Chapter

# Centralised Traffic Control and Green Light Optimal Speed Advisory Procedure in Mixed Traffic Flow: An Integrated Modelling Framework

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## Abstract

The paper aims to develop an integrated modelling framework for urban network traffic control in the presence of connected and autonomous vehicles (CAVs). The framework is further composed of two sub models: the first of which focuses on the traffic control problem in the case of hybrid flow conditions (unequipped vehicles and connected vehicles) and the second aims to control the automated vehicles in terms of speed optimisation. The traffic control strategy drew on the hybrid combination between the centralised approach based on a multi-objective optimisation and a link metering based on a single control function; whilst with reference to the speed guidance, the GLOSA (Green Light Optimal Speed Advisory) procedure was considered. Furthermore, the presence of connected vehicles has also been considered to support the estimation procedure of location and speed of unequipped vehicles. In terms of traffic flow modelling the microscopic approach has been applied. The proposed framework was applied by considering a simple real network (in the city centre of Naples, in the Southern of Italy) that was composed by one origin–destination pair and two alternative paths. The network layout is characterised by one diversion node and two alternative paths connecting the same origin - destination pair; three scenarios were tested: the first was only based on a centralised traffic control procedure, the second on speed guidance optimisation and the third was based on the combination of both sub-models. Finally, the framework effectiveness was analised in terms of within-day dynamics with respect to the travel times and queue length performance indices.

**Keywords:** centralised traffic control, speed guidance, multi-criteria optimisation, microscopic traffic flow modelling

## 1. Introduction and motivation

In general terms, the Intelligent Transportation Systems (ITS) have historically been introduced to increase the transportation networks performances allowing for the optimisation of several indicators which are strictly related such as travel time, emissions, consumption and safety. The effectiveness of all ITS proposed strategies is mainly based on the idea of traffic congestion predictions and drivers'/travellers' behaviour anticipation. Indeed, all relevant policies such as driving guidance, information systems design and traffic management are based on the consistency between the decision/control variables design and the actual traffic conditions (degree of congestion and travel times estimation). ITS solutions may generally be distinguished for urban and non-urban network applications; in particular, in the case of urban networks, the traffic control is one of the most suitable solutions to be applied, especially in the case of on-line traffic management.

However, in more recent times the ITS field has been integrated with cooperative services (Cooperative ITS; C-ITS). The main contribution is on the communication between vehicle and infrastructure (V2I), able to further optimise the vehicle driving behaviour along arterials in uninterrupted flow conditions and at junctions in the case of interrupted flow situations. The chapter's main focus is on strategies able to optimise the vehicles' behaviour at junctions, indeed, in accordance with literature, one of the proposed approaches is that of the GLOSA (Green Light Optimal Speed Advisory) which provides a warning to the driver regarding the best speed to maintain while approaching the junction by avoiding stops at junctions. A further classification of the GLOSA may be defined in literature in terms of MULTI-SEGMENT GLOSA (MS-GLOSA) if the optimisation strategy is applied at several/successive junctions and in terms of SINGLE-SEGMENT GLOSA (S-GLOSA) if the optimisation is applied only to the next traffic light that the driver will encounter along his/her trajectory.

The chapter aims to propose the integration between the GLOSA and the Traffic control strategy. The proposed framework has been applied at real case study; the considered subnetwork is composed by successive junctions and in terms of driving control the S-GLOSA procedure has been applied and this has been combined with the traffic control method. Regarding the traffic management a hybrid approach, suitable for urban network management, has been applied combining the centralised traffic control for urban networks (interacting junctions) and the link metering. The proposed simulation environment, based on Matlab/Simulink and SUMO, is a modular platform that considers the vehicle, the driver, the infrastructure and the traffic, the driving assistance systems, and finally the communication systems for cooperative driving; all components are simultaneously simulated in a whole environment.

As already anticipated the whole framework was analysed by considering an application to simple real network (in the city centre of Naples, in the Southern of Italy) that was composed by one origin–destination pair and two alternative paths.

Three scenarios were tested: the first was only based on a traffic control procedure, the second one concerned the speed guidance optimisation and the third was focused on the combination of both sub-models.

The remainder of the paper is organised as follows: in section 2 a brief overview of the literature is proposed; the whole modelling framework and the implementation settings, the traffic control problem and the Green Light Optimal Speed Advisory (GLOSA) procedure are displayed in section 3; in section 4 is presented the numerical application whilst results and future perspectives are discussed in section 5.

## 2. State of play

In this section an overview of the literature review regarding the Vehicle to Vehicle communication (V2V) and the vehicle to infrastructure communications (V2I) and in particular the driving assistance services, and the urban traffic control problem is provided.

### 2.1 Vehicle to vehicle (V2V) /to infrastructure communication (V2I): the driving assistance

The vehicle to vehicle communication is based on the idea that vehicles may exchange information about position, speed and location. In general, most relevant enhancements in the research field of the driving assistance refer to the cooperative awareness aiming to support the active road safety and the traffic efficiency to guarantee the speed management and the road navigation. A more detailed description is provided in the following.

Firstly, the Hazardous Location Notifications (HLN) category may be identified; this kind of services aims to provide road' users about hazardous situations in particular in terms of location, type, expected duration, etc. These services may be further classified in terms of Emergency electronic Brake Light (EBL) for warning drivers of hard braking by vehicles ahead; Emergency Vehicle Approaching (EVA) for providing an early warning of approaching emergency vehicles; Slow or Stationary Vehicle (SSV) for warning drivers about slow or stationary/broken down vehicles ahead; Traffic Jam ahead Warning (TJW) able to provide an alert to the driver that in traffic jam conditions reaches the end of the queue tail; Road Works Warning (RWW) aiming to inform drivers about works on the roads; Intersection movement assist (IMA) that warms drivers of vehicles approaching from a lateral position to the junction.

