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STRUMENTI INNOVATIVI DI MODELLAZIONE DEI FLUSSI DI TRAFFICO PER IL CONTROLLO AVANZATO DEL TRAFFICO URBANO

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INNOVATIVE TRAFFIC FLOW MODELLING TOOLS FOR ADVANCED URBAN TRAFFIC CONTROL

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Acknowledgements and Dedication

This PhD has been a unique and emotional life-changing experience for me. However, it was not an easy task, and I would not have possible done it without the support and guidance I received from many people.

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To all of you who gave me part of your time (therefore of your *life*), I dedicate this Doctoral Thesis.

Contents

PREFACE

This dissertation is submitted for the degree of Doctor of Philosophy at the Department of Civil Engineering (DICIV), University of Salerno. The research here described is the result of three years of research and study (2017-2020) under the supervision of Professor Roberta Di Pace and Stefano de Luca, with the coordination of Professors Giulio Erberto Cantarella and Fernando Fraternali.

This thesis is composed by two sub sections with several papers as chapters that have been published, are forthcoming, or have been submitted for publication in a scientific peer reviewed journal or book (Transportation Research Part C, Transportation Science, Transport Reviews, European Transport Research Review, Intechopen, Transportation Reserach Part A) and in several conferences (MT-ITS, EEEIC, DTA, SIDT, COTA ISETT). Because of this structure, there is some overlap between them. However, each subsection has an outline that describes their papers and explains their relation.

This research is the outcome of a close interaction with my supervisors, the research group of the University of Salerno and the University of Naples Federico II, and of an abroad period at the Delft University of Technology, Netherlands, under the supervision of Professor Bart De Schutter. Each of them appears as co-authors of the various papers that form the Chapters of this book.

1 INTRODUCTION

There is currently an evolution of vehicles with the development of new on-board technologies, which allow for increasingly more connected vehicles. A connected vehicle uses a wireless technology to communicate with other devices, which enables the exchange of data with, for example, other vehicles (V2V), with people (V2P), with a network controller (V2N) or with the infrastructure (V2I). In general, the connected vehicle paradigm can be denoted as *Vehicle-to-Everything* V2X, being X any other element which the vehicle can communicate with. The communication can occur in three different ways: when there is a one-way communication either to the infrastructure (V2I) or from the infrastructure to the vehicle (I2V), and then when there is a bidirectional communication (V2I & I2V).

The vehicle-to-vehicle (V2V) communication is based on the idea that vehicles may exchange information about their 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.

Other kinds of applications refer to the vehicle to infrastructure communications (V2I & I2V) 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. 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. The Signal Violation/Intersection safety (SigV) is a safety-critical task focusing on the reduction of the number and severity of collisions at signalised intersections and the Traffic Signal Priority (TSP) is a service able to guarantee the priority at signalised junctions of specific vehicles as emergency vehicles, public transport, etc.

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

In general, it may be argued that, in general, vehicles are already connected devices; the development of an integrated framework combining the above-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). It will be able to guarantee the road network management by synchronising all services and all shared information.

This technological evolution of connected vehicles also enables the development of more intelligent and autonomous vehicles. The more autonomous a vehicle is, more driving tasks depend on an autonomous system and not on the human driver. To describe the degree of automation, the most used classification is defined in standards by the International Society of Automotive Engineers (SAE) (SAE International, 2018), which have been adopted by the National Highway Traffic Safety Administration (NHTSA) of the US Department of Transportation, and later embraced by several manufacturers and stakeholders.

This classification divides the level of automation in six, ranging from "Level 0" for *no automation* and neither driving assistance, up to "Level 5" for *full driving automation*. The difference between the levels depends on who is the subject (human or system) performing which operation (steering, acceleration, deceleration, monitoring, etc.) and when (at all times, under some circumstances, only on emergencies, never). In particular:

- The lowest level (0) refers to the case when the human driver performs the entire dynamic driving task. This level applies even to vehicles equipped with active safety systems (as automated emergency braking, lane keeping assistance and electronic stability control) that are triggered for short interventions during potentially hazardous situations, not replacing the role of the human driver on a sustained basis.
- The following two levels of driving automation (1-2) refer to cases in which the human driver continues to perform part of the dynamic driving task while the driving automation system is engaged.
- The upper three levels of driving automation (3-5) refer to cases in which the Automated Driving System (ADS) performs the entire the dynamic driving task on a sustained basis while it is engaged.

The result of including connected and autonomous vehicles on the network has the potential to achieve several benefits with respect to different aspects:

- The network could achieve better values of traffic flow, and reduce congested areas or congestion in general, thanks to the cooperative behaviour between vehicles, and the exchange of information with the network, avoiding or minimizing traffic disruptions.
- The mobility may become more sustainable for the effect of a more efficient driving behaviour, with a reduced energy consumption and lower emissions; combined with electrically powered vehicles offering quieter and cleaner trips. This benefit should be analysed considering not only the vehicle trips by themselves, but also contemplating the energy source, the charging behaviour of users, the integration with other modes of transport, the batteries disposal protocols, etc.
- Trips could be safer, thanks to the inclusion of active systems that help to reduce or even eliminate human driving errors.
- Other potential benefit regards an increase accessibility to transport services, becoming reachable physically or economically to people that today might not have the option to use them or find it challenging.

- The exchange of information with the network and the infrastructure generates large-disaggregated data, which is extremely valuable to comprehend the current state of the traffic, have historical data, produce better traffic predictions, and therefore obtain a better optimization of the network.

The use of these technologies does not guarantee reliable and accurate results unless they are properly enabled by specific models behind them. To do so, it is necessary to study the vehicular flow in the presence of CAVs. This arises two challenges:

- a methodological challenge, to have a vehicular flow model that allows us to implement this new technology in a mixed context of connected and unconnected vehicles.
- an operational challenge, in which by combining the data collected from the connected vehicles and a traffic flow model, it is possible to adopt an advanced control strategy, and therefore achieve the benefits of having CAVs in the network.

TRAFFIC FLOW MODELS

It is defined as a mathematical model of real-world traffic which serves to understand, describe and predict traffic flow. The development of these models began in 1934 with the study of the relation between traffic flow (vehicles/hour) with traffic density (vehicles/km), speed with density, and flow with speed to characterise the traffic (Greenshields *et al.*, 1934; Greenshields, 1935). Such relations are called *fundamental relationships* producing *fundamental diagrams*. These relations are schematically shown in Figure 1.

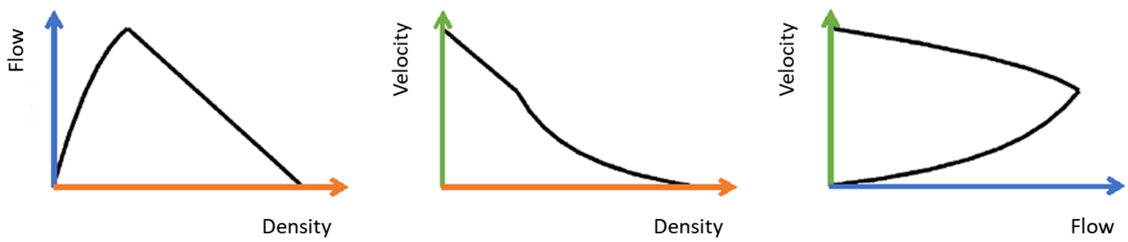

Figure 1: Fundamental relations in different planes

To describe the change of these relations over time, several mathematical models (called *Traffic Flow Models*) were developed. They can be categorised according to different criteria, such as type of variables (discrete or continuous), representation (stochastic or deterministic), scale of application, type of model equations (partial differential equations, discrete equations), number of traffic phases described by the model, etc. However, the most common criteria to classify them, is according to their aggregation level in macroscopic, mesoscopic or microscopic (Treiber and Kesting, 2013). Macroscopic models use aggregate variables such as density (average) and flow (mean), thus aggregating vehicles and traffic as a continuum, while microscopic models distinguish and track the behaviour of each individual vehicle. Between them lies the mesoscopic models, since they are classified between microscopic and macroscopic models, as they describe the vehicle behaviour in aggregate terms, e.g. with probability distributions for position and speed.

Currently, the macroscopic approach is the most widely used for modelling traffic across an entire network, but in order to better represent traffic in the presence of autonomous and connected vehicles, and to be able to apply this model to an entire network, a model must be developed that is microscopic to account for the behaviour of each individual vehicle, but also must be simultaneously efficient in order to extend the modelling to the entire network.

Other types of models obtained by combining two -or more- sub models are called *multiscale* or *hybrid* traffic flow models. Such models have been generally explored in order to provide traffic analysis at both local and network levels. The main combinations involved are mesoscopic with microscopic models (Yang and Slavin, 2002; Burghout, Koutsopoulos and Andréasson, 2005; Yang and Morgan, 2006), and macroscopic with microscopic models (Bourrel, 2003; Bourrel and Lesort, 2003).

The matching of the sub models allows two fields of investigation. The first concerns application of the hybrid model at different scales; for instance, macroscopic models can be suitable for the analysis and design of extended macro areas, whilst microscopic models can be applied to study less extensive areas such as sub-networks or specific junctions; this is the multi-scale application context. The second field of investigation entails representation of links and nodes with different levels of detail. For instance, microscopic models can be adopted for links whilst macroscopic models may be adopted to represent nodes. The latter approach is constrained by the different properties of the two models: in the case of dynamic network loading applications, macroscopic models are suitable and simpler for nodes equations specification (Jin and Zhang, 2003; Lebacque and Khoshyaran, 2005), whereas microscopic models are needed to model drivers' behaviour along links.

TRAFFIC CONTROL PROBLEM

On urban networks of intersections, one of the most common ways to control the road traffic are the traffic lights. Their settings can be changed in order to optimise such traffic depending on several indicators. Such procedure is called Network Signal Setting Design (NSSD), which involves solving an optimisation problem to design the control variables. Because of this, it is necessary to identify several components of this process:

Variables

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

For each junction,

- t_j the length of stage j as a decision variable;
- t_{ar} the so-called all red period at the end of each stage to allow for the safe clearance of the junction, assumed known (and constant for simplicity's sake);
- Δ the approach-stage incidence matrix (or stage matrix (SM) for short), with entries $\delta_{kj} = 1$ if approach k receives green during stage j and 0 otherwise, assumed known;
- $l_k$the lost time for approach k, assumed known;
- $g_k = \sum_j \delta_{kj} t_j - t_{ar} - l_k$ the effective green for approach k, where $\delta_{kj}=1$ if approach k receives green during stage j and 0 otherwise;
- q_k the arrival flow for approach k, assumed known;
- s_k be the saturation flow for approach k, assumed known;
- ϕ_i be the node offset, as the time shift between the start of the plan for the junction i and the start of a reference plan of a specific junction. Given such reference, all the other m-1 node offsets are independent variables where m is the number of junctions in the network.

Constraints

- stage lengths being non-negative

  $t_j \geq 0 \quad \forall_j$

- consistency among stage lengths and cycle length

  $$\sum_j t_j = c$$

- effective green being non-negative

  $g_k \geq 0 \quad \forall_k$

- the minimum value of the effective green

  $g_k \geq g_{min} \quad \forall_k$

- to avoid multiple equivalent solutions and non-negative values for node offsets between the start of a reference stage of junction i and the start of the reference stage of the first junction used as a reference for clock

  $c > \phi_i \geq 0$

Objective functions

The problem can be specified as a mono-objective or multi-objective optimization, depending on the number of objective functions considered.

When optimizing a multi-objective problem, a single point of the solution set that minimizes all the objectives simultaneously generally does not exist. Therefore, in order to find and choose a suitable solution, generally it is necessary to calculate a weighted sum of the transformed objective functions, aiming to minimize the distance to the Utopia Point, that is, the point which has the minimum of each of the objective functions as coordinates (Koski, 1984; Koski and Silvennoinen, 1987; Rao and Freiheit, 1991).

The function (or functions) to be optimised can vary widely. Some of the most used are:

- the Total Delay (TD), which is the most common objective function considered in NSSD. It may be evaluated according to the degree of interaction among the junction composing the network.

- the Total Time Spent (TTS), calculated as the sum of the predicted number of vehicles on all the links of the network, during the simulation horizon, multiplied by the length of each time step.
- Energy consumption and/or emissions, applying models depending on the variables and characteristics of the vehicles,
- Queue lengths, created during the red period of traffic lights,
- Saturation degree and/or capacity factor, depending on the incoming flow, the saturation flow, and the green times, etc.

The optimisation problem involves identifying the value of the decision variables which optimises the predefined objective functions.

Type of optimization

This procedure can be static or dynamic, depending on the characteristics of the input variables:

- **Static**: a traffic light plan is designed, and then remains unchanged for a period of time. As a result, the plan is independent of the actual trajectory of vehicle flows, but is obtained based on historical data. It is also called *Planning based* or *offline*, as the vehicle flow is not updated on real time.
- **Dynamic**: based on the actual values of vehicle flows on real time. It is called *Traffic responsive* or *Online*, as it uses sensors to collect information about the current state of the intersections.

Resolution

The decision variables can be optimised simultaneously or sequentially. Therefore, the signal setting design can be classified into:

- **sequential**: optimizing on a first step the green times, and on a second step the offsets. It is also called coordination.
- **simultaneous**: optimising green times and offsets on the same procedure, called synchronization.

Optimization strategy

There are various strategies that allow us to optimise a traffic network. Recently, the literature is verifying as the most effective and efficient is the Model Predictive Control (MPC) (Jia and Krogh, 2001; Lin *et al.*, 2012; Rawlings and Mayne, 2012; Zegeye *et al.*, 2012) which is one of the most powerful strategies, as it has a high quality of control and is able to coordinate all the integrated control measures at the same time, with the advantage of being scalable, since it can be used on a centralized, decentralized or distributed approach to control a network.

In general, a controller is a tool for controlling a process (system) while satisfying a series of constraints. They can be:

- **Open loop**, or feedforward, where the controller does not react if there is a disturbance of the system state. Because of this, the control action from the controller is independent of the “process output”.
- **Close loop**, or feedback, when the controller has a feedback loop which ensures the controller exerts a control action to manipulate the process variable to be the same as the "Reference input" or "set point".

The Model Predictive Control is a tool derived from the theory of automatic systems control which is able to adapt the optimisation of the traffic signal settings to the system prediction from the current system state. The controller receives information (measurements) of the current state of the system, and the expected disturbances, and starts the optimisation procedure using a prediction model over a prediction horizon. During this forecast horizon, several control inputs (solutions of the optimisation procedure) can be obtained for a control horizon, implementing only the first sample. When the next control step is reached, the prediction model is fed with new measured traffic states, the whole prediction horizon is moved one step forward and the optimisation starts again. This rolling horizon scheme closes the control loop, allowing the system to receive feedback from the real traffic network, making the MPC controller robust to uncertainty and disturbances.

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2
RESEARCH GOALS

After the current literature review, this thesis has two distinctive groups of research goals. On the traffic control side, the following issues have been addressed:

- Obtain an urban network management through the combination of a network traffic control strategy and link metering, optimising green times, offsets and stage sequences on an on-line network control and link control.
- Develop "energy-saving" control strategies considering EVs energy consumption patterns, to support the development of a unified network traffic control strategies aiming at minimising also EVs energy consumption.
- Integrate a traffic control strategy with the Single-Segment Green Light Optimal Speed Advisory (S-GLOSA), optimizing the speed of connected and autonomous vehicles.

Regarding the traffic flow modelling, the contributions of this thesis focus on:

- Develop a traffic flow model capable of simulating a mixed context of connected and unconnected vehicles, combining a macroscopic model along the arc and then a microscopic model at the nodes, concentrating there all the computational and analytical efforts, with a reduced number of parameters to calibrate.
- Integrate such model with an advanced control strategy for the optimisation of traffic light plans, with the capability to work on real time, receiving data acquired through sensors, cameras, radar, probe vehicles, etc., to obtain a more accurate and reliable prediction.
- Compare this traffic flow model with macroscopic and microscopic benchmark models.

3 SUMMARY AND CONTRIBUTION OF THIS THESIS

This thesis is subdivided in two parts, according to the research topic: the traffic control and the traffic flow modelling.

