Physica A 632 (2023) 129328

Contents lists available at ScienceDirect

Physica A: Statistical Mechanics and its Applications

journal homepage: www.elsevier.com/locate/physa

Signal setting design to reduce noise emissions in a connected environment

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ARTICLE INFO

Keywords:
Traffic control
Urban
Multi-objective optimisation
Externalities

ABSTRACT

To meet the zero-pollution target on noise by 2030, it is necessary to develop mobility management policies that directly act on noise exposure. This paper proposes traffic signal optimisation in an environment with fully connected vehicles (CVs), combining noise pollution minimisation with total travel time minimisation to improve traffic flow. Traffic signal optimisation was tested on a network with signalised interacting junctions, comparing different approaches and scenarios based on short-range communication between the infrastructure and CVs approaching the junctions. The results show that the proposed traffic control method may be adopted to effectively reduce the impact of traffic noise and improve traffic performance.

1. Introduction and research gap

Reducing exposure to noise pollution is a crucial objective for city authorities aiming to improve public health and quality of life. In 2018, the World Health Organization [49] stated that traffic noise harms the health of almost one-third of Europe's population. Indeed, living in an area affected by transport noise is associated with worse health, well-being and quality of life. In 2017, approximately 18 million people in the European Union (EU) were affected by long-term high annoyance due to transport noise from road, rail and aircraft sources (EEA, 2022). One of the key targets of the *zero-pollution* action plan is to reduce the number of individuals chronically disturbed by transport noise by 30% by 2030. The number of those subjected to high noise disturbance would therefore need to be reduced by roughly 5.3 million compared to 2017. The above objective may well prove particularly challenging, as the number of people exposed to harmful noise levels has remained stable over the last decade (EEA, 2020).

Some major strategic measures concerning road traffic have been identified to meet the zero-pollution target on noise by 2030, such as fleet electrification and the use of low-noise asphalt and noise barriers on main roads. Other tactical measures based on developing enhanced mobility management policies that directly target noise exposure should also be considered. Designing specific traffic control strategies to reduce the impact of vehicles is promising in urban areas, where large variations in speed linked to the effect of congestion are known to increase noise levels. Interest in such policies has been demonstrated through pre- and post-measurement campaigns (Bendtsen and Raaberg, 2005; [22,36]).

The main challenge of this work was to implement a traffic control strategy which minimised noise emissions while optimising travel times. Indeed, different traffic control strategies affect the speed profile of each vehicle running on the network and can thus

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https://doi.org/10.1016/j.physa.2023.129328
Received 4 April 2023; Received in revised form 23 July 2023; Accepted 2 October 2023

directly influence the noise emitted by the traffic flow [53,52].

At urban level, traffic control based on traffic lights is considered one of the most effective strategies to implement. Furthermore, according to the literature, optimising externalities such as noise is usually combined in a multi-objective network design problem with traffic management measures [32], achieving several objectives, such as travel time savings and reduced impacts (e.g., noise pollution, fuel consumption and vehicle emissions; [47]).

However, finding a solution to the optimisation problem becomes challenging for conflicting objectives. Little would appear to be known about simple networks without interacting junctions [50]. Given the scant literature, this paper aims to design a traffic control procedure for multi-objective optimisation of an urban network with interacting junctions for two different objectives, namely minimising total travel time and noise levels.

However, the availability of reliable traffic measurements is generally one of the prerequisites for traffic control strategies to be effective. In the context of conventional vehicles (non-connected vehicles), such measurements are typically obtained from roadside traffic sensors placed at specific locations. This information is easily collected nowadays thanks to developments in vehicle technologies and smart infrastructures in the context of cooperative, connected and automated mobility (CCAM). Communication protocols between each vehicle and the infrastructure and/or between/among vehicles [10] support data collection on vehicles and traffic status [48] and provide users with accurate and reliable travel information and driving assistance.

The automation and communication systems of vehicles provide an opportunity to expand and improve real-time measurement capabilities using information collected on board. Several studies have shown that network performance may be significantly improved by applying enhanced control strategies on networks with connected and automated vehicles rather than with human-driven alone ([13]; Liebner et al., 2012; Fajardo et al., 2011). Using the single data provided by connected and automated vehicles, the limitations of aggregate measures may be overcome, allowing the application of disaggregated models for performance and impact estimation, leading to the development of consistent, more effective traffic control strategies.

Traffic signal optimisation in the presence of connected vehicles has been extensively investigated elsewhere [1,2,13,14,15,18,19,25,34,40,45,46,7,29], some of which focus on minimising externalities, especially emissions and fuel consumption ([12]; Zhao et al., 2021; Zegeye et al., 2013; Zegeye et al., 2009; [40]). However, only Stoilova and Stoilov [41] and Wismans et al. [50] investigated the combination between traffic dynamics and noise emissions for the simple layout of signalised single junctions. To fill the gap, we propose traffic signal optimisation to minimise the total time spent and the noise pollution generated, integrating models for traffic control, traffic flow and noise pollution in the presence of connected vehicles.

The aims of our paper are thus twofold:

- to design a traffic control procedure for multi-objective optimisation of an urban network with interacting junctions for two minimisation objectives, namely total travel time and noise pollution;
- to extend this strategy to the case of the presence of connected vehicles.

The strategy was tested on a network with signalised interacting junctions and short-range communication to exchange information between the infrastructure and the vehicles. The communication region is identified with the control zone centred on each signalised junction. Since the network layout involved interacting junctions, network optimisation strategies to compute the traffic light plans (synchronisation and coordination approach; [5,11,26]) had to be pursued.

This paper is structured as follows: Section 2 presents the methodology and details of the proposed traffic signal approach, as well as the noise power emission model; Section 3 provides the details of the case study and the model settings; Section 4 discusses the numerical results. Finally, Section 5 concludes with policy implications and outlines future research perspectives.

2. Methodology

This section describes the proposed traffic signal strategy. An overview of the proposed strategy with the relevant models is given in Fig. 1. The strategy is suitable for applications in urban contexts to simulate vehicle-to-infrastructure communication when vehicles approach signalised junctions. In general the modelling framework comprises three stages: 1) the initialisation stage; 2) the optimisation stage combining implementation of the traffic control model based on the input variables (TTS and NP) and of the traffic flow model; 3) the final (optimal) decision variables computation.