Further services within HLN category concern the collision risk minimisation (i.e. Cooperative Collision Risk Warning, CCRW) and the drivers of motorcycles warning (i.e. Motor Cycle Approaching indication, MCA).

Other kinds of applications refer to the vehicle to infrastructure communications and in particular to the signage; as the in-Vehicle SiGNage (VSGN) aiming at providing users' with road signs advanced information in the vehicle surroundings (this may facilitate drivers' gap at the signalised junctions), the in-Vehicle SPeeD limits (VSPD), aiming to provide users' with speed limits as well the ShockWave Damping (SWD) service able to recommend drivers about the optimal speed to be adopted by displaying the information in the vehicle. More in general there are the vulnerable road user (VRU) applications aiming at targeting crashes in case of vulnerable situations (for instance work areas, pedestrian detections, presence of emergency vehicles).

Other enhanced applications in case of urban contexts are Green Light Optimal Speed Advisory (GLOSA), Signal Violation/Intersection safety (SigV), Traffic Signal Priority etc.

Concerning the Green Light Optimal Speed Advisory (GLOSA) this is able to provide drivers with speed advice when they are approaching the traffic lights in order to uniformly mitigate the driving conditions by reducing the impact of acceleration/braking. With reference to the Signal Violation/Intersection safety (SigV) and the Traffic Signal Priority (TSP) these are respectively a safety-critical task focusing on the reduction of the number and severity of collisions at signalised intersections and a service able to guarantee the priority at signalised junctions of specific vehicles as emergency vehicles, public transport, etc.

Finally, other services are also referred to the in vehicle - infotainment applications that may be adopted in order to provide drivers with different kinds of information not only in terms of routes but also in terms of available services as parking or charging stations.

An overview of the main V2V and V2I applications is provided in the following table (see **Table 1**).

In general, it may be argued that in general vehicles are already connected devices; the development of an integrated framework combining the above

| V2V | V2I |
|---|---|
| Emergency electronic Brake Light | in-Vehicle SiGNage |
| Emergency Vehicle Approaching | in-Vehicle SPeeD limits |
| Slow or Stationary Vehicle | ShockWave Damping |
| Traffic Jam ahead Warning | Vulnerable Road User applications |
| Road Works Warning | |
| Intersection movement assist | |

**Table 1.**
*V2V & V2I applications.*

described services in which the vehicles will be able to interact each other and with the road infrastructures, is defined within the domain of Cooperative Intelligent Transport Systems (C-ITS). The C – ITS will be able to guarantee the road network management by synchronising all services and all shared information.

In conclusion in terms of driver guidance this research focuses on the implementation of GLOSA algorithm aiming to improve the traffic efficiency. The algorithm firstly calculates the distance and the travel time to the front traffic signal, then estimate the target speed constrained to the rules that were predefined considering different signal phases at the estimated arrival time.

## 2.2 V2I – intersection applications: the urban traffic control

The first criterion of classification of proposed methods in literature refers to the level of aggregation of input variables suitable for consideration in the optimisation procedure; in general two different kinds of variables may be adopted: the aggregate *flow* variables or the disaggregate *arrival* variables; therefore methods based on aggregate variables are also called flow based whereas methods based on disaggregate variables are also called arrival based methods.

Within *flow based methods* a further categorisation may be introduced in terms of junctions interaction; in particular the methods may be divided under single junction and networks depending on the degree of interaction between successive junctions that is isolated junction and interacting junctions [1]; then in case of interacting junctions the urban networks methods have to be applied whilst in case of isolated junction the single junction methods have to be considered. On the methodological point of view in case of interacting junctions the delay of the downstream approaches is influenced by delay of upstream furthermore the set of decision variables needed is also composed not only by stage durations and cycle time but also by an additional variable represented by the offset. Indeed, the offsets are introduced to describe the leg between the green stage at upstream and the green stage at downstream on the same flow direction. In this paper the interacting junctions' approaches are considered. It must be clarified that in case of urban traffic control the interaction between successive junctions may not be neglected therefore methods referring to the interacting junctions are needed in case of urban traffic control.

Alternatively, the *arrival based methods* may be considered in which starting from the number of arriving vehicles collected through loop detectors, the timing plans may be dynamically adapted to the traffic changes by allocating different green timings durations (extend/shorten) and by optimising the cycle length.

In terms of time dependency, it may be argued that flow based methods may be stationary or dynamic over time differently from arrival based methods that are intrinsically dynamic; this paper mainly focuses on dynamic approaches in order to provide a method suitable for on-line traffic management.

More in general two main traffic control paradigms may be related to the traffic flow input variables: the *centralised* and the *decentralised* approaches [2]. Indeed in case of centralised paradigms the traffic measurements are supposed to be received by a single central control agent which is responsible for deriving and implementing all control actions system considered consisting of three components respectively for regulating green splits, offsets, and cycle time; in case of decentralised paradigms the controller does not require information about global network inflow and the controller locally adjusts the traffic signal decision variables. In the last case depending on the adopted method variables adjustment may depend on both upstream and downstream local measurements (e.g. queue length) at each junction.