The first part, chapter 4 dealing with the traffic control problem, is composed by three sub-chapters, in which:

a) Chapter 4.1 focuses on the implementation of an online application of a network traffic control strategy based on a schedule synchronization approach, with a simultaneous optimization of not only green times and offsets, but also stage sequences.
b) Chapter 4.2 develops a methodological framework for the design of a control strategy at signalised junctions in the presence of Electric Vehicles with a link-based macroscopic energy consumption function calibrated from real-world vehicle trajectories and power data.
c) Chapter 4.3 contains a hybrid implementation of the centralised traffic control method for urban networks (interacting junctions) and the link metering approach, to then integrate it with a speed guidance algorithm for Connected Vehicles. This framework uses a multi - objective optimisation procedure based on the combination of two criteria: the queue length optimisation and the queue equidistribution, applying a metaheuristic algorithm.

The second part, chapter 5, covers the traffic flow modelling. It is also composed by three sub-chapters, in which:

a) Chapter 5.1 proposes a hybrid traffic flow model combining two submodels: a deterministic macroscopic Cell Transmission Model with a stochastic microscopic Cellular Automata model, both connected with a Link Transmission Model. This chapter analyses the local consistency between submodels.
b) Chapter 5.2 develops a similar hybrid traffic flow model, combining the same submodels with an alternative approach for the transition zones between submodels. This chapter analyses the consistency between submodels, and has several applications to test its performance. This model can also be adopted for traffic control based on an optimisation (prescriptive approach) method, especially in the context of multi-objective optimisation (for instance based on surrogate indicators) or in the case of the presence of connected vehicles.
c) Chapter 5.3 compares the previous hybrid traffic flow model (CA&CTM), with respect to several established macroscopic and microscopic models used as benchmarks. In particular, the comparison was made with the macroscopics CTM and CTM with dispersion, while microscopically with the Krauss model, considered the stochastic enhancement of the Gipps model, reference model in the context of the collision avoidance class of approaches, and with the Intelligent Driver Model, based on the idea of combining the ability to reach the desired speed limit in a traffic-free situation with the ability to identify how much braking is necessary to steer clear of any collision situations.

4

TRAFFIC CONTROL

Outline

The current chapter deals with the traffic control problem. It is composed by three sub-chapters, in which:

a) **Chapter 4.1** focuses on some methodological issues and operational effects/benefits which can be derived from the joint implementation of two simultaneous traffic control strategies: a link metering and the scheduled synchronisation approach (e.g., network decision variables, green timings, offsets, stage sequences, on a single optimization procedure).

   The proposed modelling framework integrates:

   1. a within-day model through a microscopic and a proper simulation environment.
   2. an enhanced on-line optimisation model able to design the traffic signal decision variables for both methods based on interacting junctions and metering control.
   3. a rolling horizon model able to forecast traffic flows and which is suitable for consistent traffic control.

   This framework was tested on a simulated case study using a calibrated network consisting of a highly congested subnetwork in the city centre of Naples, Italy.

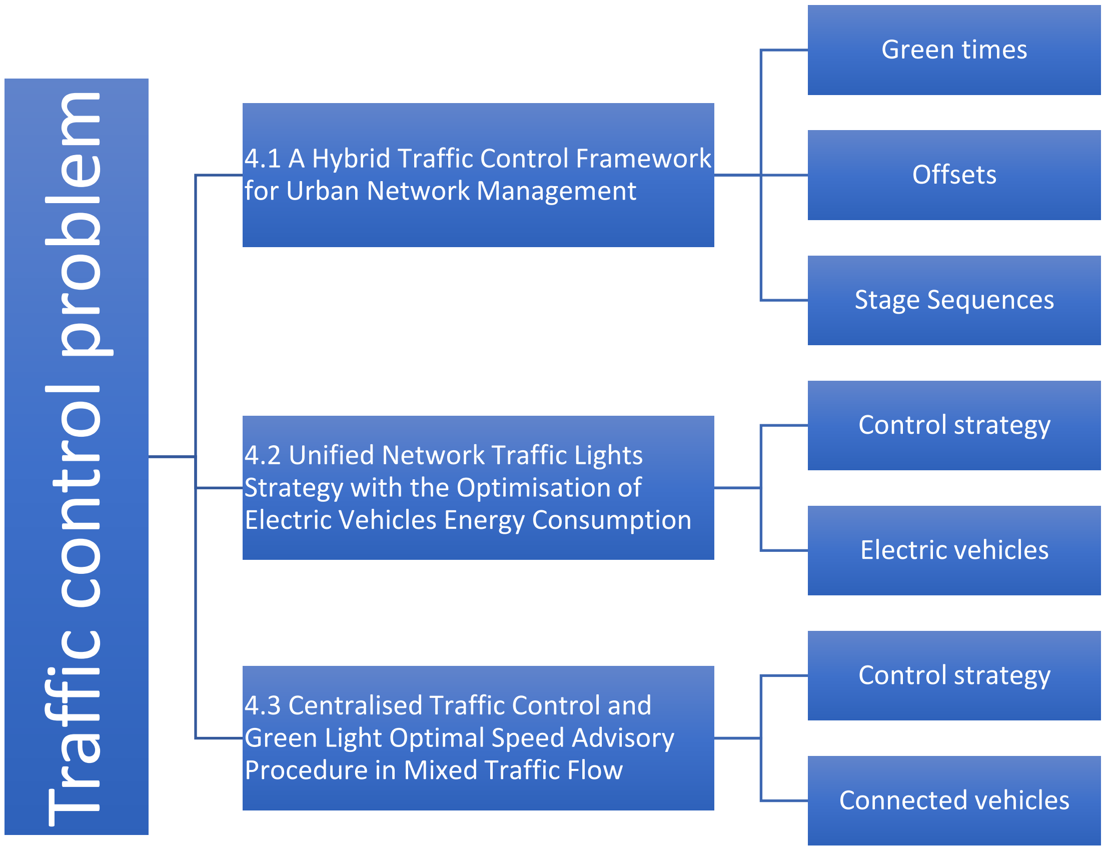
   Three scenarios were analysed: i) the single junction modelling; ii) the on-line scheduled synchronisation; iii) the on-line scheduled synchronisation with the activation of link metering at upstream pedestrian crossings.

b) **Chapter 4.2** develops a methodological framework for the design of a control strategy at signalised junctions in the presence of Electric Vehicles with a link-based macroscopic energy consumption function calibrated from real-world vehicle trajectories and power data. Therefore, it presents a method to support the development of a Unified network tRaffic control strAtegies aiming at minimising also EVs energy coNsumptiOn (URANO).

   In particular, a link-based macroscopic energy consumption function for EVs is derived from microscopic data. The function can be applied to extend the objective function of any control strategy design, In this study, the function has been derived based on the VT-CPEM model to simulate consumptions at signalised junction. The model has been thoroughly calibrated based on real-world individual trajectories at signalised junctions. Trajectories have been extracted from a large dataset through the integration of the modelling framework with an innovative tool – Trajectories Extraction Tool for Traffic Control Systems Applications (TET-TCSA).

c) **Chapter 4.3** contains a hybrid implementation of the centralised traffic control method for urban networks (interacting junctions) and the link metering approach, to then integrate it with a speed guidance algorithm for Connected Vehicles. With respect to the driving control, the S-GLOSA procedure has been applied and this has been combined with the traffic control method.
This framework has been applied at a case study on simple real network, composed by one origin–destination pair and two alternative paths. 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.
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.

An outline of this section can be seen in the following figure.



4.1

A hybrid traffic control framework for urban network management

ABSTRACT

In order to address the very complex problem of urban traffic congestion the paper aims to investigate some “methodological” issues and “operational” benefits which can be derived from the implementation of a hybrid traffic control (TC) strategy. The main focus is on the integration of a within day traffic flow modelling coupled with a traffic control method in particular: (1) a microscopic traffic flow representation was considered, (2) an enhanced on-line optimisation model able to design the traffic signal decision variables was adopted. Regarding the on- traffic control a hybrid approach combining the interacting junctions optimisation (e.g. the decision variables are the green timings, the offsets and the stage sequences) and the link metering control was considered.

The proposed framework was tested on a simulated case study using a calibrated network 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; two scenarios were analysed: i) the single junction modelling; ii) the on-line scheduled synchronisation with the activation of link metering at upstream pedestrian crossings. The framework effectiveness is evaluated in terms of within-day dynamics with respect to the travel times performance index.

Keywords: Traffic control; Link metering; within-day dynamics; optimisation.

I. INTRODUCTION

With the aim of reducing the impact of traffic congestion and guarantee higher network performances, an enhanced traffic control framework combining the network interacting junctions optimisation and a link metering approach can be implemented in order to address typical challenges in urban networks [1].

TC may rely on different strategies. By firstly taking into consideration the seminal works, several theoretical implementations and real case study applications have been proposed. The main research efforts focused on the design of isolated and interacting junctions. Moreover, further relevant approaches evaluated the metering flows of significant links through feedback-based strategies or of urban area/network parts through perimeter/gating control. Within the aforementioned context, the present paper focuses on some methodological issues and operational effects/benefits which can be derived from the joint implementation of two simultaneous TC strategies, the scheduled synchronisation approach (e.g. network decision variables, green timings, offsets, stage sequences which are optimised together; [2]) and a link metering.

The proposed modelling framework integrates:

1) a within-day model through a microscopic and a proper simulation environment (SUMO; SUMO 2016).
2) an enhanced on-line optimisation model able to design the traffic signal decision variables for both methods based on interacting junctions [2] and metering control [3], [4];
3) a rolling horizon model able to forecast traffic flows and which is suitable for consistent traffic control.

Everything was tested on a simulated case study using a calibrated network consisting of a highly congested subnetwork in the city centre of Naples, Italy.

Three scenarios were analysed: i) the single junction modelling; ii) the on-line scheduled synchronisation; iii) the on-line scheduled synchronisation with the activation of link metering at upstream pedestrian crossings.

The remainder of the paper is organised as follows: section II briefly summarises the research goals and provides a brief state-of-the-art description with respect to TC; in section III, the methodological framework is discussed; the case study is presented in section IV while the numerical results are shown and discussed in section V; finally, some concluding remarks and future perspectives are summarised in section 6.

II. RESEARCH GOALS AND STATE OF PLAY

The main research goal is the urban network management through the combination of a network traffic control strategy (NTC) and link metering (LM). In short, the combined design of decision variables for on-line network control and link control has been addressed. To this aim a within day loop aiming to supply update, has been implemented.

Indeed, the within-day loop is able to implement the optimal control consistently with the existing traffic flows (for a given day t), and the route choice is determined by the route guidance information system; on the other hand, the day-to-day loop is able to simulate the users' updating behaviour.

With respect to TC, the main issues addressed in literature refer to

i) the static or dynamic timing plans computation;

ii) the traffic control decision variables (i.e. green timings for a single junction, green timings and offsets in the case of network junctions, gated flows in the case of perimeter control);

iii) the objective function in the case of the optimisation approach (NTC) or the control objective in the case of the feedback control approach (LM).

Firstly, the classification of these methods may be identified as the off-line and on-line approaches. The main difference between the two methods is in terms of the timing plans decision variables design which is pursued, in the first case, on the basis of the historic values of flows and, in the second case, on the basis of real-time detected flows. In the context of off-line implementations, the main contributions rely on optimising the signal plans at the single junction (e.g. [5], [6]) or interacting junctions (i.e. the off-line network traffic control – NTC; e.g. [7]; Coordination and Synchronisation, [8]).

Regarding the on-line implementations, main research efforts refer not only to the single junction (e.g. [9]) and arterials and network junctions control (i.e. the on-line NTC (e.g. [10], [11]) but also to the control of some sensitive links, arterials [12] or 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 [13], [14]).

With respect to the existing literature, the main paper contributions are listed as follows: first of all, the considered NTC strategy which is based on the scheduled synchronisation approach, as proposed in [2] (green timings, offsets and stage sequences are optimised together), is not yet implemented for on-line application but only for off-line implementation through historic flows; secondly the TC issue is addressed through the hybrid combination of two on-line strategies: the NTC and a LM method based on the implementation of a simple feedback regulator [3] which is designed to be used with TTS estimator,while in this paper the observed occupancy has been considered as control objective in accordance with literature[1]; thirdly, a bi-level procedure which includes the total delay minimisation at the first stage and the queue equidistribution in the following stage is pursued (equidistribution; [15]).

Finally, a rolling horizon forecasting model was adopted in order to ensure the consistency between NTC decision variables and flows [16]. Furthermore, an iterative procedure has been implemented in order to solve the consistency between traffic control decision variables and traffic flows.

III. METHODOLOGY

The within-day loop combines the on-line network traffic control problem with a link metering strategy. As regards the traffic control, the adopted strategy is the scheduled synchronisation method which aims to create the joint optimisation of green timings, offsets and stage sequences; in particular, the timing plan computation strategy is implemented where signal settings, link offsets and the stage sequences are considered as decision variables.

On the basis of the detected and predicted network levels of congestion, the optimised green timings, offsets and stage sequences are calculated following an off-line optimisation design method. Therefore, every interval for traffic signals updating, starting from on-line detection of the network, new traffic scenarios are predicted thus traffic control decision variables are optimised and subsequently sent to each controller.

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[1] It must be clarified that in case of LM strategy only the instantaneous measurement of occupancy in the downstream link are required.

Regarding the optimisation criterion, a bi-level procedure is adopted; alternatively the multi-criteria optimisation could be applied however the application of multi-criteria optimisation at network level is still worth of investigation in the literature. Furthermore, the considered optimisation criteria have been previously tested however for sake of brevity only the results of a bi-level implementation are shown. Firstly, the total delay minimisation is considered and then a queue growth equalisation [15] criterion is introduced.

In summary the proposed framework is composed by a network traffic control based on the optimisation procedure, the microscopic model which is the plant model, and the KF [17] which acts as traffic flow prediction model. Based on the assumption that the state transition matrix is constant, the covariance of the state transition matrix and the covariance of the measurement noise may be determined. In this case, the off–line calibration approach was adopted then a constant value over all simulation intervals was considered and considering a multiple trial-and error runs with the 15- min survey data, a diagonal matrix was estimated.

Therefore the whole framework consists of three steps:

- The optimisation procedure, based on a bi-level procedure starting over again at every control interval which is consistent with the roll period length (e.g. fifteen minutes) and minimises at upper level the total delay and the queue growth equalisation criterion at lower level;
- The traffic flow prediction model (the prediction horizon equals to fifteen minutes);
- The rolling horizon approach; the real-time traffic information may be collected at every assigned subinterval (e.g. five seconds) in order to adjust the prediction and aggregate every rolling period (also called rolling horizon step size e.g. five minutes).

A. Optimisation procedure

The traffic control framework is composed by two strategies: the *on-line scheduled synchronisation* and the *link metering*. Furthermore the scheduled synchronisation is based on a bi-level optimisation approach where at first stage the Network Total delay is considered as objective function and at second level the following criterion is introduced.

Let

i	be the generic links,
r	the turning rates,
$\alpha_{l,r}$	the split ratio of the traffic demand in the l-th link and r-th movement,
$\gamma_{l,r}$	the number of lanes assigned to the r movements in the l-th link,
Q_l^{in}	the total inflow,
$q_{l,r}^{out}$	the discharging capacity expressed as vehicles/hour/lane,
$t_{l,r}$	is the sum of the signal phase ratios for the r-th movement in the l-th link,

the following *queue equidistribution* [15] objective function is defined

$$f(g_k,\varphi_i) = \sum_{l=1}^{n}\sum_{r=1}^{3}\left(\max\left(\alpha_{l,r}Q_l^{in} - \gamma_{l,r}q_{l,r}^{out}t_{l,r},0\right)\right)^2 \qquad (1)$$

On-line scheduled synchronisation:
stage generation & optimisation

As already noted in the introduction, stage-based methods can be used to solve the scheduled synchronisation by explicitly including the stage sequencing within the optimisation method, after the stage generation as described below.

A *stage* is a set of *approaches* that have green at the same time. For safe operations all the approaches in a stage must be mutually compatible, namely they may have green without any conflict− *compatibility requirement*−. Usually, it is also required that each stage be maximal – *completeness requirement* –, meaning that no further approach may be added to any of them without violating the compatibility requirement.

All candidate stages satisfying both the compatibility and completeness requirements can easily be generated by [18]for finding all maximal cliques of a graph; in this case, the adjacency matrix of the graph is the (square symmetric) compatibility matrix with as many rows and columns as the number of approaches and ‘0/1’ entry for each ‘incompatible/compatible’ pairs of approaches.

Let $n \geq 2$ be the number of candidate stages ($n = 1$ meaning there is no pair of incompatible approaches, there is no need for traffic control). A candidate stage that contains an approach not included in any other stage is called *compulsory*, otherwise it is called optional. Let n_c and $n_o = n - n_c$ be the number of compulsory and optional candidate stages, respectively.