Further details are provided below regarding the noise power model and traffic signal optimisation. It should be noted that traffic flow is modelled through a hybrid model [42,44,6] able to support the analysis of the control strategies in the presence of CVs [12,43].

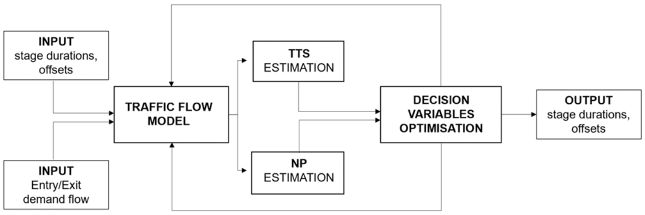

Fig. 1. Overview of the traffic signal optimisation strategy.

2.1. Noise power emission model

Estimating single-vehicle noise emissions is usually performed by employing physical and mathematical models, so-called noise emission models (NEMs). These models depict the emissions of the complex source “vehicle”, including all the sub-sources, such as the engine, transmission, exhaust, rolling and others. The key point is estimating the source power level (L_w) as a function of the main variables and parameters [30]. The prediction chain requires a model to propagate the predicted emission at a sensitive receiver or towards any position (to draw noise maps). Therefore, NEMs are usually coupled with propagation models based on wave propagation and phenomena [4]. The complexity of the propagation models can vary, according to the required degree of precision, from a simple spherical or cylindric propagation, for a point (vehicle) or a line source (flow) respectively [17], to a model that includes relevant phenomena (such as reflection, absorption, diffraction, downward and upward bending of sound waves, wind, etc.). Simple propagation models have proved effective in many applicative conditions, while Kephalopoulos et al. [21] report a more detailed description of sound propagation (CNOSSOS and others).

Combining an NEM and a propagation model leads to a Road Traffic Noise Predictive Model (RTNM). RTNMs were developed several years ago, mainly with a statistical approach based on regression on measured data [35]. This approach is still the most widely adopted at the NEM level. Usually, the vehicle is depicted as a point-like source, whose source power level can be estimated through single vehicle transits, measuring the maximum pressure level with A-weighting ($L_{AF,max}$) at a distance of 7.50 m from the lane centre, and backpropagating to the source to obtain the L_w. It is possible to repeat this procedure for different speeds and car types, including combustion engine vehicles, as well as hybrid and full electric cars [31]. The ISO 11819–1 standard recommends the above procedure for statistical pass-by (SPB) measurements and was also adopted in the IMAGINE project to calibrate the overall noise levels produced during a single transit at a given speed. The same project provided the coefficients A_R, A_P, B_R and B_P of the sound power for the following equations:

$$LW_R(f) = A_R(f) + B_R(f) \cdot \log 10\left(\frac{v}{v_{ref}}\right) \tag{1}$$

$$LW_P(f) = A_P(f) + B_P(f) \cdot \left(\frac{v - v_{ref}}{v_{ref}}\right) \tag{2}$$

where L_{wR} and L_{wP} are the source power levels related to rolling and propulsion respectively, expressed as a function of the frequency octave band f. The IMAGINE project pursued the distinction between the two contributions, based on several complex data collection campaigns, with on-board, pass-by and coast-by measurements [Gijsjan van Blokland, Bert Peeters: The noise emission model for European road traffic, Deliverable 11 of the IMAGINE project, IMA55TR060821-MP10, July 2007]. The coefficients thus obtained are applicable to the average European vehicle fleet in standard conditions. The same approach was followed by the EU reference model “Common noise assessment methods in Europe” (CNOSSOS-EU), for estimating the sound power coefficients for rolling and propulsion, for five categories of vehicles, namely light motor vehicles, medium-heavy vehicles, heavy vehicles, powered two-wheelers, and an open category for new powertrains (see Table 1).

Since the coefficients are obtained through statistical pass-by (SPB) measurements, the parameter tuning strongly depends on the datasets used for the calibration and cannot be easily extended to different conditions. The above characteristic is the main shortcoming of statistical modelling, which is why the dynamic and microscopic modelling of noise emissions and propagation represents a breakthrough in the acoustic research community [16].

For this reason, the possibility of implementing a multi-objective urban traffic control framework for optimisation of noise emissions, together with other parameters, in a network with interacting junctions appears to be an interesting research aim to pursue.

Although this may represent a limitation of the CNOSSOS model described above, for practical applications, the errors observed when comparing CNOSSOS results with field measurements are usually small (approximately ± 2 dBA) in standard conditions. This encourages the adoption of the modelling scheme that suggests a log dependence of the rolling source power level, and a linear slope of the propulsion source power level, as a function of speed (see Fig. 2). The latter approach was used by Pascale et al. [31] and will be used in this paper to define an indicator to evaluate the noise power emission level (NPEL) of a link at a given time step.

Table 1
CNOSSOS-EU, categories of vehicles.

Category	**Name**	**Description**	**Vehicle category in EC** Whole Vehicle Type Approval
1	Light motor vehicles	Passenger cars, delivery vans $\leq$ 3.5 tons, SUVs, MPVs including trailers and caravans	M1 and N1
2	Medium heavy vehicles	Medium heavy vehicles, delivery vans $>$ 3.5 tons, buses, touring cars, etc. with two axles and twin tyre mounting on rear axle	M2 M3 and N2, N3
3	Heavy vehicles	Heavy duty vehicles, touring cars, buses, with three or more axles	M2 and N2 with trailer, M3 and N3
4	Powered two-wheelers	4a mopeds, tricycles or quads $<$ 50 cc 4b motorcycles, tricycles or quads $>$ 50 cc	L1, L2, L6 L3, L4, 15, L7
5	Open category	To be defined according to future needs	N/A

Importantly, modelling the source power level as a function of speed, when the speed is provided at every time step, makes it possible to simulate also "non-standard" conditions, such as those occurring at intersections, in traffic jams and others [16]. For this reason, the possibility to implement a multi-objective urban traffic control framework for optimisation of noise emission, together with other parameters, in a network with interacting junctions appears to be an interesting research aim to be pursued.