In summary two main dynamic approaches may be distinguished: the *planning-based traffic signal control* within centralised paradigms and the *actuated traffic signal control* within decentralised paradigms. In the first case, optimisation method starting from observed data and a traffic flow prediction model in forward time horizon, the actual input flows are estimated [3]. In general, the approach is oriented to decision variables design every control interval. Concerning the actuated traffic signal control, starting from the number of arriving vehicles collected through loop detectors, the timing plans may be dynamically adapted to the traffic changes by allocating different green timings durations (extend/shorten) and by the cycle length optimisation.

Alternatively, to these methods are approaches are also discussed in literature in particular:

- the control of some sensitive links, arterials [4–7],
- parts of the urban network through the implementation of gating control at the perimeter of the protected network (e.g. link metering or gating control; LM; see [8–11].

All these methods usually adopted in presence of unequipped vehicles must be extended to the case of connected vehicles. One of the most limiting points in case of centralised traffic control is the traffic flow prediction necessary to guarantee the consistency between traffic flow inputs and decision variables optimisation every control interval. The presence of connected vehicle may be useful in terms of estimation of location and speed of unequipped vehicles supporting the traffic flow prediction robustness. In terms of traffic flow modelling a microscopic approach has been considered.

In conclusion in terms of traffic control the paper aim is twofold:

- To apply a hybrid implementation of the centralised traffic control method and the link metering approach;
- To integrate these approaches with a procedure for traffic flow estimations.

In particular, one of the main problems in case of centralised control is the queue spillback and propagation in oversaturation conditions and queue may not be properly managed with respect to the longitudinal capacity.

To this aim a further refinement of the optimisation criteria is herein introduced: the queue equidistribution. A multi - objective optimisation procedure has been considered based on the combination of two criteria: the queue length optimisation and the queue equidistribution and a proper metaheuristics algorithm has been applied. Regarding the link metering control as further discussed in sub-Section 2, this is based on occupancy as a control variable.

## 3. Modelling framework and implementation settings

### 3.1 Overview of the proposed control framework

The proposed framework is composed by two sub-models: the first one aims at the traffic lights decision variables optimisation whilst the second one aims at the vehicle control trough speed optimisation.

Furthermore, in terms of traffic management an on-line procedure based on the combination of a centralised method and a link metering approach is adopted.

Regarding the driver guidance this paper focuses on the implementation of GLOSA algorithm aiming to improve the traffic efficiency. The algorithm firstly calculates the distance and travel time to the front traffic signal, then calculate the target speed constrained to the traffic signal decision variables and then to the estimated travel times.

Two sub-models operate simultaneously, and an overview of the framework is displayed in **Figure 1**.

In particular, the vehicle control is actuated depending on the vehicles distance from the infrastructure, whilst the traffic control procedure operates every control interval as it will be further discussed in the following Section 3 focusing on the implementation settings.

As already anticipated, the whole framework is composed by two sub- models:

- The first one aims at the traffic control decision variables design;
- The second one aims at the vehicle control decision variables optimisation.

In **Figure 2** a further overview of the whole framework including the vehicle control and in particular the traffic management, is shown then in the following a detailed description of each sub-model is provided.

Regarding the traffic control framework, this operates as a predictive control in which the network traffic control is the optimisation procedure, the proposed