A set of candidate stages (not necessarily all of them) in a given order are a *sequence*. A sequence is called *feasible* if each approach belongs to at least one stage in the sequence – *feasibility requirement* –. If all the compatible and maximal stages are considered such condition surely holds (in the limit case each stage contains only one approach). Moreover, a compulsory candidate stage, as defined above, must be included in each sequence since it contains an approach not included in any other stage. The number of feasible sequences may be very large.

If there is no optional stage, $n_o = 0$ and $n = n_c$, the number of feasible sequences is given by $n!$, say the number of permutations of the n stages. However, it is worth noting that any periodic rotation of a sequence, for instance such that the sequence (1,2,3) becomes (2,3,1), then (3,1,2), then (1,2,3,) again, does not affect optimal green and performance indicators, while optimal offsets change in an easily predictable way.

Thus, for each junction all the sequences are considered grouped into $(n_i! \,/\, n_i) = (n_i - 1)!$ equivalence classes, and only one sequence for each equivalence class is further analysed. Thus, if only two stages are available, two possible sequences can be built up {(1,2); (2,1)} which are equivalent, thus, only one equivalent class exists.

If there is at least one optional stage, $n_o > 0$, $n > n_c$, the stages can be grouped into 2^{no} sub-sets, each including all the n_c compulsory stages and some (or none at all) of the no optional stages; stages belonging to any of such sets may be arranged in a number of feasible sequences equal to the factorial of its size minus one, as described above.

Quite often it is also required that each approach has green in consecutive stages within the sequence, if more than one – *consecutiveness requirement* –. This requirement is effective only for sequences containing four or more stages.

The sequence of stages and their composition is commonly described by Δ, the approach-stage incidence matrix (or stage matrix for short), with entries δ_{kj} if approach k receives green during stage j and 0 otherwise.

A mixed discrete-continuous linear optimisation problem with non-linear objective function (not available in closed form for interacting approaches) is obtained by combining:

- the discrete variables needed to define the optimal stage sequence, constrained by the feasibility and the consecutiveness requirements;
- the continuous variables needed to completely define the signal plan, that is: (i) the stage lengths, as many as the stages, constrained by the consistency among the stage lengths and the cycle length, (ii) the $m - 1$ (independent) node offsets, and possibly (iii) the cycle length;
- the objective functions, as described below.

The number and/or the kind of discrete variables may be reduced if no minimum length constraint is introduced, in this case indeed if the optimal length of a (optional) stage is zero it means that this stage is not in the optimal solution. Finally regarding the optimisation two optimisation functions are identified.

Link metering control

Regarding link control, the feedback method is implemented in accordance with the proportional integral type proposed by [3] and [4], based on occupancy as a reference indicators. Let

s be the section,
$\hat{o}$ be the desired downstream occupancy,
q_s be the gated flows,
o_s be the observed downstream occupancy,

the model structure aiming to maintain the observed occupancy around the desired value is:

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

Finally, in terms of algorithm, to solve optimisation problems of the kind described in the previous sub-section, meta-heuristic algorithms are usually adopted such as Simulated Annealing (SA) [19].

B. Traffic flow prediction model

As described above, the control strategy is carried out every 5 minutes thanks to the supporting of a plant model build up through a Kalman filtering. The filter has two distinct stages: the time update (*Predictor*) and the measurement update (*Corrector*). In the first stage (*Time Update*) the state of the process x_k under investigation (traffic flows in our case) is projected or predicted. This initial estimate is called the a priori estimate $\hat{x}_{\bar{k}}$.

The *a priori* estimate $\hat{x}_{\bar{k}}$ is then used to predict an estimate for the output z_k. The difference between the estimated output and the actual output, called the residual or innovation, is then used to refine the initial estimate for the state x_k to obtain a new estimate called the a posteriori estimate, $\hat{x}_k$.

In the second stage (*Measurement update*) the Kalman gain K is first computed. The computed gain is then used to update the *a posteriori* estimate via the output z_k. The error covariance is finally updated. To begin, the two errors of the estimate, the a priori error $\bar{e}_k$ and the a posteriori error e_k, are defined. The *a priori* and *a posteriori* errors are defined as the difference between the actual value of x_k and the *a priori* and *a posteriori* estimates respectively.

Based on the assumption that A, B and H are numerical constants and setting each of their values to 1, Q and R may be determined. Q and R are variances of the process and measurement errors respectively. Q represents the noise introduced into the prediction process as a result of imperfections in the prediction model developed.

The network traffic data is known to exhibit strong autocorrelation, thus for the larger trend of information larger value of Q could be set as input parameter. R is usually fixed because it is a representation of errors in measurement arising from imperfections in the instruments used to measure the traffic (measurement error is usually fixed for a particular measuring instrument). It is therefore important in this case to choose traffic data measured with instruments with less error, i.e. more accurate instruments. To start the process effectively, the initial estimates of x_0 and p_0 have to be assumed. The filter usually arrives very quickly at a stable value for P, regardless of the initial value P_0. As such, the value P_0 generally should have little or no effect on the filter efficiency.

IV. CASE STUDY

A. Network description

The study area is located in the city centre of Naples which is the regional capital of Campania, southern Italy. The population is 978,399 and the density is 8,220 per km^2.

With regard to the metropolitan area, the number of inhabitants is around 3,118,000 and the population density is 2,645 per km2. Furthermore, the total number of internal systematic trips is around 685,000. The sub-area considered connects two main roads, 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. The more frequently used path goes through the Galleria Vittoria (path 1), and an alternative path, consists of the roads: Via Chiatamone, Via Nazario Sauro and Via Acton (path 2). A representation of the current sub-network layout is shown in Fig. 1.

The network comprises four signalised junctions, three of which regulate pedestrian crossings (sections 1, 2 and 5) and which are controlled through call buttons and the other which is set for fixed time regulation.

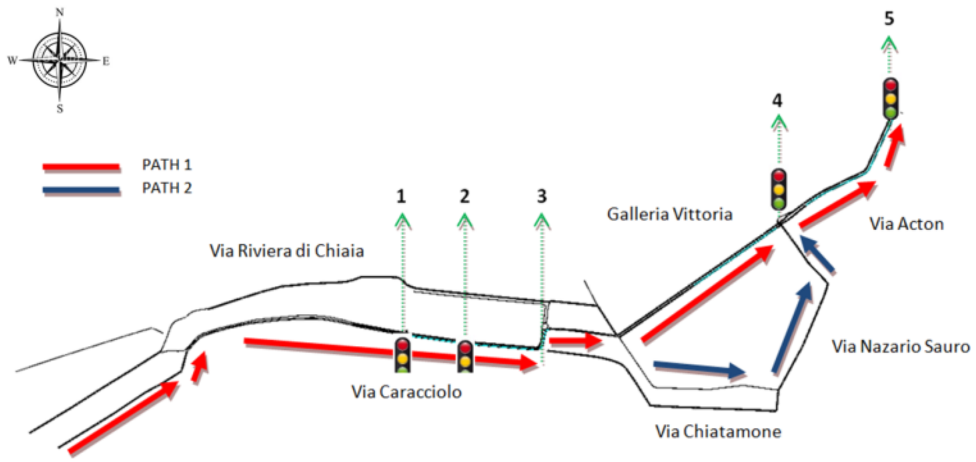

Fig. 1. Topology of the tested network

On the operational point of view sections 1 and 2 will be regulated through LM (i.e. are the set - points) method whereas sections 4 and 5 will be managed through NTC. In particular the traffic signal controller in section 4 regulates five signalised approaches and was characterised by three stages whilst the traffic signal controller in section 5 which regulates the approach from via Acton and the conflicting movement of pedestrians. The cycle length is 110 seconds: stage 1 lasts 19 seconds, stage 2 lasts 65 seconds and stage 3 26 seconds.

B. Demand flows

Origin-destination (O-D) flows estimation was based on the combination of model and traffic counts. O-D matrices already estimated in previous works, starting from the supply model of the network of Naples, were used to compute flows entering and exiting the study area. The estimate from the model predicts the incoming and outgoing flows to and from our study area and also an estimate of traffic flows on each link. However, a dynamic microscopic simulation requires that the internal paths be known.

To this aim, it was necessary to carry out an ad-hoc survey to further characterise the traffic flows, regarding their classification (in terms of vehicle types) and, at each junction within the study area, the actual turning percentages (rates). Traffic counts were appropriately collected at each junction of the study area during a weekly interval in January/February 2017 at times 7:30 – 10:30 and 17:30 – 20:00

C. Microscopic traffic flow simulation

As previously mentioned, SUMO was used for the scenario implementation. The required code for user behaviour modelling and traffic control was provided by the authors and developed in MATLAB (the R2018b was adopted). Furthermore, in order to guarantee the on-line interoperability between modelling and traffic flows, the TraCI interface was used. The traffic flows model was calibrated and validated [20] considering two kinds of point measures, collected through loop detectors and manual counts. Furthermore, the used indicators were the travel times (TT) and queue location and lengths (QL). In terms of the goodness-of-fit function for model calibration, the Geoffrey E. Havers statistic was adopted considering the observed and modelled data. In particular, the calibration aims to ensure that the correspondence between observed and modelled data is less than 5 for 75% of the pairs. Moreover, each day was simulated 20 times and the result provided is the mean value.

In Table I, the travel times obtained during peak hour simulation after model calibration are shown, as well as the RSME.

TABLE I. CALIBRATION RESULTS (TT) OF THE SIMULATION MODEL

Path 1 [min]	**Path 2 [min]**	**RSME**
44	35	3.14

The speed limit on both paths is 50 km/h, and there is a difference in length of 650 m (the length of the main path is 650 m, whilst the length of the alternative is 1300 m). Both paths merge in an intersection controlled through traffic lights (section 4).

V. NUMERICAL RESULTS AND DISCUSSION

In this section the simulation results are shown[2]. For each scenario, 40 consecutive days were run (in order to reproduce the day-to-day choice updating process) and for each day, the simulation interval consisted of 1 hour (peak hour) and a warm-up period was fixed which was equal to 10 minutes. The travel time was computed every 5 minutes.

In particular the results of three scenarios are displayed and discussed; the considered scenarios are listed in following:

1) The single junction modelling;
2) The on-line scheduled synchronisation;
3) The on-line scheduled synchronisation with the activation of link metering at upstream pedestrian crossings.

Scenarios were compared considering two main indicators: two performance indicators, Queue Length (QL), and Travel Times (TT). It is worth noting that performance indicators are computed every 5 minutes. Moreover, each simulation starts after a warm up period of 10 minutes. A more detailed description of the scenarios is provided in the following.

A. Scenario 1

In this scenario only the timing plan for junction 4 and junction 5 were computed; the adopted strategy was based on the signal setting design approach in case of single junction, thus two junctions are considered as isolated.

TABLE II. SECTIONS QLs

Interval [s]	Queue Length [m]				
	Section 1	*Section 2*	*Section 3*	*Section 4*	*Section 5*
600-900	181.5	185.3	88.2	45.6	39.3
900-1200	146.7	146.6	87.7	48.1	40.0
1200-1500	182.6	211.7	89.0	53.0	144.6
1500-1800	162.8	191.2	88.5	52.3	169.7
1800-2100	186.8	70.2	88.4	71.2	204.0
2100-2400	193.5	194.2	89.1	90.4	198.3
2400-2700	135.2	212.5	88.9	113.0	195.4
2700-3000	198.5	216.1	88.3	126.4	183.2
3000-3300	197.4	218.6	89.1	190.2	216.5
3300-3600	187.4	202.3	88.4	136.8	211.7

[2] Simulations were run on a server machine Intel(R) Xeon(R) CPU E5-1620 v3, clocked at 3.50GHz and with 8GB of RAM

With reference to QL (Table II), it must be observed that in this scenario at the beginning of the simulation values increase from section 1 to section 5, however the value in section 5 increases over time and the backward propagation is observed until section 4.

Regarding the second indicators (see Table III), comparable results are obtained in terms of TT, in fact the mean value for path 1 is around 28 minutes whilst the mean value for path 2 is around 26 minutes.

TABLE III. PATH TTS

Interval [s]	**Travel Time [s]**	
	Path 1	***Path 2***
600-900	21.6	20.9
900-1200	24.2	23.2
1200-1500	29.5	28.5
1500-1800	30.4	29.5
1800-2100	33.09	31.5
2100-2400	27.16	24.6
2400-2700	27.75	25.2
2700-3000	28.12	24.3
3000-3300	28.14	25.1
3300-3600	32.25	28.56

B. Scenario 2

The proposed scenario was an extension of scenario 2 in which junctions 4 and 5 are managed through the implementation of a proper network traffic control strategy (through the adoption of a plant model for traffic flow prediction), and the two upstream pedestrian crossings are designed in order to metering the vehicles travelling from those traffic signals to junctions 4 and 5. The scenario provides the combination of a widely tested strategy for network traffic control (scheduled synchronisation) with an adjustment of the link metering strategy. This aims to the metering of the outgoing flow from pedestrian crossings on the base of the observed coefficient of occupancy along each of two roads connecting i) two successive pedestrian crossings (see ‘junctions’ 1 and 2); and ii) the downstream crossing junction with the first managed junction (see junctions 2 and 3).

As described in previous section, a Kalman filter has been applied to iteratively predict traffic flows approaching the Vittoria tunnel. Once obtained the traffic flows which are likely to propagate on such a link for every 5 minutes time interval the off line synchronisation approach is performed in order to carry out and actuate best green times and offsets.

Table IV, and V report the performance indicators for this scenario. Again, the relative variations with respect to Scenario 1 are used to evaluate the performance of the proposed solution. In terms of QL, except for section 3, performances are significantly improved, with an overall average of about 34%.

Even TT reductions (see Table V) are worthwhile, with a value around 16% for path1, and around 12% for path2.

TABLE IV. SECTIONS QLs VARIATION WRT QLs OF SCENARIO 1

Interval [s]	**QL variation wrt Scenario 1**				
	Section 1	***Section 2***	***Section 3***	***Section 4***	***Section 5***
600-900	17.1%	21.3%	-0.5%	24.9%	-53.2%
900-1200	-2.9%	-10.4%	-1.7%	1.1%	-53.1%
1200-1500	22.0%	38.5%	0.0%	-4.2%	38.0%
1500-1800	12.4%	8.0%	0.1%	12.9%	57.6%
1800-2100	15.8%	-56.9%	-0.7%	43.5%	91.0%
2100-2400	86.6%	60.9%	-0.1%	53.3%	54.1%
2400-2700	-7.8%	42.0%	0.2%	102.9%	48.1%
2700-3000	37.8%	44.2%	-0.8%	116.5%	29.3%
3000-3300	42.3%	57.3%	0.2%	136.2%	57.4%
3300-3600	38.4%	28.4%	-0.2%	73.1%	39.9%
	Mean of QL variation wrt Scenario 1				
	26.2%	23.3%	-0.3%	56.0%	30.9%

TABLE V. PATH TTS VARIATION WRT TTS OF SCENARIO 1

Interval [s]	**TT variation wrt TT of Scenario 1**	
	Path 1	***Path 2***
600-900	20.47%	21.34%
900-1200	-11.59%	-12.96%
1200-1500	6.23%	5.33%
1500-1800	22.60%	22.19%
1800-2100	29.21%	22.92%
2100-2400	16.42%	10.21%
2400-2700	11.36%	5.66%
2700-3000	12.66%	1.67%
3000-3300	4.77%	-2.75%
3300-3600	47.33%	38.31%
Mean of TT variation wrt Scenario 1		
	15.94%	11.19%

VI. MAJOR FINDINGS AND CONCLUSIONS

The main focus of the paper is on the combination of different Intelligent Transportation Systems (ITS) strategies in order to reduce the impact of urban traffic congestion. To be more precise the considered strategies are the Traffic Control and Link Metering. Thus, the paper contribution is fourfold:

i) the combined analysis of two ITS strategies;

ii) the application to a real context (a sub network of the city centre of Naples, Southern of Italy, was considered);

iii) the consideration of an enhanced traffic control method; the approach was based on the scheduled synchronisation not yet implemented on-line.

In order to evaluate the effectiveness of the proposed framework two scenarios were implemented in a microsimulation platform (SUMO) and compared on the base of two performance indicators, the queue lengths and the travel times on each one of (two) alternative paths within network; indicators point out that the last scenario which includes the combination of all ITS methods is the best one.