2.2. *Traffic signal optimisation model: a global optimisation approach*

This section discusses the details of traffic signal optimisation, whose method refers to the case of signalised interacting intersections [38]. The whole framework is shown in Fig. 1 whilst in Fig. 2 the variables and the models are detailed in accordance with the following analytical expressions. The strategy consists of i) a traffic flow model to compute network performance indicators, such as total time spent (TTS); iii) the noise power (NP) model to estimate it at each junction; iii) a traffic control model to design traffic light decision variables (model for signal settings design). Fig. 3.

2.2.1. *Definition of variables*

Let the intersection network be represented by an undirected graph with a node for each intersection and an edge for each pair of adjacent intersections (the actual traffic directions are irrelevant). Assuming that the green scheduling is described by the stage composition and their sequence, let $c > 0$ be the cycle length, common to all intersections, assumed known.

For each intersection let.

$t_j \in [0, c]$ be the length of stage j as an optimisation variable;.

$t_{ar} \in [0, c]$ be the so-called all-red period at the end of each stage to allow for the safe clearance of the intersection, assumed known (and constant for simplicity's sake);.

$l_k \in [0, c]$ be the lost time for approach k, assumed known. This term consists of two terms: the start-up lost time which occurs every time a queue of vehicles starts moving on a green signal and the clearance lost time, which is a lost time associated with the queue stopping at the end of the green signal, occurring each time a flow of vehicles is stopped. This is defined as the time interval between the last vehicle's front wheels crossing the stop line and the initiation of the green signal for the next stage. The clearance time is considered to eliminate conflict between incompatible vehicle movements within an intersection area (see [39]);.

$g_k = \sum_j \delta_{kj} t_j - t_{ar} - l_k \in [0, c]$ be the effective green for approach k needed for computing the total time spent through a traffic flow model;.

$q_k > 0$ be the arrival flow for approach k, assumed known;.

$s_k > 0$ be the saturation flow for approach k, assumed known.

Apart from non-negativity of optimisation variables, a constraint[1] needs to be introduced for each intersection to guarantee consistency among the stage lengths and the cycle length:

$$\sum_j t_j = c$$

Moreover, for each intersection i let.

$\phi_i \in [0, c[$ be the node offset between the start of a reference stage of intersection i and the start of the reference stage of the first intersection used as a reference for clock.

For each pair of (adjacent) intersections (i, h) in the network, let.

$\phi_{ih} = \phi_h - \phi_i$ be the link offset between intersections i and h, needed for computing total times spent through a traffic flow model.

Summing up, green timings and link offsets are the decision variables.

To solve the problem, simultaneous optimisation (synchronisation) is usually applied, and the stage durations and offsets are optimised together [5]. However, in this paper, the results of the synchronisation approach are compared with those of the sequential approach (coordination) in which the stage durations and offsets are optimised in two successive steps.

2.2.2. *Specification of optimisation functions*

As the selected objective functions to optimise, the two criteria identified are total time spent (TTS) and an indicator of the noise power emission level (NPEL). Optimisation is applied to all interacting junctions in the meantime to achieve global optimisation at all network levels.

TTS is calculated as the sum of the number of vehicles on each link of the network multiplied by the length of the time step, equal to 1 s in this study. Given that there are no vehicles at the beginning of the simulation, there is an initial "warm-up" period in which the indicator is not calculated, and the simulation then proceeds for another 3600 s

Let:

1. t be the time step;
2. T_1, the initial warm-up period;

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[1] Other constraints are sometimes used; for instance, to guarantee the minimum value of the effective green the following constraint must be included: $g_k \geq g_{min} \forall_k$; however, this was not considered in the presence of CVs.

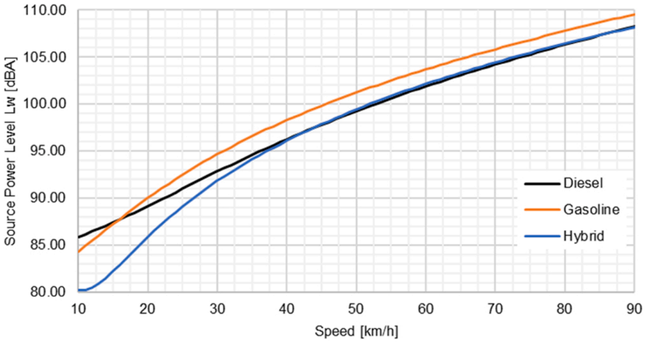

Fig. 2. Regression functions: comparison among vehicles [31].

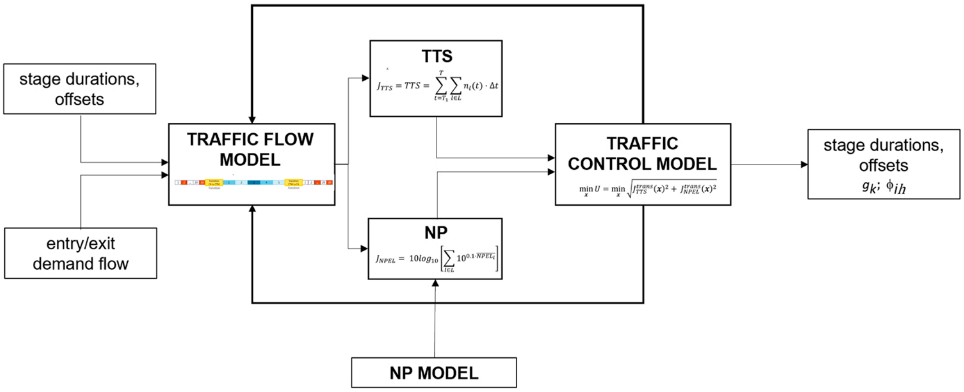

Fig. 3. Traffic signal optimisation strategy.

3. T, the simulation horizon;
4. l, the link that belongs to the set L of links composing the network;
5. $n_l(t)$, the number of vehicles on link l at time step t;
6. Δt, the time step length.

Then the first objective function J_{TTS} is the TTS calculated as:

$$J_{TTS} = TTS = \sum_{t=T_1}^{T}\sum_{l\in L} n_l(t)\cdot\Delta t \tag{3}$$

The indicator to evaluate the NPEL is a function that depends on the mean speed and the number of vehicles of each link at each time step with the same initial "warm-up" period of the TTS.