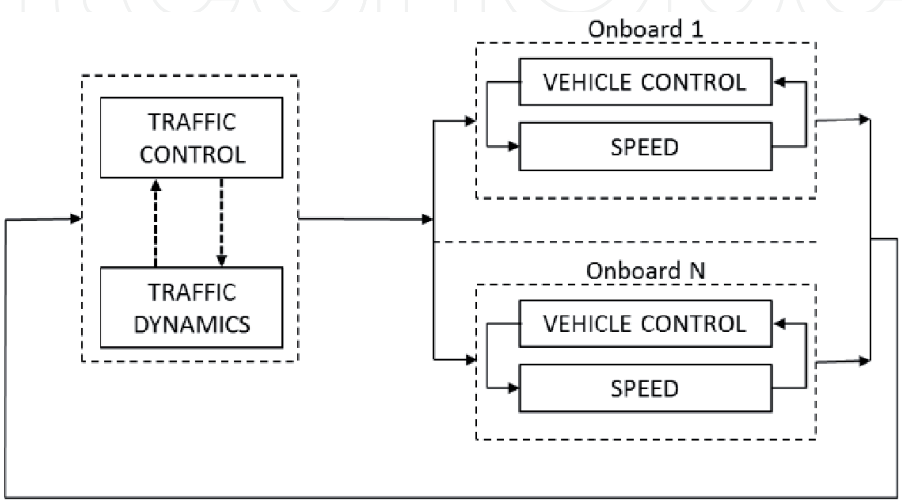


**Figure 1.**
*Overview of the proposed control framework.*

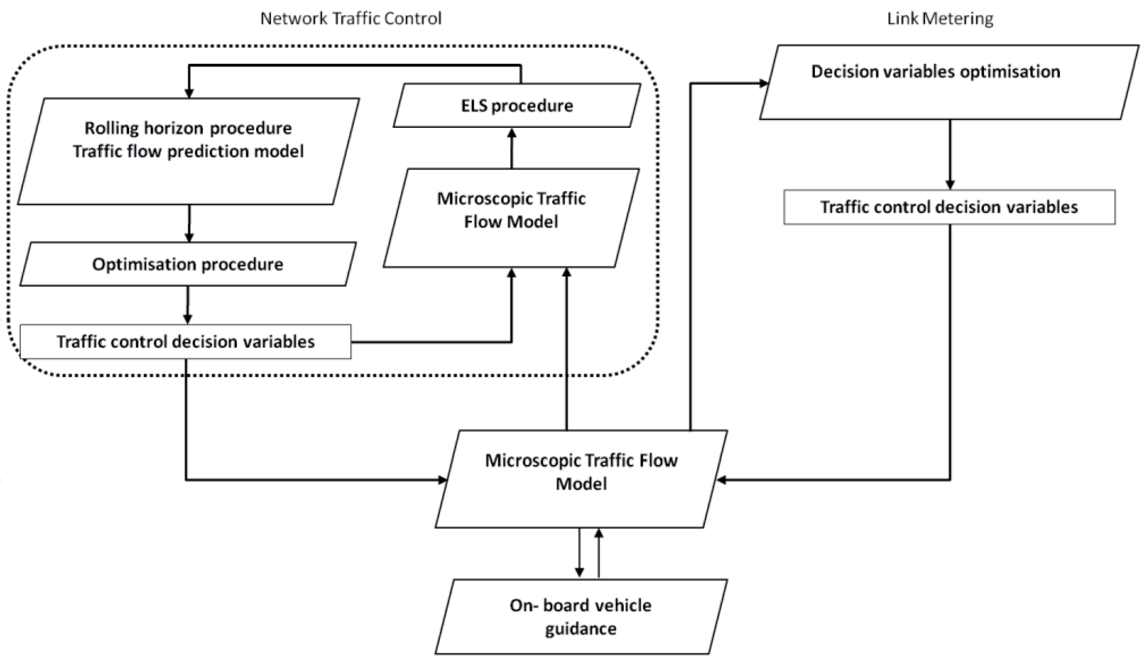


**Figure 2.**
*Further description of the framework overview.*

traffic flow models are the plant models, the Kalman Filter acts as prediction model and the ELS algorithm [12] for unequipped vehicles location and speed estimation.

Then this framework is composed by:

1. The microscopic traffic flow model;
2. The traffic flow prediction and estimation model providing input flows for the implementation of a traffic signal centralised approach;
    a. The rolling horizon approach;
    b. The KF;
    c. The unequipped vehicles status estimation;
3. The traffic control procedures.

As already anticipated, in order to guarantee the consistency between the traffic signals decision variables and the traffic flow two prediction terms are applied: the first one is related to the traffic flow model which is predicted with reference to the prediction horizon (e.g. fifteen min) the second one is the rolling horizon of the control. Concerning the rolling horizon, it must be clarified that the optimisation procedure works every control interval and the traffic information are updated every roll period (e.g. five minutes). Finally, the traffic information is collected in general every sub-interval (e.g. five seconds).

The second sub - model is represented by the on-board vehicle control procedure and operates depending on the vehicle distance as it will be discussed in more detail in Section 5 about the algorithm explication. As already anticipated in the introduction in this paper the S-GLOSA algorithm has been implemented. Therefore, the considered traffic control method is able to consider the interaction among junctions, whilst the vehicles control is applied only to the vehicles approaching each junction.

### 3.2 Centralised traffic control strategy

The Network Traffic Control (NTC) may be classified as a continuous linear optimisation problem and a multi - objective approach is pursued combining the total delay minimisation and the minimisation of the queue equidistribution criterion [13].

The parameters and constraints used in the model are listed below

- k approach
- j stage
- Δ approach-stage incidence matrix with entries $ä_{kj} = 1$ if k receives green during j and 0 otherwise
- $C > 0$ the cycle length
- $s_j \in [0,C]$ the length of stage j as an optimisation variable; if no minimum length constraint is introduced
- $AR \in [0,C]$ the so-called all red period at the end of each stage
- $l_k \in [0,c]$ the lost time for approach k, assumed known
- $g_k$ the effective green for approach k
- $g_{\min} \forall_k$ the minimum value of the effective green
- $q_k > 0$ the arrival flow for approach k, assumed known
- $sat_k > 0$ the saturation flow for approach k, assumed known
- $b \in [0,1]$ and eventually $t \in [1,,2,,3]$ the discrete variables for stage sequence definition, as decision variables
- $i$ the generic links
- $tr$ the turning rates
- $\beta_{l,r}$ the split ratio of the traffic demand in the $l^{th}$ link and $r^{th}$ movement
- $\xi_{l,r}$ the number of lanes assigned to the r movements in the $l^{th}$ link
- $m_i^{in}$ the total inflow
- $m_{(i,tr)}^{out}$ the discharging capacity expressed as vehicles/hour/lane
- $s_{(i,tr)}$ the sum of the signal phase ratios for the $r^{th}$ movement in the $l^{th}$ link

Finally, for each junction the node offset is needed; it represents the period between the start of a reference stage of junction i and the start of the reference stage of the first junction used as master for clock.

Regarding the queue equidistribution the following objective function (*of*, see Eq. 1) has been considered:

$$of\left(g_k,\varphi_i\right)=\sum_{i=1}^{n}\sum_{tr=1}^{3}\left(\max\left(\beta_{i,tr}m_i^{in}-\xi_{l,r}m_{i,tr}^{out}s_{i,tr},0\right)\right)^2 \tag{1}$$

The criterion aims to balance the rates of queue growth (or equalise them in an ideal case) in a network and then minimises the spill-over risk; it is based on traffic control decision variables design able to minimise the difference between the discharging capacity and the traffic demand at each link.