Starting from the analyses shown and with reference to the considered network, the main conclusion is about the framework effectiveness. Further research perspectives are about the day-to- day evaluation and the analysis of the system convergence and stabilisation and the implicit representation of users' behaviour modelling [21] in particular in presence of information systems. Finally, the impact in terms of fuel consumption and emission will be properly evaluated [22].

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4.2

Unified Network Traffic Lights Strategy with the Optimisation of Electric Vehicles Energy Consumption

ABSTRACT

The available strategies for control systems have been built basing mainly on energy consumption patterns of internal combustion engine vehicles (ICEVs). As shown in recent studies the energy consumption patterns of Electric Vehicles (EVs) with regards to the variability of traffic flow characteristics is very different, and even opposite, compared to that of ICEVs. To consider such difference, developed control strategies must be updated by also considering the minimisation of EVs energy consumption.

In this paper an integrated framework aiming at the multi-objective traffic control decision variables optimisation for EVs, by deriving a link-based macroscopic energy consumption function from microscopic data is proposed. Concerning the function, it can be applied to extend the objective function of control strategy design usually based on total delay or queue.

In this study, the energy consumption function has been derived based on the VT-CPEM model (Fiori et al., 2016) to simulate consumptions at signalised junctions and it has been thoroughly calibrated based on real-world individual trajectories at signalised junctions. Trajectories have been extracted from a large dataset through an innovative tool – Trajectories Extraction Tool for Traffic Control Systems Applications (TET-TCSA).

Keywords: electric vehicles; traffic control; energy consumption/recovery; traffic flow modelling, calibration, metaheuristics.

1. INTRODUCTION AND MOTIVATION

The damage to human health caused by road transportation is now recognised both by regulatory bodies and by industry. The strategy to reduce the effect of road transportation is based on three pillars: the first aims to encourage the use of vehicles with alternative powertrains (e.g., electric, plug-in hybrid, fuel cells etc.), the second one is based on the shift of our mobility patterns to make better use of resources and the third one is based on the improvement of existing modes of transport by using enhanced technologies. In particular, Electric Vehicles (EVs) represent one of the possible solutions to comply with environmental issues. The presence in their powertrain of electric and electronic component allow for higher efficiency on-board and for the consequently reduction of energy consumption and emissions. Additionally, this technology guarantees the recovery of the energy while braking and can be easily integrated with renewable energy systems for the pursuing the goal of zero emissions in urban area and a reduction of global emissions.

To this regard, the European Union (EU) has set an ambitious target for reducing its greenhouse gas (GHG) emissions, aiming for an 80% reduction in 2050 compared to 1990 levels, with a 60% reduction target for the transport sector over the same period. The first out of ten goals for a competitive and resource-efficient transport system is to "*halve the use of 'conventionally fuelled' cars in urban transport by 2030; phase them out in cities by 2050*", as mentioned in the ("White paper 2011 - Mobility and Transport - European Commission," 2011). Indeed, EVs are by common consent recognized as a key technology to achieve near-zero local emissions (Chan, 2007; Chan and Wong, 2004) if compared with conventional, with higher particulate matter (PM) emissions, or hybrid vehicles.

Several studies are available on Electric Vehicles (EVs). The majority of them are related to the charging station location problem (Li et al., 2016; Wang and Lin, 2013) or to the charging planning and the impact to the electric infrastructure (Daina et al., 2017; Dong et al., 2014; Hardman et al., 2018; Kontou et al., 2019; Marmaras et al., 2017). Additionally, many studies available deal with the electric vehicle acceptance (Jensen et al., 2013; Tamor et al., 2015, 2013; Will and Schuller, 2016).

However, more recently, some studies started focusing on EVs transportation systems efficiency. The simulation of alternative powertrains, focusing mainly on hybrid ones, with microscopic traffic models was addressed by (Bhavsar et al., 2014; Zulkefli et al.,

2014) while very few studies focused on EVs and traffic control (Li et al., 2018). Given the importance of this topic and the growing attention that open literature has provided recently, this field deserves to be further explored.

In particular, with respect to internal combustion engine vehicles (ICEVs), recent studies proved that EVs energy consumption patterns are very different, and even opposite under certain traffic conditions e.g. stop-and-go, to that of ICEVs (Fiori et al., 2020, 2019).

In the traffic control field, the aforementioned difference is expected to have big impact on control strategy design, especially at signalised junctions. However, "energy-saving" control strategies developed so far in the literature are mainly based on the consumption patterns of ICEVs. Very few studies have focused on EVs, though the proposed methodologies were limited. In particular, some studies adopt fuel/energy consumption maps, that can exclusively be generated by testing a vehicle on an engine or chassis dynamometer (Luo et al., 2017).

Therefore, the objective of this work is to solve these limitations and present a method to support the development of a Unified network tRaffic control strAtegies aiming at minimising also EVs energy coNsumptiOn (URANO).

In particular, a link-based macroscopic energy consumption function for EVs is derived from microscopic data. The function can be applied to extend the objective function of any control strategy design, and it makes the most of microscopic modeling of energy consumption of EVs, and of detailed microscopic trajectory data. In this study, the function has been derived based on the VT-CPEM model to simulate consumptions at signalised junction. The model has been thoroughly calibrated based on real-world individual trajectories at signalised junctions. Trajectories have been extracted from a large dataset through the integration of the modelling framework with an innovative tool – Trajectories Extraction Tool for Traffic Control Systems Applications (TET-TCSA).

The remainder of the paper is organised as follows: in the next Section a literature review is reported; in Section 3, the methodological framework is discussed in detail and in particular the overview of each sub model composing URANO is provided; Conclusions and future perspectives end the paper.

2. LITERATURE REVIEW

2.1 Urban network traffic control

Regarding the traffic lights decision variables optimisation, first of all methods for traffic signal decision variables optimisation may be classified in static and dynamic traffic control approaches. In the first case the implemented strategies are usually called fixed time (Gartner et al., 1991; Little et al., 1981; Stamatiadis and Gartner, 1996; Webster, 1958; Wong and Wong, 2003a) and may further classified in stage-based (Akcelik, 1981; Allsop, 1981; Tully, 1966; Webster, 1958, p. 19), group-based (phase-based) (Heydecker, 1992; Heydecker and Dudgeon, 1987; Improta and Cantarella, 1984; Silcock, 1997), and lane-based approaches (Wong and Heydecker, 2011; Wong and Wong, 2003a, 2003b). In case of traffic control most adopted are the vehicle-actuated based on vehicles arrivals (Yin et al., 2007; Yun and Park, 2012), and adaptive signal control based on arrival flows (Gartner et al., 2001; Gregoire et al., 2014; Hajbabaie and Benekohal, 2015; Le et al., 2015; Mercader et al., 2020; Mirchandani and Head, 2001; Robertson and Bretherton, 1991; Sims and Dobinson, 1979; Varaiya, 2013a, 2013b). In both cases input flows may be collected through historical data or detectors (for instance loop detectors) or more recently starting from probe vehicles trajectories (Ma et al., 2020).

A further classification is about methods for isolated and interacting junctions, where in case of isolated junctions methods for single junctions may be adopted, whereas in case of interacting junctions in which delays of downstream junctions depends on the flow entering upstream, methods for urban networks must be adopted (Cantarella et al., 2015). The main field of investigation of the paper is about network traffic control. Dynamic methods for urban traffic control are usually classified in centralised and distributed approaches depending on the adopted procedure for network decision variables optimsation (simultaneously or sequential; Lin, 2011; Zegeye, 2011).

Furthermore, regarding the formulation of the optimisation problem and the identification of the objective functions, there are several studies focusing on the mono-criterion and multicriteria optimisation at single junctions (Chen et al., 2011), but very few studies are about the multi-criteria optimisation at network level (Di Pace, 2020). Concerning the decision variables, Stevanovic et al. (2009) proposed an integrated tool for off-line traffic signal timings optimisation combining fuel consumption and emission reduction, whilst Zegeye et al. (2009) designed a model predictive control (MPC) strategy focusing on online control of both the total travel time and the total emissions, and

(Zegeye et al., 2013) proposed a framework combining macroscopic traffic flow models and microscopic emission and fuel consumption models with reference to the freeway traffic networks. At urban level, (Zhu et al., 2013) adopted a similar approach aiming at the minimisation of delays and emissions.

Summing up in this study the model predictive control has been adopted and the multicriteria optimisation at network level is dealt with based on the combination between total time spent and EVs consumption minimisation is considered.

2.2 Electric Vehicles

Real-world simulation of fuel consumption of conventional vehicles is a well-known research area. The majority of these studies use models based on the efficiency map of the vehicle engine, either provided by the manufacturer or generated by testing the vehicle on a chassis dynamometer (Brooker et al., 2015; Kim et al., 2012; Lee et al., 2013; Newman et al., 2016; Wipke et al., 1999).

A common drawback of simulation models available is that they critically depend upon the availability of efficiency maps, significantly varying by type of vehicle, yielding transferability issues and limited application flexibility. In addition, automakers, the only who could provide efficiency maps, are reluctant to share these maps because of obvious industry-related protection policies.

To overcome this shortcoming, some models have been developed for conventional vehicles (Rakha et al., 2011). Specifically, (Rakha et al., 2011) adopted a second-order polynomial to approximate the convexity of the fuel consumption function in the range of positive values, attaining a good compromise between model accuracy and applicability. The model was proved to predict well vehicle fuel consumption rates and CO2 emissions consistent with in-field measurements. Following a similar approach, (Fiori et al., 2016; Fiori and Marzano, 2018) generalized the above model to the powertrain of electric vehicles (EVs) and electric freight vehicles (EFVs), by developing the Virginia Tech Comprehensive Power-based EV Energy consumption Model (VT-CPEM) and the EFVs energy consumption model (EFVs-ECM), respectively, aimed at evaluating the vehicle energy consumption as a function of vehicle’s speed profile and characteristics, independently of efficiency maps. Notably, these models were estimated and validated based on real data. Another interesting and inedited feature is their capability to quantify the energy while braking, i.e. the so-called energy efficiency recovery, as a function of the deceleration levels.

Moreover, about the integration of energy consumption models with traffic control systems, several studies are available regarding conventional powertrains (Almutairi et al., 2017; Kamalanathsharma et al., 2015; Li et al., 2009; Yang et al., 2016) but only in the last few years the attention focused also on electric powertrains.

Additionally, to the best of the authors knowledge, available studies on this topic adopt, for the evaluation of EVs energy consumption, models with some limitations. For example (Luo et al., 2017) in their work aimed at developing a novel optimal speed advisory board strategy for successive junctions for hybrid vehicles. They adopted in the energy consumption model the fuel/energy consumption maps, that can exclusively be generated by testing a vehicle on an engine or chassis dynamometer. Therefore, there are critical limitations in the flexibility of adoption of these models as reported in the open literature (Fiori et al., 2018; Park et al., 2013).

(Zhang and Yao, 2015) analysed the EV eco-driving at signalised junction using an EV data driven model tested on the New European Driving Cycle (NEDC), that was no longer an accurate representation of average driving behaviour. Indeed, the 1st September 2017 a new measure, the World-wide harmonized Light duty Test Procedure (WLTP) was introduced. This testing procedure has been developed under the supervision of the UNECE (United Nations Economic Commission for Europe), to provide uniform and more realistic test conditions worldwide (Pavlovic et al., 2016).

(Liu et al., 2019) in their work on eco-speed guidance for the mixed traffic of electric vehicles and internal combustion engine vehicles at an isolated signalised junction, for EVs used data from (Wu et al., 2015a) model based on a specific case scenario.

Also, (Wu et al., 2015b) in their study about the energy-optimal speed control for electric vehicles on signalised arterials used a data driven model on a test vehicle that is not one of the commercially produced vehicles and this might bring biases the testing results which needed to be further verified using current commercially produced EVs.

Finally, in this study the use of the VT-CPEM model (Fiori et al., 2016), that is not characterised by the previous mentioned limitations such as use of efficiency map, re-calibrated on a specific dataset of real-world data including signalised junction is adopted.

3. METHODOLOGICAL FRAMEWORK

Starting from the framework developed by (Di Pace, 2020) based in within day traffic flow modelling and focusing on the multi-objective optimisation at network level, in this paper a further development is discussed. In particular, the main focus of the paper is on the objective functions integration combining in the multi-objective optimisation the total travel time spent and the energy consumption (EC) function.

To consider energy consumption in the control strategy, a novel cost function, based on microscopic simulation of energy consumption of electric vehicles, has been developed. Such function makes the most of detailed vehicle trajectory data and microscopic energy consumption models, in a quasi-Monte Carlo framework. To be more precise, the portion of vehicle trajectories in the proximity of signalised junctions have been extracted and used to feed a microscopic energy consumption model of electric vehicles - VT-CPEM,(Fiori et al., 2016). By running the model in a quasi-Monte Carlo framework, an energy consumption function for each link is estimated.

In particular, starting from a real-world dataset of vehicle trajectories of electric vehicles, the framework is composed by two following sub-modules:

1. The first sub-module is able to solve a dynamic traffic control problem therefore every control interval traffic flows are collected through a traffic flow model and the multi-objective optimisation problem is run considering the network traffic control decision variables for each junction within network (green timings and offsets) and a traffic flow model operates also as plant model from one control interval to the other;
2. The second sub-model is able to provide the energy consumption function for each link. To be more precise the developed trajectory extraction tool (TET-TCSA) allows for the extraction of portions of microscopic trajectory data – i.e. individual vehicles' GPS and power data – on a given network area (e.g. traffic control systems, critical road sections, roundabout etc.). The extracted trajectories are then used to calibrate the VT-CPEM (Fiori et al., 2016). Ultimately, the model is applied to simulate the microscopic energy consumption of EVs and to estimate a link-based macroscopic energy consumption function. Such function describes the mathematical relation between the energy consumption and the average speed, and it can be used to complement the objective function in traffic control strategy design.

Finally, through an off-line procedure, the energy consumption is combined in terms of objective function with the total delay in order to optimise the traffic lights decision variables.

An overview of the methodological framework proposed in this work is shown in Figure 1.

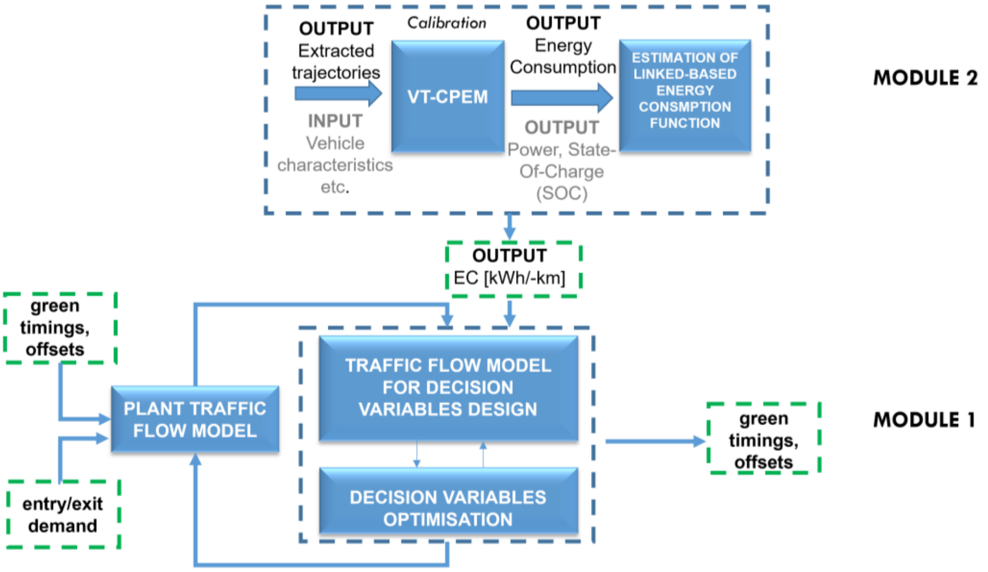

Figure 1: Methodological framework.

3.1 Multi - objective optimisation module

3.1.1 Modelling framework and implementation settings

The proposed framework employs a Model Predictive Control to optimise the control input of the system (green lights and offsets) with the aim to minimise two indicators: Total travel time spent and Energy Consumption. To this end, the case study is modelled with a Cell Transmission Model to predict the future states of the system over a prediction horizon (given the measured current state, the expected future disturbances and future control inputs) and obtain the values of said indicators, which are the objectives to minimize with the optimisation strategy. Therefore the CTM has been adopted as prediction model and plant model. The result of the optimisation is a sequence of control inputs to be implemented on each control step. The length of the control step should be long enough so the system can respond to each control sample, but not too long in order to react to variations of the state of the system due to the disturbances. The control horizon is the number of control steps that the system applies over the prediction horizon on the prediction model.