In particular, let:

7. t be the time step;
8. T_1, the initial warm-up period;
9. T, the simulation horizon;
10. l, the link belonging to the set of links L of the network;
11. i, the vehicle index;
12. $v_l^i(t)$, the speed of vehicle i on link l at time step t;
13. $n_l(t)$, the number of vehicles on link l at time step t;
14. $NPEL_l(t)$, the noise power emission level of the vehicles on link l, for each time step, obtained from the mean speed of the vehicles;
15. $NPEL_{N,T_1+T}$, the indicator of the noise power emission level of the vehicles for the entire network N, between the initial warm-up period T_1 and the simulation horizon T;
16. J, the final indicator included in the multi-objective problem.

The mean speed of vehicles on link l at time step t is obtained as:

$$\overline{v}_l(t) = \sum_{i=1}^{n} \frac{v_l^i(t)}{n_l(t)} \quad \left[\frac{km}{h}\right] \tag{4}$$

The indicator to evaluate the *NPEL* of link l at time step t is defined as:

$$NPEL_l(t) = 10\log_{10}\left[10^{0.1\left(A+B\frac{\overline{v_l}(t)-v_{ref}}{v_{ref}}\right)} + 10^{0.1\left[C+D\log_{10}\left(\frac{\overline{v_l}(t)}{v_{ref}}\right)\right]}\right] + 10\log_{10}[n_l(t)] \tag{5}$$

where A, B, C, D and v_{ref} are coefficients estimated dependent on the powertrain (in our case the considered scenario referring to all Diesel vehicles. Thus A= 98.77, B=15.28, C=102.76 and D=35.74, and the considered $\mathrm{v_{ref}}$ equals $70km/h$.) of the vehicles, with speeds expressed in [km/h] [31]. This value is calculated only for $n_l(t) > 0$.

Then, for each link l, we calculate the mean value of the NPEL between the warm-up period and the simulation horizon as:

$$\overline{NPEL_l} = \frac{\sum\limits_{t=T_1}^{T} NPEL_l(t)}{\sum\limits_{t=T_1}^{T} (n_l(t) > 0)} [dBA] \tag{6}$$

Lastly, the indicator J_{NPEL} to evaluate the *NPEL* of the network is calculated as:

$$J_{NPEL} = 10\log_{10}\left[\sum_{l \in L} 10^{0.1 \cdot \overline{NPEL_l}}\right] \tag{7}$$

2.2.3. Multi-objective problem

As this problem involves multi-objective optimisation, it is unlikely to find a single point of the solution set that minimises simultaneously all the objectives. Hence, to identify a suitable solution, a weighted sum of transformed objective functions needs to be computed. The aim is to minimise the distance to the utopia point, which has as coordinates the minimum of each objective function, sometimes known as the ideal point.

To transform each objective function, the *upper-lower-bound approach* [23,24,37,51] is applied. Let:

1. $J_o(\boldsymbol{x})$ be the objective function o, evaluated as a function of variables $\boldsymbol{x}$;
2. $J_o^{\min Pareto}$, the minimum value of the objective function o, referring to the utopia point;
3. $J_o^{\max Pareto} = \max_{1 \le j \le k}\left(J_o\left(\boldsymbol{x}_j^*\right)\right)$, the Pareto maximum of the objective function o, with $\boldsymbol{x}_j^*$ being the point that minimises the j-th objective function (such that it is a vertex of the Pareto optimal set in the design space and $J_o\left(\boldsymbol{x}_j^*\right)$ is a vertex of the Pareto optimal set in the criterion space), coordinate of the nadir point.

Each objective function is transformed as

$$J_o^{trans} = \frac{J_o(\boldsymbol{x}) - J_o^{\min Pareto}}{J_o^{\max Pareto} - J_o^{\min Pareto}} \tag{8}$$

The solution with the closest distance to the Utopia point is then x, that is:

$$\min_{\boldsymbol{x}} U = \min_{\boldsymbol{x}} \sqrt{J_{TTS}^{trans}(\boldsymbol{x})^2 + J_{NPEL}^{trans}(\boldsymbol{x})^2} \tag{9}$$

2.2.4. Solution algorithm

Finally, the solution algorithm was the differential evolution (DE) method, a metaheuristic procedure [27,33]. Differential evolution was applied with the following parameter settings [12]:

- Population size: $5D$
- Combination probability: 0.90
- Scale factor F: $0.50 \cdot (1 + rand)$
- Maximum iterations: 1500

The stage durations and the absolute (node) offset of the traffic light plan for each junction are the set of control variables D. The population size is set equal to the number of variables multiplied by 5 (Storn and Price, 1997). In the scale factor F, the value *rand* represents a random value with a uniform distribution between 0 and 1, which produces a differential evolution with a random scale factor (Das et al., 2005) to reduce z, the risk of stagnating at a local optimum.

3. Case study

To test the proposed strategy, the following case study was designed. A network comprising five interacting junctions was considered: four signalised junctions compose a grid network, and one junction is connected to the grid through an arterial. Altogether, the network consists of five external and five internal mono-lane and two-way links. Each internal link is 810 m long, whilst each external link (300 m long) connects the sources with the network. In terms of traffic signal optimisation each signalised junction is characterised by three approaches with a green light in only one stage, a clearance period of three seconds between successive stages and a cycle length of 90 s

Table 2 summarises the flows from each origin to each destination.

With regard to path behaviour modelling, the Logit choice model was applied, and two paths were considered for each origin-destination pair as summarised below (Table 3).

In terms of simulation interval, a horizon of 4500 s including a warm-up period of 900 s was considered. As regards traffic flow models the main settings refer to the time step (Δt), jam density (k_{jam}), cell length, vehicle length, free flow (v_f) and the shock wave speed (w), maximum flow rate (qi), the dawdling probability (p) and the minimum speed to apply the dawdling rule. The settings in question are specified in the following table. (Table 4).

4. Numerical results and discussion

Regarding the different optimisation functions, the mono-criterion TTS and NP minimisation was first tested, followed by a multi-criteria optimisation that combined both criteria. The synchronisation and coordination approaches were applied for each optimisation procedure, as described in Section 2.2 [5].

4.1. Synchronisation approach

Table 5 shows the values of the indicators computed for the entire network for each optimisation, and the percentual difference to each minimum value.