Summing up the on-line synchronisation [14] is obtained by combining together:

- the continuous variables needed to completely define the signal plan, that is are: (i) the stage lengths, constrained by the consistency among the stage lengths and the cycle length, (ii) the node offsets;
- the objective functions defined by the total delay and the queue equidistribution.

The procedure is able to simultaneously optimise the green timings and the offsets.

Regarding the solution algorithm in this paper the meta-heuristic Multi - objective Simulated Annealing [15, 16] has been applied. As a matter of fact, meta-heuristic algorithms can effectively address even optimisation problems with objective function not expressed in closed form, so that derivatives are not easily available, as it occurs for the scheduled synchronisation.

In particular the basic Simulated Annealing algorithm is a neighbourhood based meta-heuristic, which is inspired by the statistical mechanics to find solutions for both discrete and continuous optimisation problems.

Regarding the link metering (LM), is a feedback method implemented in accordance with the proportional integral type proposed by [6, 17–19] and it is based on occupancy as a control variable.

We list here the parameters used in the model

- k be the time step
- s be the section
- $\hat{o}$ be the desired downstream occupancy
- $q_s$ be the gated flow
- $o_s$ be the observed occupancy at downstream
- $K_p$ be the proportional gain
- $K_I$ be the integral gain

Regarding the control function, a proportional-integral-type (PI) feedback controller (2) aiming to maintain the observed occupancy around the desired value as in following displayed has been applied:

$$q_s(k)=q_s(k-1)-K_p\left[o_s(k)-o_s(k-1)\right]+K_I\left[\hat{o}-o_s(k)\right] \tag{2}$$

### 3.3 GLOSA (green light optimal speed advisory)

The Green Light Optimal Speed Advisory (GLOSA) is a Traffic LightS (TLS) time information system for advising drivers by means of using V2I communication. Messages are received by the vehicles on the times of the next TLS. Additionally, an on-board system calculates an ideal approach speed. The convenience on using this system relies on an increasing in safety, reducing the consumption and increasing efficiency of the unction.

In particular, the system adopted provides information about recommended speed level to the vehicle at 300 m from the TLS. If the current speed allows it to cross the intersection without stopping, the vehicle maintains the speed. Otherwise, the speed value allowing it is calculated. If the specific speed value detected is higher or lower than the maximum speed or less than the minimum speed allowed, no communication is provided to the driver and he will stop at the intersection. If the GLOSA is not active, the vehicle stops at signalised junctions; with the presence on-board of the GLOSA the vehicle travels through the same path and stops only 1 time.

It must be clarified that, the research does not focus on the type of communication between infrastructure and vehicle assuming that the messages are always delivered.

Furthermore, the algorithm has been designed aiming to guarantee that the vehicle will be able to cross the unction as soon as possible preferring, therefore, the travel time at fuel consumption or emission. The considered algorithm and the adopted variables are summarised in the following:

- D is the communication distance between the On-Board Units (OBU) and Road-Side-Units (RSU);
- $T_{attr}$ is the crossing time for the vehicle;
- $T_{switch}$ is the remaining time for green phase;
- $T_{next,phase}$ interval of the next green phase [$T_{initial}$, $T_{final}$];
- $V_{set}$ is the set of tested speed to cross the junction in the next phase. The possible speeds are defined with a 10 steps interval between the minimum and maximum speed;
- $T_{attr,Vset,i}$ is the crossing time for each speed of $V_{set}$.

The main successive steps of the algorithm are summarised in the following:

- Traffic signal control (TS) may be green or red;
    - If red, then the optimisation of the next green intervals is activated;
    - Otherwise, if the phase is green, it is verified if the vehicle speed is able to guarantee the vehicle crossing the section without stopping;

        a. If yes, the algorithm does nothing

        b. Otherwise, it is calculated a new green interval for the TS and a set of speeds is calculated (composed by teen values); it is calculated the crossing time and the consistency with the initial value of the green (within green interval) [the optimal value of the speed will guarantee the minimum value of the crossing time].

## 4. Application

### 4.1 Case study

The area identified for the case study is the city centre of Naples (regional capital of Campania, southern Italy). This area is characterised by a population of 978,399 and a population density of 8220 per km$^2$. Moreover, the metropolitan area has a number of inhabitants is around 3,118,000 and the population density is 2645 per km$^2$. Also, the total number of internal systematic yearly trips is around 685,000.

Two main roads are connected, Via Francesco Caracciolo and Via Riviera di Chiaia, from the West to the East side of the city. Current traffic rules and the connection between these two sides with two concurrent paths are implemented. Two paths are identified, path 1 goes through the Galleria Vittoria, and path 2 is composed of Via Chiatamone, Via Nazario Sauro and Via Acton. The sub-network layout is reported in **Figure 3**.

The network comprises four signalised junctions, among them traffic signals in Section 1, 2 and 5 are pedestrian traffic signals.

In terms of implementations remarks it must be highlighted that the whole traffic control procedure operates every control interval (every five minutes).

To optimise the traffic signal decision variables, the rolling horizon approach is adopted combined with a traffic flow prediction model. In particular, the rolling horizon itself is characterised by two terms the roll period (equal to five seconds) and the look ahead period (starting at the end of the roll period and ending at the upper bound of the prediction); in order to further guarantee the consistency with the traffic flow, traffic information are collected every roll period.

It must be distinguished that traffic signals in Section 1 and 2 are managed through LM whereas traffic signals in sections 4 and 5 are optimised through NTC. In general, the duration of the cycle length is 110 seconds and the stages 1 2 and 3 are respectively equal to 19 seconds, 65 seconds, and 26 seconds.

