installation choice of an automotive after-market mild-solar-hybridization kit*. Transportation Research Part C: Emerging Technologies, 56, 426-445.
[7] Di Gangi, M., Cantarella, G. E., Di Pace, R., & Memoli, S. (2016). *Network traffic control based on a mesoscopic dynamic flow model.* Transportation Research Part C: Emerging Technologies, 66, 3-26.
[8] Daganzo, C.F. (1994) *The cell-transmission model*. Part 2: Network traffic, University of California, Berkeley, California.
[9] Guo, R., & Zhang, Y. (2014). *Exploration of correlation between environmental factors and mobility at signalized intersections.* Transportation Research Part D: Transport and Environment, 32, 24-34.
[10] Hausberger, S. (2003) *Simulation of Real World Vehicle Exhaust Emissions*", VKM-THD Mitteilungen Technical University Graz, Vol. 82, Graz, 2003.
[11] Kwak, J., Park, B., & Lee, J. (2012). *Evaluating the impacts of urban corridor traffic signal optimization on vehicle emissions and fuel consumption*. Transportation Planning and Technology, 35(2), 145-160.
[12] Lee, J., Park, B. B., Malakorn, K., & So, J. J. (2013). *Sustainability assessments of cooperative vehicle intersection control at an urban corridor.* Transportation Research Part C: Emerging Technologies, 32, 193-206.
[13] Osorio, C., & Nanduri, K. (2015). *Urban transportation emissions mitigation: Coupling high-resolution vehicular emissions and traffic models for traffic signal optimization.* Transportation Research Part B: Methodological, 81, 520-538.
[14] Scora, G., & Barth, M. (2006). *Comprehensive modal emissions model (CMEM), version 3.01. User guide.* Centre for Environmental Research and Technology. University of California, Riverside.
[15] Simulation of Urban MObility, www.sumo-sim.org
[16] Sjödin, Å., Ekström, M., Hammarström, U., Yahya, M.-R., Ericsson, E., Larsson, H., Almén, J., Sandström, C., Johansson, H. (2006) *Implementation and Evaluation of the ARTEMIS Road Model for Sweden's International Reporting Obligations on Air Emissions.* 2nd conf. Environment & Transport, incl. 15th conf. Transport and Air Pollution, Reims, France, 12-14 June 2006 proceedings, no 107, Vol. 1 Inrets ed., Arcueil, France, 2006, 375-382.
[17] Webster, F. V. (1958). Traffic signal settings (No. 39).
[18] Zhou, Z., & Cai, M. (2014). *Intersection signal control multi-objective optimization based on genetic algorithm.* Journal of Traffic and Transportation Engineering (English Edition), 1(2), 153-158.