It can be observed that each of the two indicators assumes the lowest value depending on the objective function considered. Furthermore, in the case of multi-objective optimisation, the indicators assume intermediate values of 183928 [veh s] for TTS and 111.62 [dBA] for JNPEL. The TTS increases by around 260% from TTS minimisation to noise minimisation, whereas JNPEL increases by around 6% from noise minimisation to TTS minimisation. Finally, in the case of multi-objective optimisation, TTS increases (with respect to its minimum value) by around 46% whilst JNPEL increases (against its minimum value) by around 0.7%.

The effects of the optimisation criteria on traffic signals are reported in Table 6 and Fig. 4.

The observed increase in TTS value when minimising J_{NPEL} was an expected result, given the trend of the L_w function against speed, as demonstrated in Fig. 2. Minimising TTS entails an increase in average vehicle speed, while minimising JNPEL means a reduction in their average speed. Thus, a coordination approach was conducted to investigate further.

4.2. Coordination approach

The indicators computed for the entire network for each optimisation and the percentage difference at each minimum value are shown in Table 7. It can be observed that each of the two indicators assumes the lowest value depending on the objective function considered. For the multi-objective optimisation, the indicators assume an intermediate value of 151840 [veh s] for TTS and 114.136 [dBA] for J_{NPEL}. TTS increases by around 50% from TTS minimisation to noise minimisation, whereas J_{NPEL} increases by around 5% from noise minimisation to TTS minimisation. Finally, in the case of multi-objective optimisation TTS increases (with respect to its minimum value) by around 20% whilst J_{NPEL} increases (against its minimum) by around 2%.

The impacts of the optimisation procedures can also be observed in terms of the results of traffic signals. Table 8 and Fig. 5 show the traffic light plans of each intersection corresponding to each objective function (minimum total time spent, minimum sum of noise power emission level, and minimum multi-objective function). (Fig. 6).

Finally, Figs. 7 and 8 show the indicators of TTS and noise-specific power (sum) for each link. Firstly, it can be observed that the internal links (IDs from 1 to 10) and the external links (IDs from 11 to 20) exhibit different behaviours in terms of higher and lower values of the indicators, which relates to the varying number of vehicles on each link. Secondly, concerning internal links, it is possible to observe a different behaviour of each indicator depending on the objective function considered.

The noise indicator depends on the speed of the vehicles. As a result, minimising this indicator entails a reduction in vehicle speed and hence an increase in total time spent. Table 9 summarises the mean speed of vehicles in the internal links of the network under the synchronisation and coordination approach for each objective to optimise. In this table we may observe the large reduction in mean speed for J_NPEL minimisation under the synchronisation approach, which increased the TTS in Table 5.

5. Conclusions, implications and future perspectives

This paper focused on implementing the traffic signal optimisation strategy to be applied to an urban network with connected vehicles (CVs). Designing specific traffic control strategies to reduce vehicle-related impacts is particularly promising in urban areas [3,22,36,8,9] where large variations in speed, whose amplitude is linked to congestion, are known to raise noise levels.

Table 2
Origin-destination matrix.

		DESTINATION [PCU/h]					
		12	14	16	18	20	TOTAL
ORIGIN	11	0	100	50	50	0	200
[PCU/h]	13	50	0	50	50	50	200
	15	50	20	0	20	50	140
	17	50	20	20	0	50	140
	19	0	50	50	50	0	150
	TOTAL	150	190	170	170	150	830

Table 3
Flow for each O-D pair.

Origin	Destination	Path ID	Arc sequence						Probability	No. of vehicles per hour	No. of vehicles in simulation
11	14	1	{ 1	11	13	4	-	-}	0.9	90	113
		2	{ 1	11	15	17	19	4}	0.1	10	12
	16	1	{ 1	11	13	20	18	6}	0.1	5	6
		2	{ 1	11	15	6	-	-}	0.9	45	56
	18	1	{ 1	11	13	20	8	-}	0.5	25	31
		2	{ 1	11	15	17	8	-}	0.5	25	31
	20	1	{ 1	10	-	-	-	-}	0.5	0	0
		2	{ 1	10	-	-	-	-}	0.5	0	0
13	12	1	{ 3	14	12	2	-	-}	0.9	45	56
		2	{ 3	20	18	16	12	2}	0.1	5	6
	16	1	{ 3	14	15	6	-	-}	0.5	25	31
		2	{ 3	20	18	6	-	-}	0.5	25	31
	18	1	{ 3	14	15	17	8	-}	0.1	5	6
		2	{ 3	20	8	-	-	-}	0.9	45	56
	20	1	{ 3	14	12	10	-	-}	0.9	45	56
		2	{ 3	20	18	16	12	10}	0.1	5	6
15	12	1	{ 5	16	12	2	-	-}	0.1	5	6
		2	{ 5	17	19	14	12	2}	0.9	45	56
	14	1	{ 5	16	13	4	-	-}	0.5	10	12
		2	{ 5	17	19	4	-	-}	0.5	10	12
	18	1	{ 5	16	13	20	8	-}	0.9	18	23
		2	{ 5	17	8	-	-	-}	0.1	2	2
	20	1	{ 5	16	12	10		-}	0.9	45	56
		2	{ 5	17	19	14	12	10}	0.1	5	6
17	12	1	{ 7	19	14	12	2	-}	0.5	25	31
		2	{ 7	18	16	12	2	-}	0.5	25	31
	14	1	{ 7	9	4			-}	0.9	18	23
		2	{ 7	18	16	13	4	-}	0.1	2	2
	16	1	{ 7	19	14	15	6	-}	0.1	2	2
		2	{ 7	18	6			-}	0.9	18	23
	20	1	{ 7	19	14	12	10	-}	0.5	25	31
		2	{ 7	18	16	12	10	-}	0.5	25	31
19	12	1	{ 9	2				-}	0.5	0	0
		2	{ 9	2				-}	0.5	0	0
	14	1	{ 9	11	13	4		-}	0.9	45	56
		2	{ 9	11	15	17	19	4}	0.1	5	6
	16	1	{ 9	11	13	20	18	6}	0.1	5	6
		2	{ 9	11	15	6		-}	0.9	45	56
	18	1	{ 9	11	13	20	8	-}	0.5	25	31
		2	{ 9	11	15	17	8	-}	0.5	25	31

According to the literature, the optimisation of externalities is usually combined with network performance measures in a multi-objective problem [32]. In this case, several objectives may be achieved, such as travel time savings and reduced impacts (e.g., noise pollution, fuel consumption and vehicle emissions; [47]), while finding a solution to the optimisation problem becomes a challenge when dealing with conflicting objectives. Given the complexity of the optimisation problem for the objective function, the literature comprises studies [50] for simple networks without interacting junctions.