Regarding the origin - destination flows (and then the entry exit matrix definition) these have been obtained by combing the results of a macroscopic static traffic assignment procedure (PUMS - NAPOLI) [20] with a traffic counts survey done in 2017; in

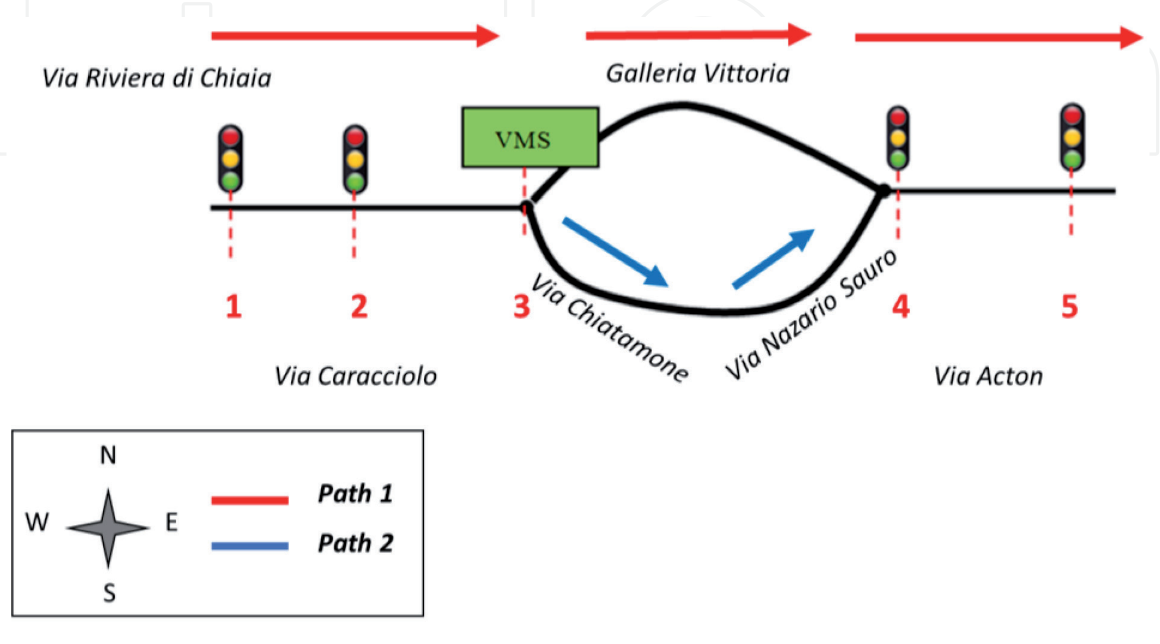


**Figure 3.**
*Topology of the tested network.*

particular traffic counts were collected at the beginning of 2017 in two peak hours of the day (mooring, from 7. 30 until 10.30 and afternoon, from 17.30 until 20.00).

The traffic flow was microscopically model through SUMO which is able to guarantee the on-line consistency of the procedures by adopting the TraCI interface, and the supporting code was developed in MATLAB (the R2018b was adopted). The input of the optimisation procedures are the travel times (TT) and the queue lengths (QL) that are collected through specific detectors located on the network. Due to the stochastic nature of the microsimulation approach, each simulation is run twenty successive times and the final values are provided by averaging the value of each simulation.

In terms of the goodness-of-fit function for model calibration, the Geoffrey E. Havers statistic [21] was adopted considering the observed and modelled data and the correspondence is less than 5 for 75% of the pairs (in accordance with the guidelines provided in [22].

### 4.2 Numerical results

In **Table 1**, the travel times obtained during peak hour simulation after model calibration are shown as well as the RSME. **Table 2** shows the queue lengths obtained during peak hour simulation after model calibration are shown. Let us observe that with reference to the results displayed in **Table 2** regarding the simulation of the current scenario, the main critical points are identified on Via Caracciolo (see **Figure 3**, junctions 1 and 2 are along Via Caracciolo) and Galleria Vittoria, direction W-E. For these two roads it was possible to reconstruct (in the condition of full network loading) the mean maximum queue lengths for intervals of 900 seconds or 15 minutes that fluctuate between 200 and 300 m on Via Caracciolo and between 300 and 400 m on Galleria Vittoria W-E. In the same table the root mean square (RSME) is summarised as a goodness of fit indicator of the calibration procedure (**Table 3**).

The considered path are two urban roads thus the speed limit is constrained to the 50 km/h; the difference in terms of length is around 650 m (indeed the alternative path is 1300 m); both paths diverge from the same node and merge to the same junction (Section 4).

| Path 1 [min] | Path 2 [min] | RSME |
|---|---|---|
| 44 | 35 | 3.14 |

**Table 2.**
*Calibration results (TT) of the simulation model.*

| | Simulation intervals [s] | | | | |
|---|---|---|---|---|---|
| | 300–1200 | 1200–2100 | 2100–3000 | 3000–3900 | RSME |
| Road | Queue lengths [m] | | | | |
| Caracciolo | 296.54 | 294.95 | 243.08 | 234.4 | 6.72 |
| Galleria Vitt. $^{E-W\,(1)}$ | 81.93 | 83.7 | 95.76 | 98.53 | 2.76 |
| Galleria Vitt. $^{W-E\,(2)}$ | 277.41 | 339.13 | 390.39 | 384.56 | 6.18 |

(1) *From Via Acton to Piazza Vittoria (junction 3 in **Figure 3**).*
(2) *From Piazza Vittoria (junction 3 in **Figure 3**) to Via Acton.*

**Table 3.**
*Calibration results (QL) of the simulation model.*

The reader may refer to **Figure 3**, showing the traffic signal controllers (sections 4 and 5) and the link controllers (sections 1 and 2) are represented.