The whole procedure of prediction of states and optimisation of the control inputs is applied on a rolling horizon approach, since after obtaining the optimal control sequence only the first control sample is implemented on the system, then the horizon is shifted, and the optimisation is restarted with updated information of the state of the system. The interval between measurements of the system is the sample time, in which the optimized control input is applied and stays constant.

3.1.2 Traffic Control

In this subsection it is firstly summarised the problem statement and the decision variables, then some details about the adopted MPC are provided then the details of the multi-objective optimisation are discussed in detail with reference to the functions transformation.

Problem statement and decision variables definition

The adopted optimisation approach is based on the centralised method which aims to optimise all junctions in a given network together. A more detailed description of the strategy is provided below.

Let:

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

For each junction, let:

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

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

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

$g_k = \sum_j \delta_{kj} t_j - t_{ar} - l_k$ be the effective green for approach k, where $\delta_{kj}=1$ if approach k receives green during stage j and 0 otherwise;

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

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

ϕ_i be the node offset;

and let us consider the following constraints:

stage lengths being non-negative

$t_j \geq 0 \quad \forall_j$

consistency among stage lengths and cycle length

$$\sum_j t_j = c$$

effective green being non-negative

$g_k \geq 0 \ \forall_k$

the minimum value of the effective green

$g_k \geq g_{min} \qquad \forall_k$

to avoid multiple equivalent solutions and non-negative values for node offsets between the start of a reference stage of junction *i* and the start of the reference stage of the first junction used as a reference for clock

$c > \phi_i \geq 0$

Finally, in terms of the objective function two criteria were identified. The first is total delay to be minimised the second criterion concerns the Energy Consumption function which is described in more detail in the following; both terms are explicitly computed depending on the traffic flow model considered.

Optimization procedure

The optimisation strategy uses a metaheuristic procedure as a solution algorithm; in this case the Differential Evolution method (O'Hora et al., 2006; Price, 2013)

There is no proof of convergence for DE, however it has been shown to be effective on a large range of classic optimisation problems. In a comparison by (Storn and Price, 1997) DE was more efficient than simulated annealing and genetic algorithms. (Ali and Törn, 2004) found that DE was both more accurate and more efficient than controlled random search and another genetic algorithm.

In (Lampinen and Storn, 2004) demonstrated that DE was more accurate than several other optimisation methods including four genetic algorithms, simulated annealing and evolutionary programming. DE was applied with the following setting of the parameters:

- Population size: variable depending on each scenario
- Combination probability: 0.90
- Mutation factor: 0.50·(1+rand)
- Maximum iterations: 1000

Function-transformation methods for multi-objective Optimisation

a) **Total Time Spent**

The Total Time Spent is calculated as the sum of the predicted number of vehicles on all the links of the network, during the simulation horizon, multiplied by the length of each time step. However, since the simulation starts with an empty network, a first warm-up period was considered in which the indicator is not calculated. Then, the simulation continues with a simulation horizon of 3600 seconds, with a time step of 1 second.

Since the Cell Transmission Model calculates the vehicle density at each cell, the number of vehicles can be obtained by multiplying it by the cell length.

$$TTS = J_{TTS} = \sum_{t=T_1}^{T_1+T} \sum_{l \in L} \sum_{i \in l} (k_i(t) \cdot \Delta x) \cdot \Delta t$$

Where:

t time step

T_1 initial warm-up period

T Simulation horizon

l link belonging to the set of links L of the network

i cell index of link l

$k_i(t)$ density in cell i

Δx cell length

Δt length of the time step

b) **Energy Consumption**

The aggregated speed of each cell of the Cell Transmission Model can be obtained as:

$$S_i(t) = \frac{Y_i(t)}{k_i(t)}$$

Then, with the aggregated speed in km/h, it is possible to apply the function of the estimation of the link-based energy consumption for each cell (some details about the adopted function are provided in the section 3.2.4). This value is summed for all the cells of each link, for all links in the network to obtain the overall energy consumption during the whole simulation horizon.

$$EC = J_{EC} = \sum_{t=T_1}^{T_1+T} \sum_{l \in L} \sum_{i \in l} f\left(S_i(t)\right)$$

c) **Pareto optimality solution**

Since the problem is a multi-objective optimisation, a single point of the solution set that minimizes all the objectives simultaneously generally does not exist. Therefore, in order to find and choose a suitable solution, it is necessary to calculate a weighted sum of the transformed objective functions, aiming to minimize the distance to the Utopia Point, that is, the point which has the minimum of each of the objective functions as coordinates.

Each objective function is transformed using the *upper-lower-bound approach* (Koski, 1981; Koski and Silvennoinen, 1987; Rao and Freiheit, 1991; Yang et al., 1994):

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

Where:

$J_o(\boldsymbol{x})$ Objective function o, valuated at variables x

$J_o^{\min Pareto}$ minimum value of the objective function o, coordinate of the utopia point

$J_o^{\max Pareto} = \max_{1 \le j \le k}\left(J_o(\boldsymbol{x}_j^*)\right)$ The Pareto maximum of the objective function o, with $\boldsymbol{x}_j^*$ being the point that minimizes the j-th objective function (such that is a vertex of the Pareto optimal set in the design space and $J_o(\boldsymbol{x}_j^*)$ is a vertex of the Pareto optimal set in the criterion space), coordinate of the nadir point.

Then, the solution with the closest distance to the Nadir point was chosen, that is:

$$\min_{\boldsymbol{x}} U = \min_{\boldsymbol{x}} \sqrt{\sum_{o=1}^{k} \left[J_o^{trans}(\boldsymbol{x})\right]^2}$$

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

3.1.3 Cell Transmission Model

In this paper, the Cell Transmission Model was adopted to perform the optimization. Historically, it was introduced to support the solution of the continuous time – continuous space LWR model, and it is based on a *finite-difference* method: the time is divided into constant time intervals, while the road segment is divided into cells of constant length, with an index *i* increasing in the downstream direction. At each time step, every cell has single values of density and speed (as a function of the speed - density relationship) while the flow between neighbouring cells is constant during the time interval. The most common integration method for LWR models is the *Godunov scheme* (Treiber and Kesting, 2013). This method is based on an exact solution of the continuity equation for one time step, assuming stepwise initial conditions given by the actual densities of the cells. The road is divided into cells of length □x equal to the distance that a vehicle would travel in a free flow condition during one-time step. Hence it is equal to the free flow speed multiplied by the duration of the time step (also called clock tick), $V_f \Delta t = \Delta x$. It should be pointed out that the relation between the cell length and the time step complies with the *Courant-Friedrich-Lewy* condition ($V_f \Delta t \leq \Delta x$) for the stability of explicit solution methods. Following the Godunov scheme, the densities are initially averaged for each cell (each cell has a constant value of density), and from one time step t, to a successive one, t+Δt, the solution evolution is averaged again in order to obtain a piecewise constant solution. The main variables of the method are

- k_i density in cell i;
- k_j jam density;
- Q_i maximum flow rate in cell i;
- V_f free flow speed;
- ω shock wave speed in congested traffic;
- Δx cell length;
- Δt time step;
- Y_i flow exiting the boundary of cell i.

The density is then obtained as a function of flows at the cell boundaries as in the following:

$$k_i(t+1) = k_i(t) + [Y_{i-1}(t) - Y_i(t)] \cdot \frac{\Delta t}{\Delta x}$$

Finally, the key quantities of the method can be introduced based on the (trapezoidal) fundamental diagram (see Figure 2)

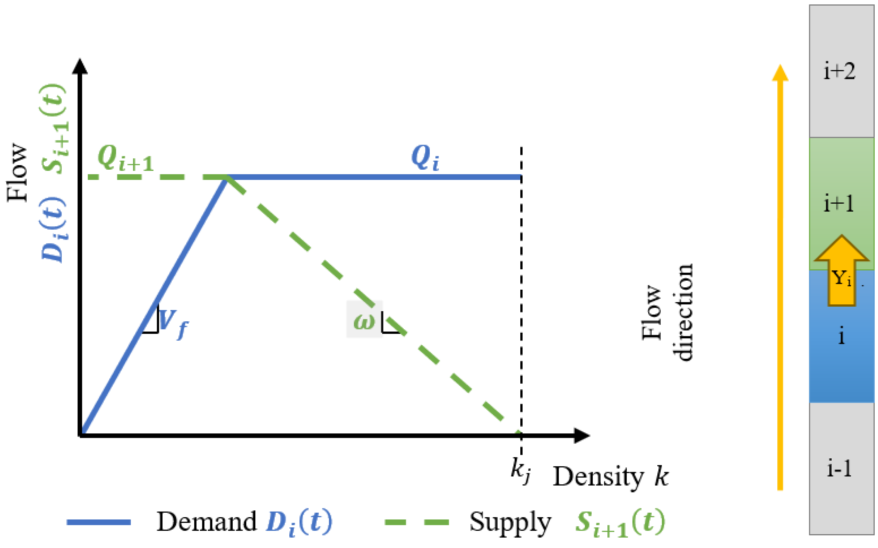

Figure 2: Trapezoidal fundamental diagram – link representation.

The flow of vehicles moving through the boundary between cell i and cell $i+1$ (see Figure 2) is given by the result of a comparison between the maximum flow that can be *sent* (that is the *demand*) by cell i (upstream of the boundary):

$$D_i(t) = \min(Q_i, V_f \cdot k_i)$$

and the maximum flow that can be *received* (that is the *supply*) by the downstream cell *i+1*:

$$S_{i+1}(t) = \min\left(Q_{i+1}, \omega \cdot (k_j - k_{i+1})\right)$$

Since every cell has a maximum value of density (k_j), the incoming flow is not only constrained by the maximum value Q_{i+1}, but also by the difference between the maximum density and the current density $(k_j - k_{i+1})$, which allows to describe the spillback phenomena and is able to model the effects of horizontal queuing.

Therefore, in accordance with the *Godunov scheme*, the flow $Y_i(t)$ can be rewritten in accordance with the demand (*sending*)-supply (*receiving*) rule of the cell transmission model as:

$$Y_i(t) = \min(D_i(t), S_{i+1}(t))$$

3.2 Energy consumption module

In this section the details of the energy consumption module are described; in particular the details of i) the vehicle simulator for EVs, ii) the trajectory extraction tool, iii) the VT-CPEM calibration with reference to the signalised interacting junctions real data and iv) the estimation of the link-based energy consumption.

3.2.1 Vehicle simulator for EVs

The VT-Comprehensive Power-based EV Energy consumption Model (VT-CPEM) is a backward highly-resolved power-based model. Specifically, the model requires as inputs the instantaneous speed, grade, payload on-board and the vehicle characteristics, and produces as output the energy consumption (EC) [kWh/km] by the vehicle for a specific drive cycle, the instantaneous power consumed [kW], and the state of charge (SOC) of the electric battery [%] at the end of the simulation. This model accurately estimates the energy consumption, producing an average error of about 6% relative to empirical data (Fiori et al., 2016). The model first calculates the instantaneous power at the wheels $P_W(t)$ on the basis of the path (e.g. slope), trajectory (e.g. speed profile) and vehicle characteristics and after the instantaneous required traction power $P_T(t)$ is determined based on vehicle efficiencies (engine, braking system, batteries). Finally, integration of $P_W(t)$ and $P_T(t)$ over the entire duration of the driving cycle allows calculation of energy consumption/recovery and the corresponding variation of the state-of-charge, given its value at the beginning of the driving cycle.

For the sake of brevity, only the formula applied to calculate the power required for traction $P_T(t)$ is reported, as to show the 4 model parameters to be calibrated against trajectory data shown in Section 6. Additional details on the VT-CPEM are reported in (Fiori et al., 2016).

In more detail, once calculated the power at the wheels $P_W(t)$ as reported in (Fiori et al., 2016), the power necessary to provide traction (P_T) is:

$$P_T(t) = \begin{cases} \dfrac{P_W(t)}{\eta_{DL} \cdot \eta_{EM} \cdot \eta_{BAT}} & if \;\; P_W(t) \geq 0 \\ \left(P_W(t)\right) \cdot \left(\eta_{DL} \cdot \eta_{EM} \cdot \eta_{BAT}\right) \cdot \eta_{RB}(t) & if \;\; P_W(t) < 0 \end{cases}$$

where η_{DL} is the driveline efficiency, η_{EM} is the efficiency of the electric motor, η_{BAT} is the efficiency of the battery system and $\eta_{RB}(t)$ the regenerative braking energy efficiency. It is worth mentioning that the three efficiency parameters η_{DL}, η_{EM} and η_{BAT} are inherent characteristics of each vehicle, and they usually fall in between 0.90 and 0.98: this enables setting proper upper and lower bounds in the estimation of such efficiency parameters, as it will be described in Section 6. On the contrary, the parameter $\eta_{RB}(t)$ is defined as a function of time t as follows, in accordance with (Fiori et al. 2016):

$$\eta_{RB}(t) = \begin{cases} e^{-\frac{\alpha}{|a(t)|}} & if\ a(t) < 0 \\ 0 & if\ a(t) \geq 0 \end{cases}$$

Where in the parameter α depends upon the specific vehicle under analysis and should be therefore estimated as well, usually in the [0.005,1] range. Specifically, such range is identified to comply with expected lower and upper bounds of the regenerative braking energy efficiency η_{RB}, as discussed in detail in (Fiori et al., 2016).

3.2.2 Trajectory Extraction Tool for Traffic Control Systems Applications (TET-TCSA)

The tool has been developed to extract, from a large trajectory dataset, portions of vehicle trajectory which drive through a selected network area.

This choice allows the development of a flexible tool useful also for applications in the urban environment for interacting junctions (Cantarella et al., 2015; Di Pace, 2020; Memoli et al., 2017).

In this work, the tool is applied to extract portions of individual trajectories in the nearby of two traffic control systems (500 m before and after each junction). The tool is developed in MATLAB R2019b environment to be easily integrated with other models/software.

In particular, TET-TCSA takes as input data input data: (i) trajectories GPS and power data (timestamp, latitude, longitude, voltage and current) and (ii) control systems location (lat, lon), and provide as output (i) portion of trajectories in a specific range of the control systems (e.g. +/- 500 m) and (ii) descriptive statistics on trajectories that allows for clustering drivers' behaviors (e.g. seasonal, weekly, hourly).

In Figure 3 and Figure 4, examples of extracted trajectories at two consecutive signalised junction are reported.

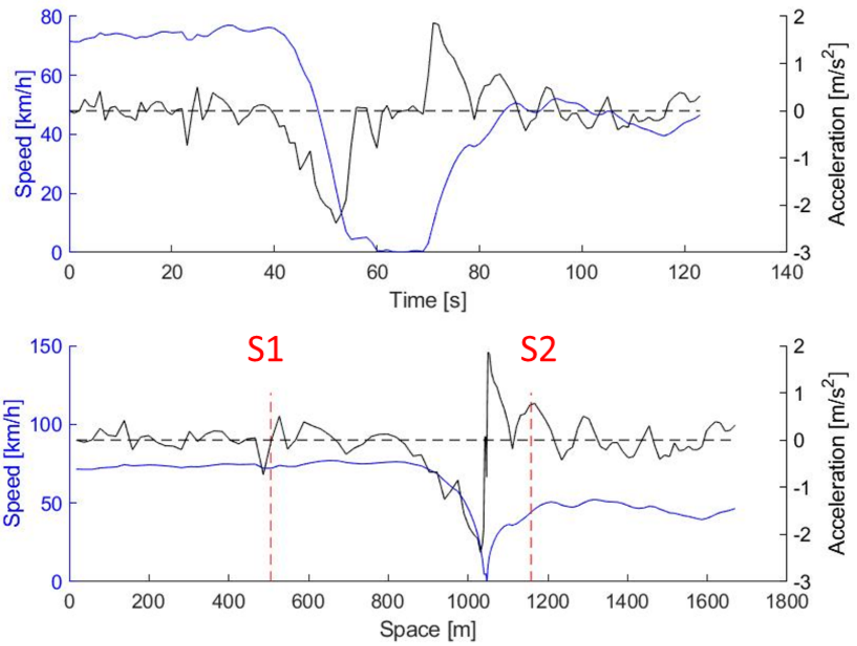

Figure 3: Example of extracted trajectory involving 2 control systems.
[black line is the acceleration, blue line is the speed, dot red lines represent the first-upstream (S1) and second-downstream (S2) traffic control systems].