This paper proposed a traffic signal strategy to minimise travel times and noise pollution for a complex network layout composed of interacting junctions. Moreover, the communication systems of vehicles allow the expansion and improvement of real-time measurement using the vehicle information available through onboard sensors and communication devices. Disaggregated models for performance and impact estimation were applied, and consistent, more effective control strategies could thus be developed. Based on previous considerations, the proposed framework aimed to minimise the total time spent (TTS) and noise pollution considering the

Table 4
Traffic flow model settings.

Parameter	CTM	CA
Δt	1 s	
k_{jam}	200 veh/km	
Cell length	22.50 m	2.50 m
Vehicle length	-	2 cells
v_f	22.50 m/s	9 cells/s
w	5 m/s	-
q_i	2000 veh/h	-
p	-	0.266
Min speed to apply dawdling	-	2 cells/s

Table 5
Indicator overview – synchronisation.

Objective to optimise	TTS [veh s]	J_{NPEL} [dBA]
TTS MIN	126356 (base)	117.42 (+5.96%)
J_{NPEL} MIN	452559 (+258.16%)	110.81 (base)
MULTI - OPTI	183928 (+45.56%)	111.60 (+0.73%)

Table 6
Green timings (GT) and offsets – synchronisation.

		Min TTS	**Min noise**	**Min multi-objective**
Junction 1	**Offset**	1	1	1
	GT Phase 1	19	43	24
	GT Phase 2	39	14	52
	GT Phase 3	32	33	14
Junction 2	**Offset**	57	41	46
	GT Phase 1	33	12	14
	GT Phase 2	18	61	54
	GT Phase 3	39	17	22
Junction 3	**Offset**	4	75	14
	GT Phase 1	34	30	32
	GT Phase 2	19	48	44
	GT Phase 3	37	12	14
Junction 4	**Offset**	66	12	20
	GT Phase 1	41	54	52
	GT Phase 2	32	6	11
	GT Phase 3	17	30	27
Junction 5	**Offset**	34	55	11
	GT Phase 1	42	51	43
	GT Phase 2	19	9	15
	GT Phase 3	29	30	32

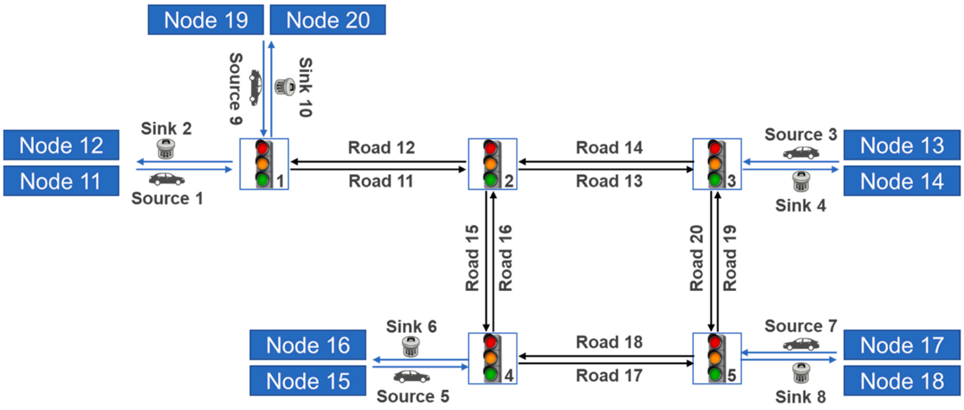

Fig. 4. Five–network layout.

Table 7
Indicator overview – coordination.

Objective to optimise	TTS [veh s]	J_{NPEL} [dBA]
TTS MIN	126356 (base)	117.42 (+4.34%)
J_{NPEL} MIN	190191 (+50.52%)	112.54 (base)
MULTI - OPTI	151840 (+20.17%)	114.10 (+1.42%)

Table 8
Green timings and offsets – coordination.

		Min TTS	**Min noise**	**Min multi-objective**
Junction 1	**Offset**	1	1	1
	GT Phase 1	19	19	19
	GT Phase 2	39	39	39
	GT Phase 3	32	32	32
Junction 2	**Offset**	57	14	38
	GT Phase 1	33	33	33
	GT Phase 2	18	18	18
	GT Phase 3	39	39	39
Junction 3	**Offset**	4	9	52
	GT Phase 1	34	34	34
	GT Phase 2	19	19	19
	GT Phase 3	37	37	37
Junction 4	**Offset**	66	62	39
	GT Phase 1	41	41	41
	GT Phase 2	32	32	32
	GT Phase 3	17	17	17
Junction 5	**Offset**	34	63	88
	GT Phase 1	42	42	42
	GT Phase 2	19	19	19
	GT Phase 3	29	29	29

exchange of information between vehicles and the infrastructure. Noise power (NP) was considered a proxy of noise pollution. The noise power emission level (NPEL) of a link at a given time step was estimated by using the approach of Pascale et al. [31] and by adopting the modelling scheme that suggests a logarithmic dependence of the rolling source power level and a linear slope of the propulsion source power level as a function of speed.

The optimisation strategy was implemented on a fully connected hybrid network combining a four-node grid with an arterial. The network layout in question comprised interacting junctions, and therefore the traffic light plans had to be computed following network optimisation strategies [5]. Synchronisation and coordination methods were applied, based respectively on simultaneous and sequential optimisation of traffic light decision variables (green timings and offsets).

In terms of metrics to evaluate the impact of the proposed strategy, *total time spent (TTS)*, computed at the network level, and a *network-wide indicator of the noise–power emission level (J_{NPEL})*, defined as a logarithmic sum of the mean noise power emission level[2] of each link, were considered.