Concerning the simulation results, it must be specified that all numerical applications were run on a server machine Intel(R) Xeon(R) CPU E5–1620 v3, clocked at 3.50GHz and with 8GB of RAM. As already anticipated in the introduction three scenarios were considered in all:

- the first was only based on a traffic control procedure;
- the second on speed guidance optimisation;
- the third was based on the combination of both sub-models.

The simulation interval considered for each scenario is equal to one hour and for each simulation a warm-up period taking teen minutes is considered.

The tested scenarios are listed below:

1. the traffic control scenario [TC], the hybrid traffic control strategy combining the centralised traffic control and the link metering are applied; this strategy has been tested considered a successive bi-level mono-criterion optimisation [TCMONO] and a simultaneously multi-criteria optimisation [TCMULTI];
2. the speed guidance scenario [S-GLOSA], providing a warning to the driver concerning the optimal speed to be maintained while approaching the junction;
3. the mixed scenario [TC& S-GLOSA], both the TC strategy and the MS-GLOSA are implemented.

To preliminarily compare the achieved results a further scenario has introduced as baseline. In particular, in the baseline scenario an Adaptive Signal Control [A - SC] strategy has been considered [23]. Furthermore, it must be also clarified that in all scenarios, the considered penetration rate of CAV (Connected Autonomous Vehicles) equals 50%, and the impact of the penetration rate of connected and autonomous vehicles has not yet been tested. Indeed, it will be remarked as future perspective then in terms of further issues to be investigated. In the following the results of each scenario are displayed.

In particular, in order to evaluate the effectiveness of the proposed strategy, the [A - SC] scenario was compared with each one of three scenarios [YY], and the relative difference (i.e. A - SC vs. YY) between the mean value of actual travel times of two alternative paths is then performed [$TT_{pathx}$] (see **Table 4**) as well as the mean value of the relative difference of the queue lengths [QL] at significant sections (see **Table 5**; sections are identified in accordance with **Figure 3**). The results

| YY - SCENARIO | Path 1 | Path 2 |
|---|---|---|
| $TC_{MONO}$ | −18.75 | −26.70 |
| $TC_{MULTI}$ | −25.31 | −33.28 |
| S-GLOSA | −15.12 | −21.27 |
| $TC_{MULTI}$&S-GLOSA | −29.11 | −37.22 |

**Table 4.**
*Mean TTS rel. Diff. [%] of [a - SC] scenario w.r.t [YY] scenario.*

| YY - SCENARIO | Section 1 | Section 2 | Section 3 | Section 4 | Section 5 |
|---|---|---|---|---|---|
| $TC_{MONO}$ | −88.70 | −75.28 | −84.46 | −68.13 | −32.18 |
| $TC_{MULTI}$ | −92.22 | −81.31 | −87.08 | −72.15 | −35.27 |
| S-GLOSA | −83.18 | −69.07 | −80.22 | −65.21 | −27.06 |
| $TC_{MULTI}$&S-GLOSA | −97.04 | −84.43 | −91.18 | −75.13 | −36.22 |

**Table 5.**
*Mean QLS rel. Diff. Of [a - SC] scenario wrt [YY] scenario.*

highlight three main considerations: the first one is about the TC and in particular it is confirmed that TC based on multi-criteria optimisation outperforms that TC based on mono-criterion optimisation and the result was not intuitively expected due to the further constrain that is introduced in case of multi-criteria optimisation. Secondly it must be observed that TC mono-criterion and S-GLOSA provide