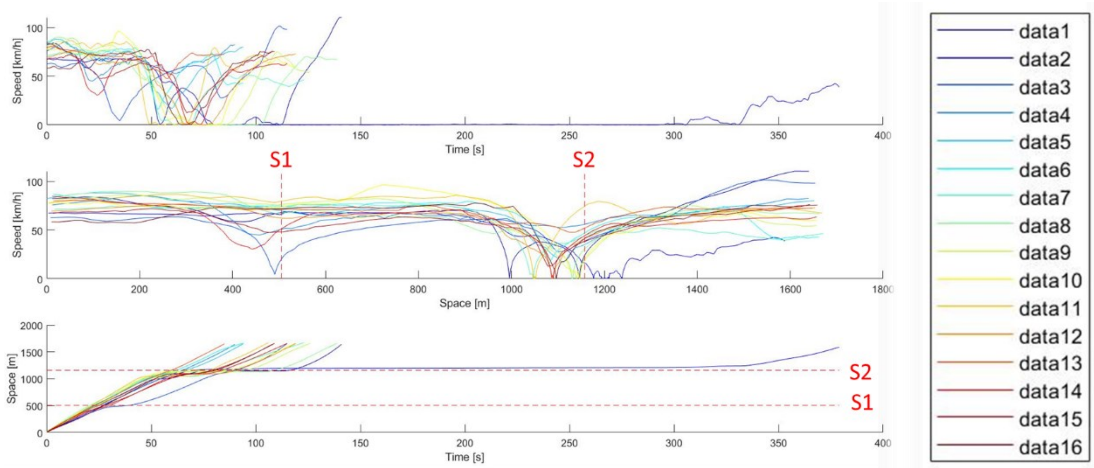

Figure 4: Example of 12 extracted trajectories, on the same path, involving 2 consecutive control systems. The dot red lines represent the first (S1) and second (S2) traffic control systems.

3.2.3 VT-CPEM calibration with extracted real-word data at signalised junction

In an integration with a traffic control strategy, the energy consumption is expected to enter in the objective function together with the delay function and other measures of performance upon which control strategy is designed. To this aim, a first step is that of applying an energy consumption model to simulate EVs consumptions in proximity of the junction. In this work, the VT-CPEM has been adopted. In particular, the model parameters are calibrated against the trajectory data extracted in Section 5.

Dataset statistics

The dataset is composed of 12 trajectories collected from the CAN bus of the EV tested. These data included the instantaneous power required for traction and for this reason has been possible proceed with the calibration with the output of the VT-CPEM. A summary statics of the kinematics paraments and energy consumption/recovered of the dataset is reported in Table 1.

Table 1: Summary statistics for the trajectories dataset adopted for the calibration.

	MEAN	STANDARD DEVIATION
Distance [km]	1,284	0,021
Duration [s]	77,583	20,118
Average speed [km/h]	62,152	13,465
Maximum speed [km/h]	82,743	8,905
Max acceleration [m/s2]	1,146	0,609
Max deceleration [m/s2]	-2,188	1,029
Average slope [%]	0,002	0,003
Energy consumption [kWh/km]	0,096	0,020
Energy recovered [kWh/km]	-0,053	0,017

Calibration setup and results

The dataset was processed to allow the calibration of the VT-CPEM for including the energy consumption in a traffic control systems strategy for EVs, by adopting as objective function a goodness-of-fit measure contrasting the total observed traction power P_T for each second on each trip with the corresponding model estimate given by the equation on section 3.2.1. That is, by definition, P_T is expressed in [kW].

Four parameters are calibrated: the three efficiency parameters (η_{BAT}, η_{DL}, η_{EM}) and the parameter α entering in the regenerative braking energy efficiency (η_{RB}).

The objective function to minimize for the estimation of parameters is the sum of root mean square errors between observed and modelled traction power P_T in each second of the trip and for each trip.

$$\mathrm{F}(\boldsymbol{\beta}) = \sum_{trip=1}^{N_{trips}} \sqrt{\frac{\sum_{i=1}^{T_{trip}} \left[{P_T}_{trip}^{sim}(i, \boldsymbol{\beta}) - {P_T}_{trip}^{obs}(i) \right]^2}{T_{trip}}}$$

Extracted trajectory data refers to the same vehicle. Thus, a single vector of four parameters $\boldsymbol{\beta}$ has been estimated for the full set of trips, yielding the following estimator:

$$\boldsymbol{\beta}^* = \underset{\boldsymbol{\beta} \in S_{\boldsymbol{\beta}}}{\operatorname{argmin}} \mathrm{F}(\boldsymbol{\beta})$$

The optimisation problems (3)-(4) have been solved by means of a genetic algorithm (GA). This method turned out to have greater chance of finding the global solution of the optimisation problem than gradient-based approaches in case of highly non-linear models. The GA was setup with an initial population of 1000 and a number of generations equal to 100, to increase the coverage of the domain of the parameters and a higher chance to detect the global optimum (Holland and Goldberg, 1989; Storn, 1996). Estimation times corresponding to this GA setup were however satisfactory.

In terms of optimisation domain, upper/lower bounds for the parameters to estimate were set as illustrated in Table 2. Specifically, upper and lower bounds for the three efficiency parameters (η_{BAT}, η_{DL}, η_{EM}) have been identified according to the relevant literature (Hayes et al., 2011; Helms et al., 2010; Tie and Tan, 2013; Waide and Brunner, 2011), whilst the parameter α in the equation on section 3.2.1 for regenerative braking energy efficiency (η_{RB}) was constrained in the [0.005-1] range as illustrated in Table 2, with the final values of the calibrated parameters in Table 3.

Table 2: Upper and lower bounds of parameters to estimate

	η_{EM}	α	η_{BATT}	η_{DL}
Lower bound	0.90	0.005	0.90	0.90
Upper bound	0.98	1	0.98	0.98

Table 3 reports the results of the parameter calibration of the VT-CPEM.

Table 3: Calibrated parameters: values identified

η_{EM}	α	η_{BATT}	η_{DL}
0.979	0.079	0.955	0.969

Moreover, the percentage error (PE) between the total simulated and observed energy consumption and recovery is reported in Table 4.

$$PE\ [\%] = \frac{1}{n_{trip}} \sum_{i=1}^{n_{trip}} \frac{|E_{Obs}^{i} - E_{Mod}^{i}|}{E_{Obs}^{i}} * 100$$

Table 4: Impact on the energy consumption and recovery

		Observed	Simulated	PE [%]
Energy consumption [kWh/km]	Mean	0.096	0.094	**1.82%**
	Std. Dev.	0.020	0.016	
Energy recovered [kWh/km]	Mean	-0.053	-0.052	**1.08%**
	Std. Dev.	0.017	0.019	

Results show that the PE is lower than 2%.

3.2.4 Estimation of the link-based energy consumption function

Running the model in a quasi-Monte Carlo framework, a macroscopic energy consumption function for each link is estimated. In particular, the relationship between average speed over a road segment and average energy consumption is calculated based on microscopic energy consumption simulated through the VP-CPEM.

Extracted trajectories in Section 5 have been randomly split into 50 m-long elemental segments over each link. The random sampling has been performed in a quasi-Monte Carlo fashion by means of the low-discrepancy Sobol sequence of quasi-random numbers (Sobol, 1976). The above procedure allowed us to generate many elemental segments from the entire trajectory database. Each elemental segment has been associated with an average speed and a corresponding distribution of electric vehicle energy consumption, from which the function is estimated.

Simulated data and results of the polynomial fitting are reported in Figure 5 and Table 5, respectively.

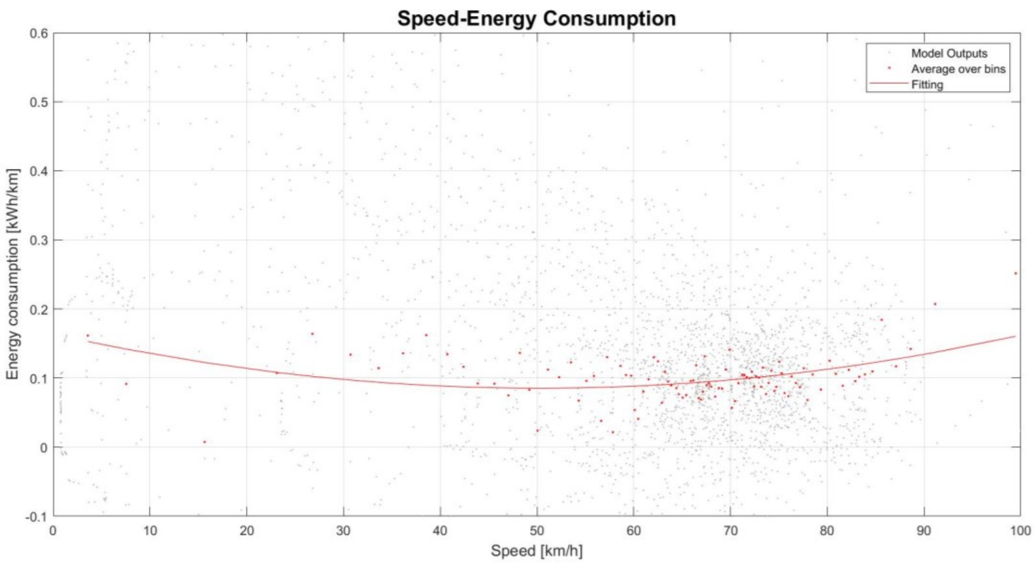

Figure 5: Speed-Energy consumption relation for the powertrain analysed (EV)

Table 5: Fitting of the powertrain analysed

f(x) = p1*x2 + p2*x + p3	Coefficients
EV	p1 = 3.102e-05 p2 = -0.003117 p3 = 0.1636

4. RESULTS OF THE TRAFFIC CONTROL OPTIMISATION PROCEDURES

In this section the results of the numerical applications are shown and discussed. To this aim a sketch of the Salaria road in Rome (Italy) composed by two successive interacting junctions has been considered. The traffic data were derived by applying the queuing theory starting from the vehicles' trajectories collected through probe vehicle. Furthermore, regarding the stage sequence and composition of the current scenario, in the following figures the stage sequences of the considered case study, composed by two successive interacting junctions, is displayed.

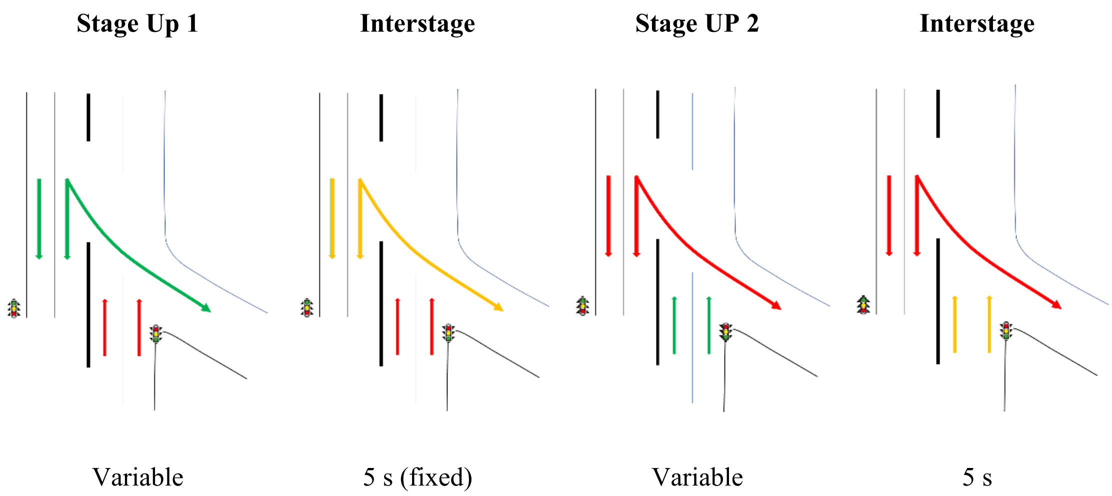

Figure 6: Upstream junction stage sequence and composition

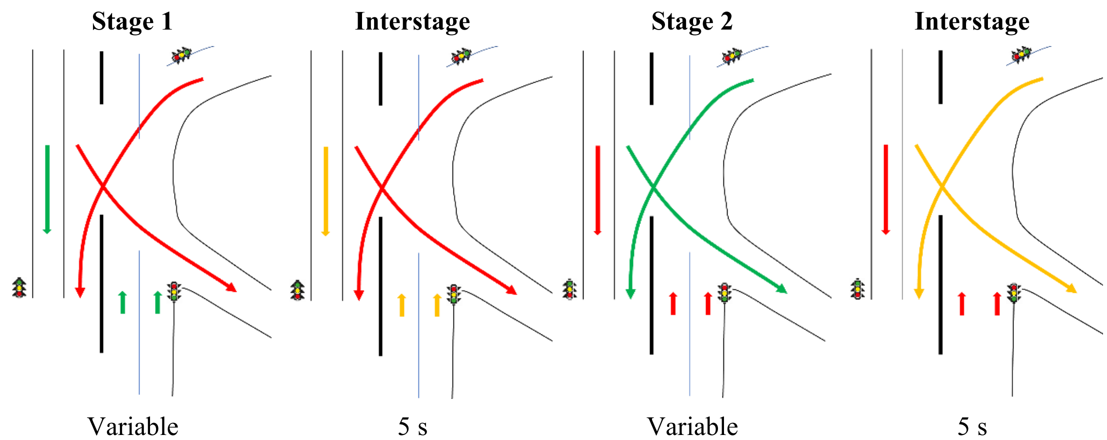

Figure 7 – Downstream junction stage sequence and composition

As previously discussed, the considered indicators were the total travel time spent and the energy consumption and the results were referred to three main applications (see Table 6): two mono-criterion based problems (i.e. the optimisation of each objective function: the total travel time spent -$MONO_{TTS}$- and the total energy consumption – $MONO_{EC}$) and one multi-criteria optimisation based on the combination of both criteria at the same time (MULTI). Results are summarised in the table below also including the decision variables durations (stages and the offset). The first consideration to be made is that, as expected, in case of the multi-objective optimisation the results of both criteria are worsen than the case of single criterion optimisation. In particular the Total travel time spent is higher than the value achieved in mono-criterion optimisation of the (around) 0.02% and the energy consumption is higher than the value achieved in mono-criterion optimisation of the (around) 0.6%. Furthermore, in terms of decision variables optimisation it can be highlighted that in the multi-objective optimisation the results achieved in the case of energy consumption must be stored for the upstream junction whereas the downstream results are intermediate with respect to the case of single criterion optimisation. In general, results of the whole multi-objective procedure, may be considered encouraging.

Table 6: Results of the mono-criterion and multi-criteria optimisation

	TTS [s]	**EC [kWh/km]**	**$Stage^{UP}_1$ [s]**	**$Stage^{UP}_2$ [s]**	**Offset [s]**	**$Stage^{DOWN}_1$ [s]**	**$Stage^{DOWN}_2$ [s]**
$MONO_{TTS}$	198032	40623.94	44	36	19	36	44
$MONO_{EC}$	201740	40050.22	41	39	6	48	32
MULTI	198064	40290.82	41	39	16	39	41

**the application has been done considering the 100% of electric vehicles penetration rate*

5. CONCLUSIONS AND RESEARCH PROSPECTS

This work has illustrated a methodological framework to support the design of control strategy at signalised junctions in presence of Electric Vehicles. In particular, a link-based macroscopic energy consumption function has been estimated based on a microscopic energy consumption model. The model has been calibrated against real-world vehicle trajectory and power data collected nearby two signalised junctions. To this aim a dedicated tool (TET-TCSA) has been developed to extract, from a large dataset, the individual trajectory data which cross the network area. The tool has been integrated with a microscopic energy consumption model, the VT-CPEM, and extracted data were applied to calibrated VP-CPEM model parameters. Results of calibration show an error, in terms of percentage error between simulated and observed energy consumption and recovered, lower than the 2%. The calibrated model has been run in a quasi-Monte Carlo framework to simulate microscopic energy consumption of individual vehicles, which allowed for the estimation of a link-based a macroscopic energy consumption.

Starting from the macroscopic energy consumption function a multi-objective traffic control problem has been solved; in particular two objective functions have been considered: the total travel time spent and the energy consumption function. Regarding the optimisation problem definition, a Cell Transmission Model as prediction model was used.

Finally, the whole analysis has been carried out by considering real data collected on the Salaria road in the city of Rome (Italy) and in particular the traffic data have been derived through the application of the queuing theory at signalised junctions.