In the first case, under the synchronisation approach, the results show that each of the two indicators assumes the lowest value depending on the objective function considered. Furthermore, in the case of multi-objective optimisation, they assume an intermediate value, respectively equal to 183928 [veh s] for TTS and 111.62 [dBA] for J_{NPEL}. From TTS minimisation to noise minimisation, TTS increases by around 260%, whereas from noise minimisation to TTS minimisation, J_{NPEL} increases by around 6%. Finally, in the case of multi-objective optimisation, TTS increases (with respect to its minimum) by around 46%, while J_{NPEL} increases (with respect to its minimum) by around 0.7%.

In the second application, under the coordination approach, the results still show that each of the two indicators assumes the lowest value depending on the objective function considered. Furthermore, in the case of multi-objective optimisation, they assume an intermediate value respectively of 151840 [veh s] for TTS and 114.14 [dBA] for J_{NPEL}. From TTS minimisation to noise minimisation, TTS increases by around 50%, whereas from noise minimisation to TTS minimisation, J_{NPEL} increases by around 5%. Finally, in the case of multi-objective optimisation, TTS increases (with respect to its minimum) by around 20%, while J_{NPEL} increases (against its minimum) by around 2%.

In conclusion, the results show that a traffic control method can be adopted to effectively reduce the impact of traffic noise. However, the strategy must be properly designed differently from common applications. Instead of following a synchronisation approach, a coordination approach should be considered. To achieve the zero-pollution target on noise by 2030, some key measures concerning road traffic have been identified, such as fleet electrification, and the use of low-noise asphalt and noise barriers on major

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[2] The noise power emission level was calculated at each time step as a function of the number of vehicles and by applying an energy law to their mean speed.

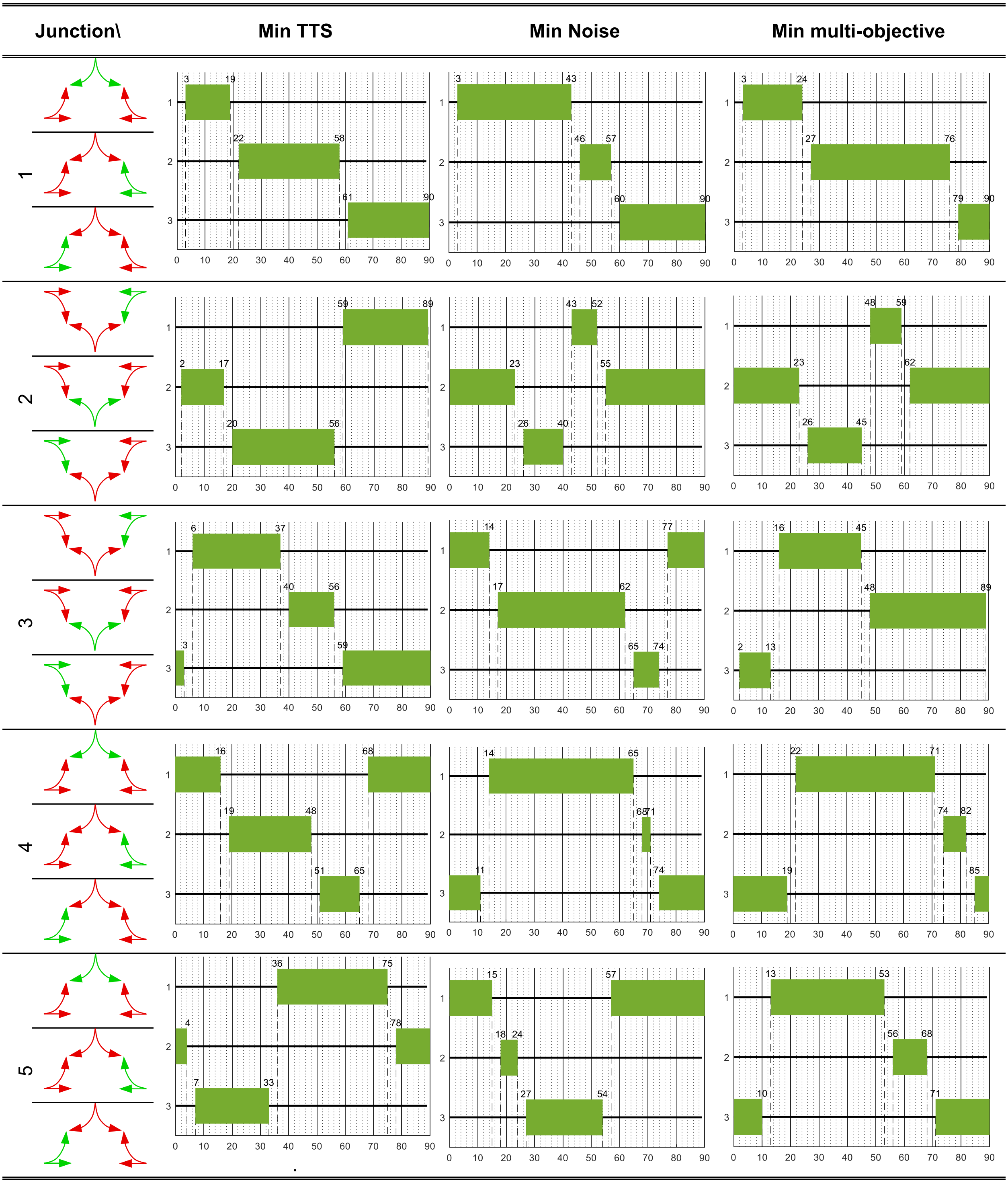

Fig. 5. Green timings and offsets – synchronisation.

roads. Moreover, the impact of such measures can be appreciated in a medium-long term horizon depending on the customers' transition to electric powertrains and on the effectiveness of public administration investments. In the short-term horizon, enhanced mobility management policies such as the proposed traffic lights strategy that directly target noise exposure should be considered. Additionally, integrating traffic control with other traffic management approaches, such as speed advisory systems, could further improve the effectiveness of this strategy and enhance its impact.

The study findings also highlight the need for a well-considered, multi-objective optimisation approach to achieve optimal results.