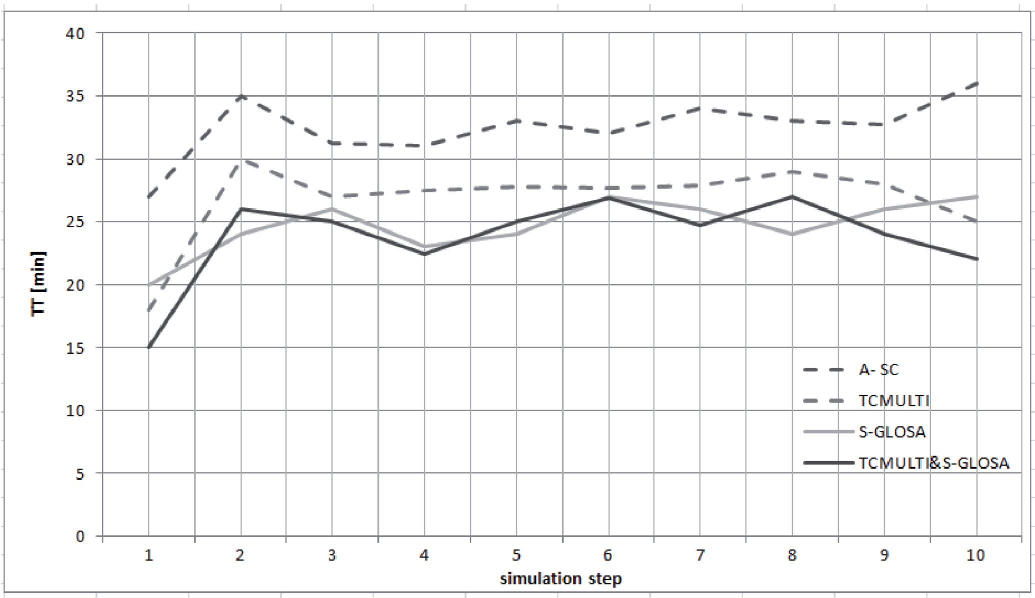


**Figure 4.**
*Results for each scenario: Mean TTs [min] against simulation step for each scenario.*

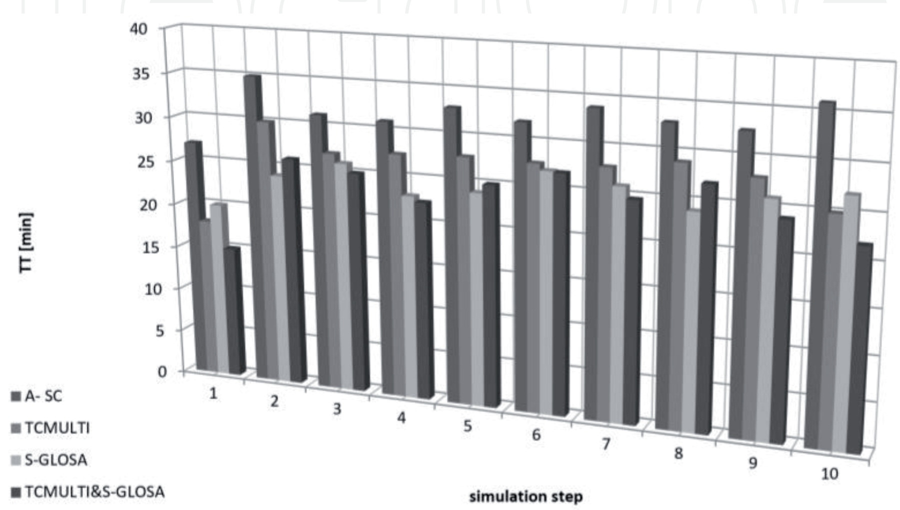


**Figure 5.**
*Results for each scenario: Rel diff [%] of the mean TT wrt the A-SC scenario, against simulation step for each scenario.*

similar results therefore better network performances may be achieved through the implementation of TC based on multi-criteria optimisation; finally, as expected, the combination of TC based on multi-criteria and S-GLOSA provides final best performances.

In order to provide a further comparison among all scenarios the results in terms of mean TT of the alternative route 2 are also displayed against simulation step for each scenario (see **Figure 4**) as well as the relative difference of the mean TT of each scenario with respect to the baseline scenario, that the Adaptive Signal Control scenario (see **Figure 5**).

## 5. Conclusions and future perspectives

The paper illustrates a unified framework which embeds a simultaneous traffic control strategy and the automated vehicle control. In particular the traffic control strategy is composed by two sub models: one is referred to the centralised traffic management the other one is characterised by the link metering strategy; regarding the vehicle control, the speed optimisation procedure based on Green Light Optimal Speed Advisory (GLOSA) has been applied in particular with reference to the next single junction approached by the vehicles (S-GLOSA). A microscopic traffic flow modelling has been adopted and all models were run in a SUMO simulation environment.

The integrated framework was then tested on a real case study consisting of a highly congested sub-network in the city centre of Naples (Italy). The network layout is represented by one diversion node and two alternative paths connecting the same origin - destination pair.

In order to evaluate the effectiveness of the proposed framework, three scenarios were tested: the first was only based on a centralised traffic control procedure [TC] that was further analysed considering the bi-level mono-criterion implementation and the multi-criteria approach; the second one was based on speed guidance optimisation [S-GLOSA] and the third was based on the combination of both sub-models the multi-criteria traffic control and the speed optimisation [TCMULTI & S-GLOSA]. Finally, the framework effectiveness was evaluated in terms of within-day dynamics with respect to the travel times and queue length performance indices.

Three main considerations have arisen: the first one is about the TC strategy and in particular it was tested that multi-criteria optimisation outperforms the mono-criterion approach; the second one refers to the comparison between $TC_{MULTI}$ and S-GLOSA therefore it is verified that S-GLOSA provides worse performances than the $TC_{MULTI}$ method; finally the combination between $TC_{MULTI}$ and S-GLOSA provide as expected best results.

Regarding future research perspectives, some preliminary modelling considerations may be summarised. First of all, the authors would like to test the proposed framework on different networks characterised by more complex topologies. Secondly, the sensitivity at different penetration rates of CAV must be analysed. Thirdly, further refinements are needed for the implementation of the S-GLOSA strategy and, for completeness, in future researches the environmental impact will be also analysed.

Finally some further technological and operational perspectives may be discussed. The situation described and analysed in the chapter has shown the benefit of the cooperation among infrastructures and vehicles control. It is worth noting that this situation is one of the possible results that technological development on one side, and normative evolution on the other, will enable in next years.

For example, the implementation of S-GLOSA (or even MS-GLOSA) in urban environments will be strongly affected by the communication technologies used, with an evident advantage for this use case of the Automotive LTE with respect of Dedicated Short Range Communication (DSRC). In summary, for this and many other reasons, the concrete future implementation of cooperative scenarios has some kinds of uncertainty, but this last observation make even probably more meaningful the kind of experiments discussed here.

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## Conflict of interest

No potential conflict of interest was reported by the authors.

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