The numerical applications have been carried out considering the 100% of electric vehicles penetration rate. In general results encourage the multi-objective optimisation even if the considered context of congestion based on undersaturation conditions slightly highlights the effectiveness of the proposed approach.

In terms of traffic control, in future work the authors would like to investigate the integration of the proposed multi-objective optimisation framework with others optimisation criteria usually adopted in the presence of connected ant automated vehicles such as the speed. Furthermore, it will be also worth of interest

- the application of the proposed approach to other contexts for instance to the case of urban networks;
- to consider different penetration rates of electric vehicles by combining the impact of EVs with the presence of conventional internal combustion engine vehicles.

With reference to the energy consumption the development of a link-based energy consumption function will be further investigated.

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4.3

Centralised Traffic Control and Green Light Optimal Speed Advisory Procedure in Mixed Traffic Flow

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 analysed 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. Th 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 are discussed in Section 3; the traffic control problem and the Green Light Optimal Speed Advisory (GLOSA) procedure are respectively displayed in Section 4 and 5; in Section 6 is presented the numerical application whilst results and future perspectives are discussed in Section 7.

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).

TABLE 1. V2V & V2I APPLICATIONS.

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	

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

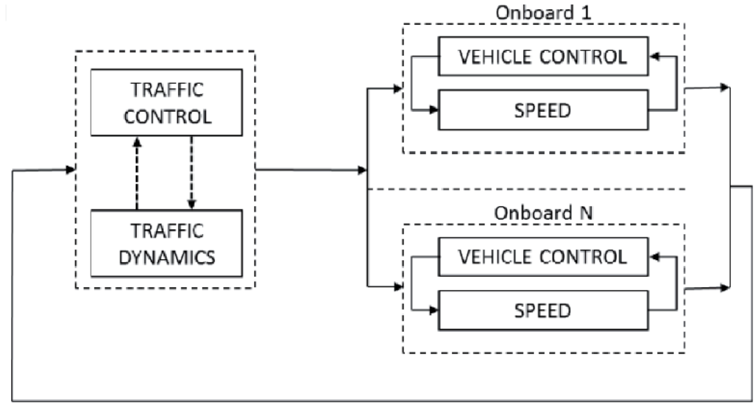

Figure 1: Overview of the proposed control framework.

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 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.

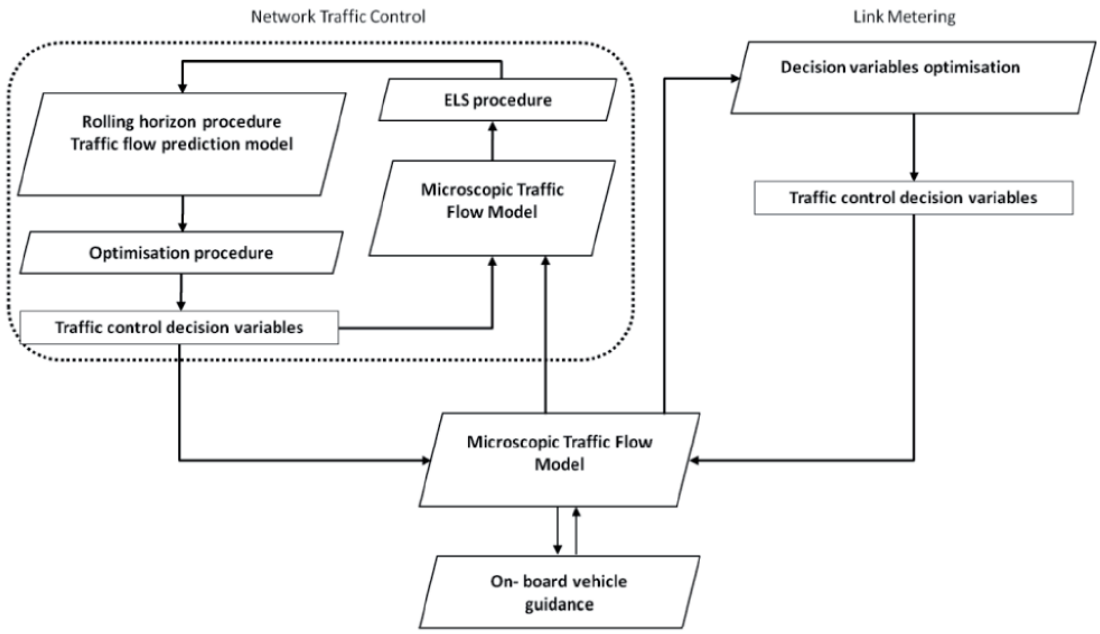

Figure 2: Further description of the framework overview.

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. 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 $\ddot{a}_{kj} = 1$ 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
t_r	the turning rates

$\beta_{i,r}$ the split ratio of the traffic demand in the i[th] link and r[th] movement
$\xi_{i,r}$ the number of lanes assigned to the r movements in the i[th] link
m_i^{in} the total inflow
$m_{i,r}^{out}$ the discharging capacity expressed as vehicles/hour/lane
$s_{i,r}$ 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:

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

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, which 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 flows,
o_s be the observed downstream occupancy,
$\mathrm{K_P}$ be the proportional gain
$\mathrm{K_I}$ 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:

$$q_s(k) = q_s(k-1) - \mathrm{K_P}[o_s(k) - o_s(k-1)] + \mathrm{K_I}[\hat{o} - o_s(k)] \quad (2)$$

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 junction.

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;
    - If yes, the algorithm does nothing
    - 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, the traffic information is 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 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.

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

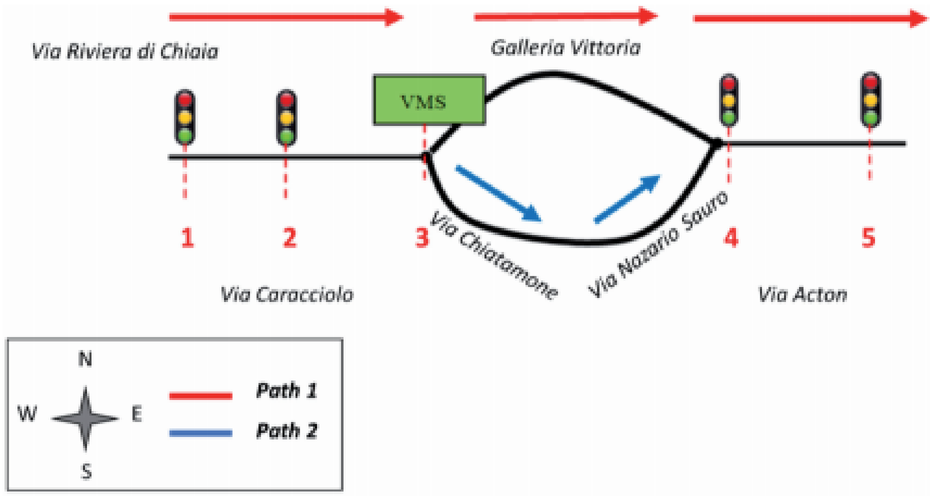

Figure 3: Topology of the tested network.

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).

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 ten 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.

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

Path 1 [min]	**Path 2 [min]**	**RSME**
44	35	3.14

Table 3: Calibration results (QL) 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	83.70	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.

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 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 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).

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

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 5: Mean QLS rel. Diff. Of [a - SC] scenario wrt [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

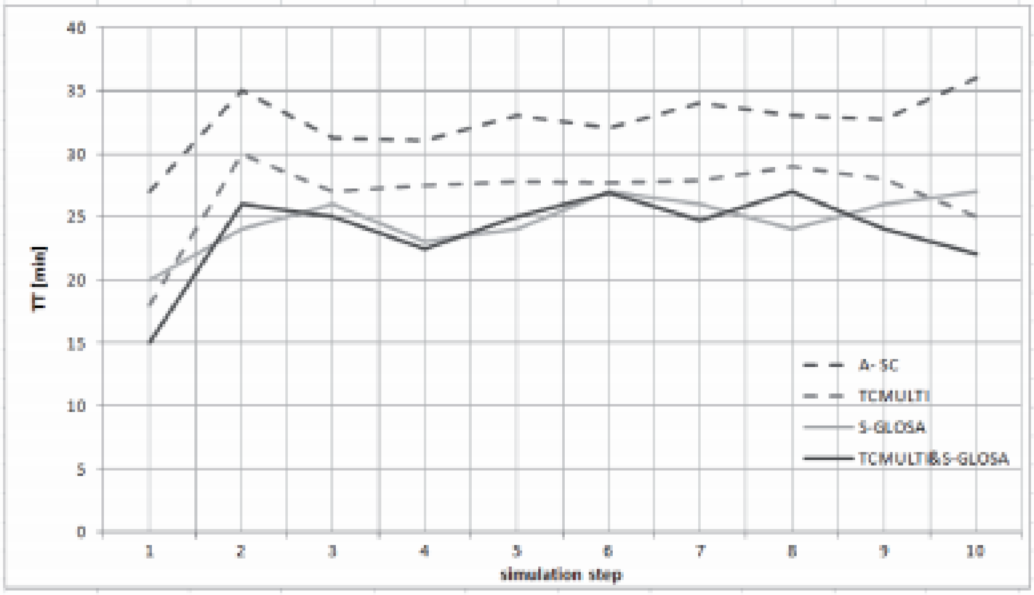

Figure 4: Results for each scenario: Mean TTs [min] against simulation step for each scenario.

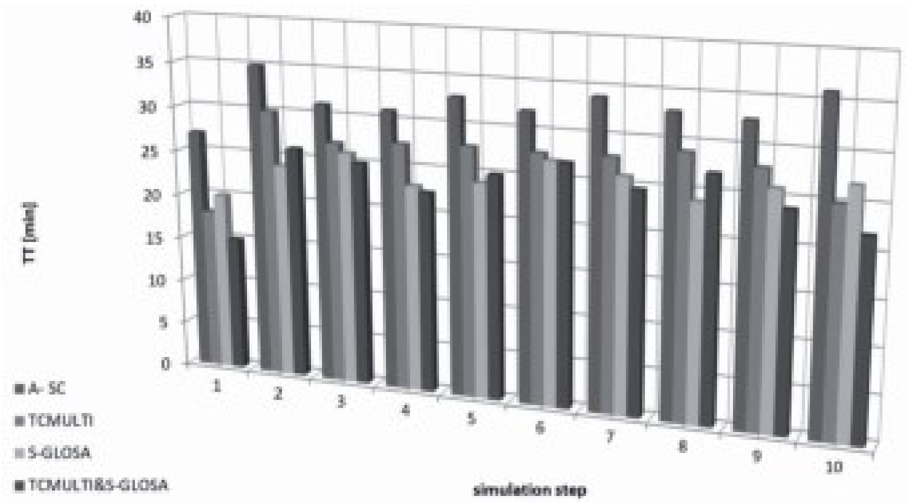

Figure 5: Results for each scenario: Rel diff [%] of the mean TT wrt the A-SC scenario, against simulation step for each scenario.

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 TCMULTI and S-GLOSA therefore it is verified that S-GLOSA provides worse performances than the TCMULTI method; finally, the combination between TCMULTI 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 research 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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5

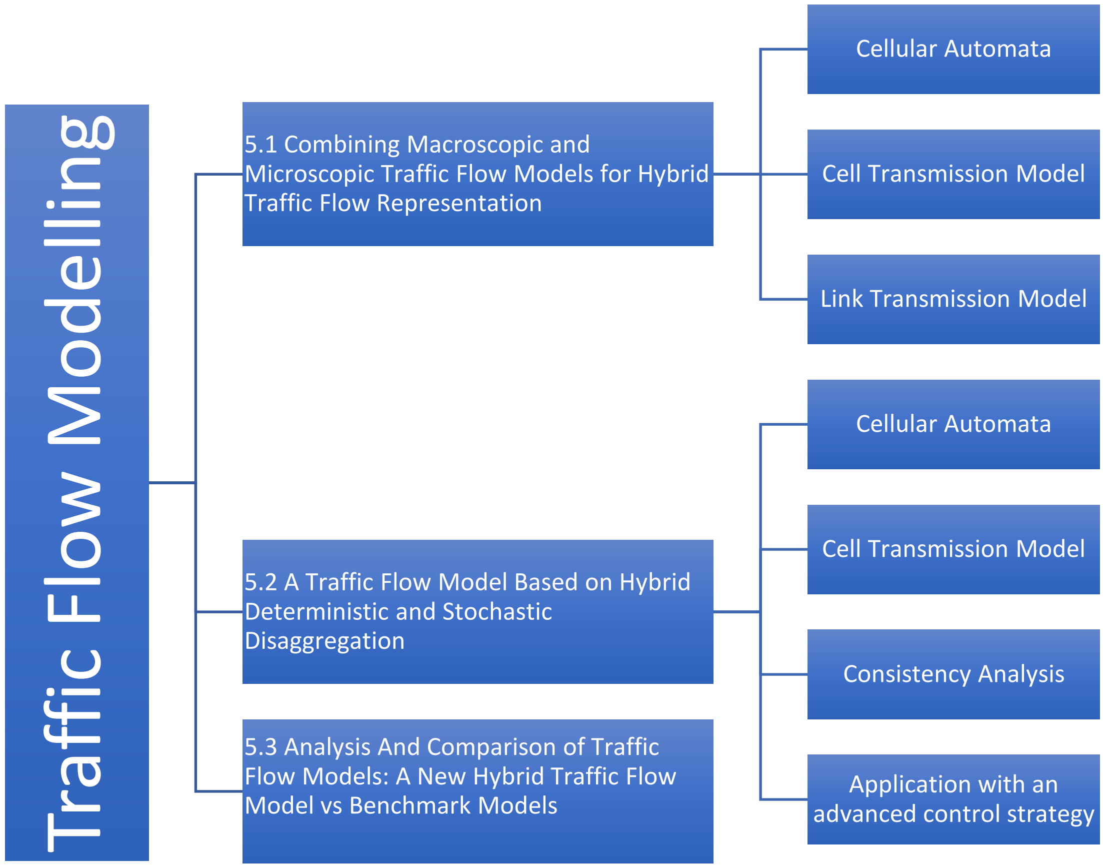
TRAFFIC FLOW MODELLING

Outline

The current chapter deals with the traffic flow modelling. It is composed by three sub-chapters, in which:

a) **Chapter 5.1** proposes a hybrid traffic flow model combining two submodels: a deterministic macroscopic Cell Transmission Model (CTM) with a stochastic microscopic Cellular Automata (CA) model, both connected with a Link Transmission Model (LTM). This chapter analyses the local consistency between sub models.
The hybrid model was tested in a close loop to check its continuity and on an arc with a traffic light downstream to analyse the creation and discharge of queues while obtaining some traffic indicators in order to compare them with the application of the basic CTM and CA
b) **Chapter 5.2** develops a similar hybrid traffic flow model, combining the same sub models (CA&CTM), with an alternative approach for the transition zones. This chapter analyses the consistency between sub models and was tested using several numerical applications. The case studies differ with respect to:
    i) the layout of the network, being a ring-shaped link, an arterial with three intersections, and a nine-node grid
    ii) the traffic flow model considered,
    iii) application of a traffic control strategy (with/without),
    iv) a capacity reduction according to the traffic flow model (a reduction in the outflow capacity for the CTM, or the dawdling probability p for the CA),
    v) the value of the entry flows (constant or variable over time) and the degree of saturation (undersaturated or oversaturated).
c) Chapter 5.3 compares the previous hybrid traffic flow model (CA&CTM), with respect to several established macroscopic and microscopic models used as benchmarks. In particular, the comparison was made with the macroscopics CTM and CTM with dispersion, while microscopically with the Krauss model, considered the stochastic enhancement of the Gipps model, reference model in the context of the collision avoidance class of approaches, and with the Intelligent Driver Model, based on the idea of combining the ability to reach the desired speed limit in a traffic-free situation with the ability to identify how much braking is necessary to steer clear of any collision situations.

An outline of this section can be seen in the following figure.



Facundo Storani

5.1

Combining Macroscopic and Microscopic Traffic Flow Models for Hybrid Traffic Flow Representation

ABSTRACT

Traffic flow modelling offers room for improvement in two main aspects: the first one is about traffic flow phenomena description, while the second one is about data collection to be used as input variables for traffic control. Three main approaches may be pursued to model traffic flow: the macroscopic, the mesoscopic and the microscopic modelling. A further approach has been recently investigated, called hybrid traffic flow modelling, which is also suitable for applications at different scales (multi-scale). This article proposes an innovative hybrid model, which was tested in a close loop to check its continuity, and on an arc with a traffic light downstream to analyse the creation and discharge of queues, while at the same time obtaining some traffic indicators in order to compare them with the application of the basic CTM and CA. Results provide three main contributions: i) the local consistency is verified; ii) it is suitable for the applications in presence of traffic control strategy; iii) it is reliable in terms of reality reproduction.