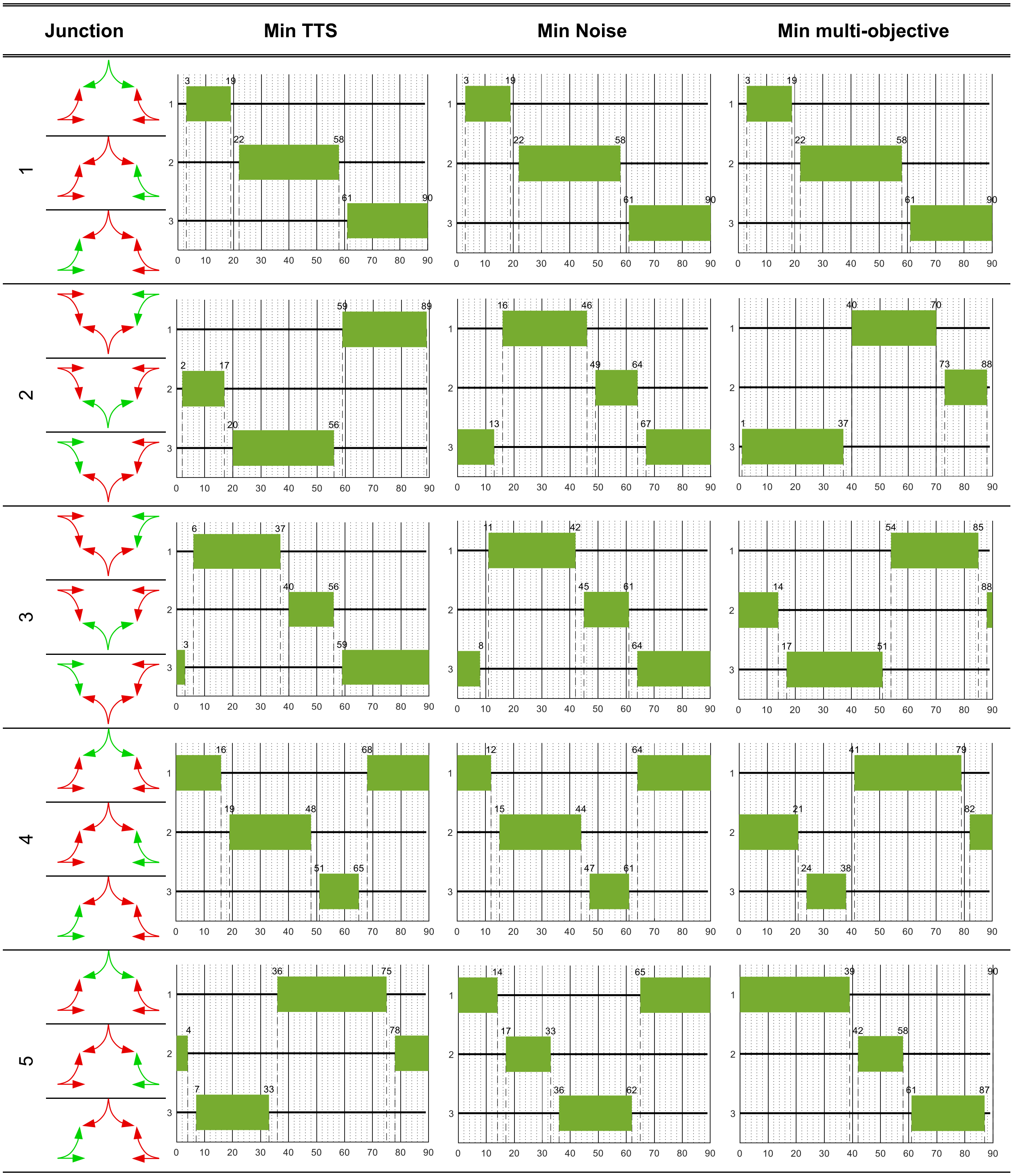

Fig. 6. Green timings and offsets – coordination.

The insights gained from this investigation can guide future research in this field and contribute to the development of efficient approaches.

Regarding future works, it would be worth investigating the integration of the proposed strategy by explicitly considering the impact of vehicle automation on traffic flow [20,28]. Additionally, the proposed traffic control framework could be further developed for cooperative optimisation by integrating other strategies, such as route guidance and speed optimisation.

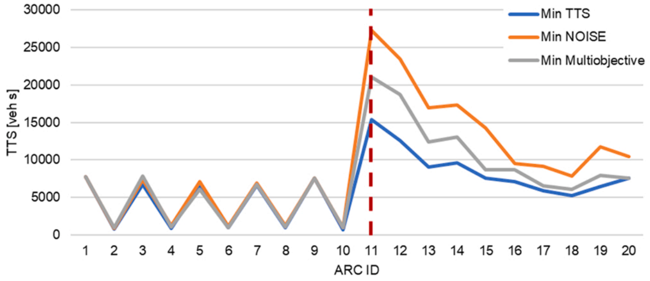

Fig. 7. Total Time Spent [veh s] for each link.

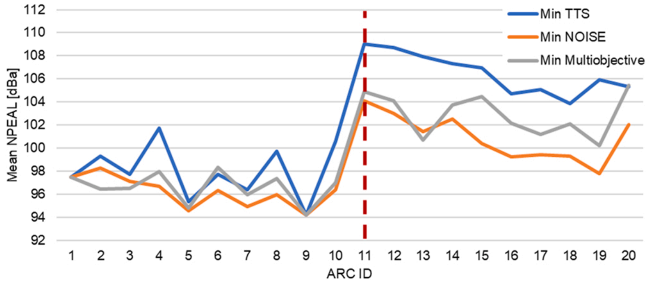

Fig. 8. Mean value of noise specific power for each link.

Table 9
Mean speed [km/h] of vehicles in the internal links 11–20.

Objective to optimise	Synchronisation	Coordination
TTS MIN	68.65	68.65
J_{NPEL} MIN	27.02	42.33
MULTI - OPTI	45.86	58.41

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was partially funded by the University of Salerno, under local grants no. ORSA214124 – 2019 and no. ORSA223793–2022. It was also partially funded by the project DIGIT-CCAM “Progetti di Rilevante Interesse Nazionale” (PRIN 2020 -MUR), the project BORGO 4.0 (POR CAMPANIA FESR 2014 – 2020). Furthermore, this study was carried out within the MOST – Sustainable Mobility National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors’ views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

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