Keywords: traffic flow model; Cell Transmission Model; Cellular Automata; Link Transmission Model; Hybrid.

I. INTRODUCTION

Traffic flow simulation is generally characterised by different phenomena such as congestion, queue propagation and dissipation, stop&go etc. As a result, during the last decades many theories have been developed to increase the level of realism of traffic flow modelling, not only in terms of phenomena explanation, but also as reproduction and prediction. It is well known that models have been classified depending on the level of aggregation of demand and supply variables; thus, three main groups can be identified: the macroscopic, the mesoscopic and the microscopic models.

Because of the different aggregation levels, they may be properly applied at different space scales; for instance macroscopic models may be suitable for the analysis and design of extended macro areas, whilst microscopic models may be properly applied in order to study less extended areas such as subnetworks or specific junctions. Indeed, macroscopic models are generally less detailed than microscopic models; but the specification of node equations is generally required for dynamic network loading, and that is very limiting in terms of realism of phenomena reproduction when using macroscopic models. On the base of these preliminary considerations, several researchers were inspired in coupling models at different scales. First studies were about the coherence between macroscopic and microscopic models ([1]) and preliminary discussions of coupling traffic flow models were by [2]. Furthermore, some contributions refer to the combinations between mesoscopic and microscopic models ([3]) however the greatest number of studies are about macroscopic and microscopic models ([4], [5], [6] and [7]). Two main issues are still open and discussed in the literature: the analysis of local and global consistencies; in particular the first one aims to ensure the vehicle conservation in the process of switching modelling paradigms, whilst the second one focuses on vehicles attributes conservation from one model to the other (for instance travel information, vehicles heterogeneity, driving styles).

In this paper an alternative hybrid traffic flow model is proposed, and it is also verified in terms of local consistency. The paper proposes a hybrid model aiming to couple the macroscopic Cell Transmission Model (CTM; [8]) with a microscopic Cellular Automata model (CA; [9]). Furthermore, the Link Transmission Model (LTM; [10]) was used to connect the two models at different scales. It must be observed that the macroscopic models are deterministic whereas the considered microscopic model is intrinsically stochastic. Finally, the proposed hybrid model is based on a hybrid deterministic and stochastic disaggregation. In the following an overview of the model is provided and the analysis of the local consistency is heuristically provided.

II. METHODOLOGICAL FRAMEWORK

The hybrid model combines the macroscopic CTM with the microscopic CA for each road, as it can be seen in Fig. 1. The microscopic model is used to simulate junctions, while the CTM is used to simulate the running links. The LTM has been adopted as intermediate model (interface between macroscopic and microscopic model). After the junction, the CA model is used to model the initial behaviour of vehicles, to then use the LTM as the connection with the CTM. In this first transition zone, vehicles are aggregated and converted into a fluid for the CTM. After they travelled the macroscopic model, they are moved into a second transition zone, to disaggregate and add them to the CA in proximity to the next junction.

A. The Cell Transmission Model

Considering **k-** the traffic density, **v** the speed and **q** the flow-rate as functions of time and space; being the flow (or speed) in local equilibrium with the density (that is, a static relation between them q = Q(k)), the continuity equation for an homogeneous road results:

$$\partial k/\partial t + \partial Q(k)/ \partial x = 0 \qquad (1)$$

The Cell Transmission Model, is a discrete version in time and space with continuous state variables. Is based on a simple Lighthill-Whitham-Richards model with a triangular fundamental diagram, as the flow has a linear relationship with the density. Considering a generic road divided into cells of length **Δx**, for each time-step and each cell, the continuity equation (1) is applied following a rule called "supply-demand". In particular, let:

$\mathbf{\Delta t}$ be the time step [s],
$\mathbf{\Delta x^{CTM}}$ be the cell length [m],
$\mathbf{v_f}$ be the free flow speed [m/s],
$\mathbf{w}$ be the shock wave speed in congested traffic [m/s],
$\mathbf{k_{jam}}$ be the jam density [veh/m],
$\mathbf{k_i}$ be the traffic density in cell i [veh/m],
$\mathbf{q^{CTM}_i}$ be the maximum flow rate in cell i [veh/s],

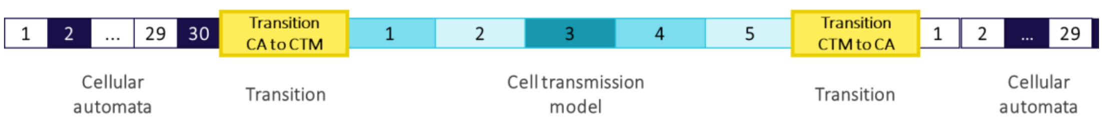


Fig. 1. Example of a link with a hybrid approach

Then, the model follows three steps: first, the demand $D^{CTM}_i(t)$ (2) and supply $S^{CTM}_i(t)$ (3) of each cell i is calculated, to then obtain the flow $Y^{CTM}_i(t)$ from each cell to the following (4), with the successive update of the cell' density $k_i(t+1)$ for the following time step (5) considering that flow.

$$D^{CTM}_i(t) = min(q^{CTM}_{i}, v_f\, k_i) \quad (2)$$
$$S^{CTM}_i(t) = min(q^{CTM}_{i}, w(k_{jam} - k_i)) \quad (3)$$
$$Y^{CTM}_i(t) = min(D^{CTM}_i(t),\ S^{CTM}_{i+1}(t)) \quad (4)$$
$$k_i(t+1) = k_i(t) + [Y^{CTM}_{i-1}(t) - Y^{CTM}_i(t)]\cdot\Delta t/\Delta x^{CTM} \quad (5)$$

The cell length and the time step have to verify the Courant-Friedrich-Lévy condition (6)

$$\Delta t \leq \Delta x^{CTM} / v_f \quad (6)$$

B. The Link Transmission Model

In the hybrid model, this model serves the purpose to connect the microscopic Cellular Automata model with the macroscopic Cell Transmission Model. It consists on a homogeneous road link of length L^{LTM} connecting two nodes. At each time step, the model updates the cumulative number of vehicles at the boundaries of the links by a sending-receiving mechanism similar to the Cell Transmission Model, based on a triangular shaped fundamental diagram. Such procedure can be extended to other linear fundamental diagrams. It is worth noting that the link length and the time step also have to verify the *Courant-Friedrich-Lévy* condition (6) to prevent vehicles skipping the link when travelling at the free flow speed.

Let

$\mathbf{\Delta t}$ be the time step [s],
$\mathbf{L^{LTM}_i}$ be the link length [m],
$\mathbf{v_f}$ be the free flow speed [m/s],
$\mathbf{w}$ be the shock wave speed in congested traffic [m/s],
$\mathbf{k_{jam}}$ be the jam density [veh/m],
$\mathbf{q^{LTM}_i}$ be the maximum flow rate in link i [veh/s],
$\mathbf{N^L_i(t)}$ be the cumulative number of vehicles at the downstream link end, of link i,
$\mathbf{N^0_i(t)}$ be the cumulative number of vehicles at the upstream link end, of link i,

Considering nodes with incoming links i, and outgoing link j, for each $\mathbf{\Delta t}$ and for each node the model follows three steps:

1. Determine the sending flow $S^{LTM}_i(t)$ at the downstream link end (7), and the receiving flow R^{LTM}_j at the upstream link end (8).

$$S^{LTM}_i(t) = \min\left[(N^0_i \cdot (t+\Delta t - L^{LTM}_i/v_f) - N^L_i(t)),\ q^{LTM}_i \cdot \Delta t\right] \quad (7)$$

$$R^{LTM}_j(t) = \min\left[(N^L_j(t+\Delta t + L^{LTM}_j/w) + k_{jam} L^{LTM}_j - N^0_j(t)),\ q^{LTM}_j\ \Delta t\right] \quad (8)$$

[Such flows consider the linear kinematic wave traffic with a free flow speed, v_f, and a shock wave speed, w, in congested traffic.]

2. Determine the transition flows $Y^{LTM}_{ij}(t)$ (9) from incoming links i to outgoing links j at nodes.

$$Y^{LTM}_{ij}(t) = \min\left[S^{LTM}_i(t),\ R^{LTM}_j(t)\right] \quad (9)$$

3. Update the cumulative number of vehicles at the upstream (10) and downstream (11) link ends.

$$N^0_j(t+\Delta t) = N^0_j(t) + \sum_i Y^{LTM}_{ij}(t) \quad (10)$$

$$N^L_i(t+\Delta t) = N^L_i(t) + \sum_j Y^{LTM}_{ij}(t) \quad (11)$$

C. *Cellular Automata*

This model, as the Cell Transmission Model, is also discrete in time and space, but with discrete state variables. In the microscopic Cellular Automata model, the road is divided into cells of a fixed length. These cells are named with an increasing index in the direction of the traffic, with a state can be either empty or occupied by a vehicle (or a part of it). The speed and acceleration of each vehicle are integer multiples of the length of each cell and the time step considered. There are several types of Cellular Automata models. The Nagel-Schreckenberg Model consider each cell with a length equal to the vehicle length (7.5 m). Barlovic Model adds a “slow to start” rule. KKW Model (Kerner, Klenov and Wolf) considers a more refined cell length equal to 0.5 m and includes an effect of synchronized traffic, consistent with the three-phase traffic theory proposed by Kerner, instead of the two-phase of the Cell Transmission Model. KKW Model with safe speed improves the deceleration of the vehicles by adding a safe speed rule obtained from a discretized version of the safe speed of Gipps’ model. Let

Δt be the time step [s],
Δx^{CA} be the cell length [m],
v_0 be the desired speed [cells/s],
p be the dawdling probability,
v_c be the speed of each vehicle c [cells/s],
g_c be the gap of each vehicle c with the following one [cells],
x_c be the position of each vehicle c, (the index of the cell where c is located),

At each time step, the basic Nagel-Schreckenberg Model follows four sequential rules for each vehicle c:

1. **Braking**: obtain the gap $\mathbf{g_c}$ at time **t**. If the speed of the vehicle is greater than the gap, then it slows down.
2. **Acceleration**: if the speed is lower than the desired speed, then accelerate by 1 cell/s. These two rules can be expressed as:

$$v_c{}^*(t+1) = \min(v_c\,(t)+1,\, v_0,\, g_c(t)) \qquad (12)$$

3. **Randomization**: the vehicle reduces its speed by 1 cell/s with a probability p. If this rule is applied, the vehicle reduces its speed only if it was already driving at the desired speed or near the following vehicle, since it would maintain the speed vc (t) as it leaves with no effect the second rule.

$$\begin{aligned} v_c(t+1) &= \max(v_c{}^*(t+1) - 1{,}0) \text{ with probability } \boldsymbol{p} \\ v_c(t+1) &= v_c{}^*(t+1) \qquad \text{otherwise} \quad . \end{aligned} \qquad (13)$$

   Such probability p can depend on the speed of the vehicle. The Barlovic Model adds a p0 greater than p if the vehicle is standing, therefore, increasing the “inertia” for the vehicle to start its motion.
4. **Car motion**: the position of the vehicle is updated for the following time-step, considering its new speed vc(t+1).

$$x_c(t+1) = x_c(t) + v_c(t+1) \qquad (14)$$

D. *The whole model*

As stated in section II, the hybrid model combines the macroscopic CTM with the microscopic CA for each road- To this end, it requires two transition zones in order to join both models.

The transition from CA to CTM uses the Link Transmission Model to receive vehicles from the Cellular Automata in the upstream node, and send them to the Cell Transmission Model in the downstream node, as can be seen in Fig. 2. In the upstream node, the sending flow from the CA is calculated as the number of vehicles that are placed in the last meters of the model, in a length consistent with the Courant-Friedrich-Lévy condition (6)First, the receiving flow of the LTM is obtained, and then the transition flow from CA to LTM is calculated; provided that the receiving flow is greater than one vehicle per time step, that is, the link in the LTM is not jammed and has a sufficient space to allocate the incoming vehicle. Then the LTM equation is applied and the vehicles in the last portion

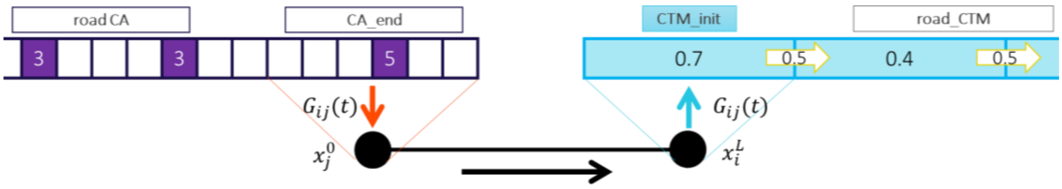


Fig. 2. Transition from CA to CTM with a Link Transmission Model.

of the CA are cancelled, if they were able to successfully move towards the LTM. In the downstream node, the sending flow from the LTM is calculated, and the supply flow from CTM is finally computed, to then calculate the minimum of both. After this, the cumulative number of vehicles at the downstream link end of the LTM is calculated for the following time step, and the cell' density $k_i(t+1)$ of the first CTM cell. In Fig. 2, the speeds of the vehicles in the CA is indicated with an integer number, as it is expressed as cells/s. In the case of the CTM, each cell indicates the number of vehicles obtained from multiplying its density with the cell length, while the arrows indicate the flows from each cell to the following.

The second transition, from CTM to CA, uses a transition cell with the characteristics of the macroscopic CTM to accumulate vehicles, until there is a density such that if an entire vehicle is located within the cell, then it is transferred towards the initial section of the following CA model, provided that there is space to fully insert a vehicle. A scheme of such a transition cell can be seen in Fig. 3. From the CTM to the transition cell, the demand flow of the last CTM cell is calculated, as well as the supply of the transition cell. In the last case, it is necessary to consider the number of vehicles that are located in the transition zone, that is, in the transition cell and in the initial part of the CA with a length equal to the CTM cell. Then, the flow is obtained, and the densities of both cells are properly updated. Then, once that the transition cell accumulates an entire vehicle inside, it is transferred towards the initial section of the CA, with a speed obtained by dividing the macroscopic flow by the vehicle density from the CTM. Once that this vehicle is inserted into the CA model, it is eliminated from the transition cell.

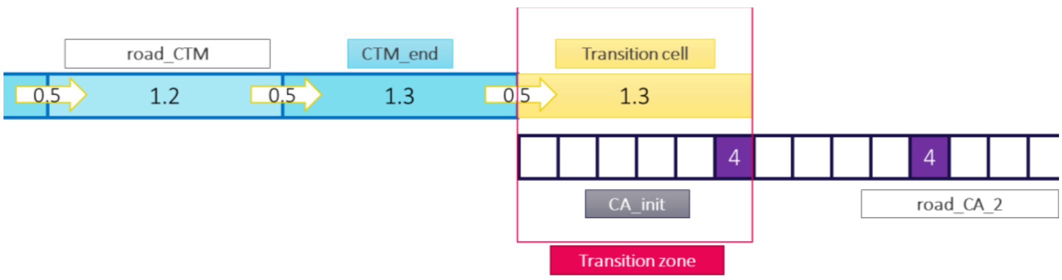


Fig. 3. Transition from CTM to CA with a cumulative transition cell.

In the example shown in Fig. 3, the total number of vehicles in the transition zone is equal to 2.3, obtained by adding 1 vehicle in the CA model (which has a speed of 4 cells/s) with 1.3 vehicles in the macroscopic transition cell.

III. APPLICATIONS: CASE STUDIES AND NUMERICAL RESULTS

The hybrid model was tested in a close loop to check its continuity, as can be seen in Fig. 4, and on an arc with a traffic light downstream to analyse the creation and discharge of queues while obtaining some traffic indicators in order to compare them with the application of the basic CTM and CA (Fig. 5). The parameters were chosen considering an urban context, as can be seen in Table 1.

TABLE I: PARAMETER VALUES

Parameter	CTM	LTM	CA
Δt time step		1 s	
v_f free flow speed	15 m/s		6 cells/s
w shock wave speed	10 m/s		-
k_{jam} jam density		200 veh/km	
Cell/link length	15.0 m	30.0 m	2.5 m
q_i maximum flow rate	1800 veh/h	1800 veh/h	-
p dawdling probability	-	-	0.20

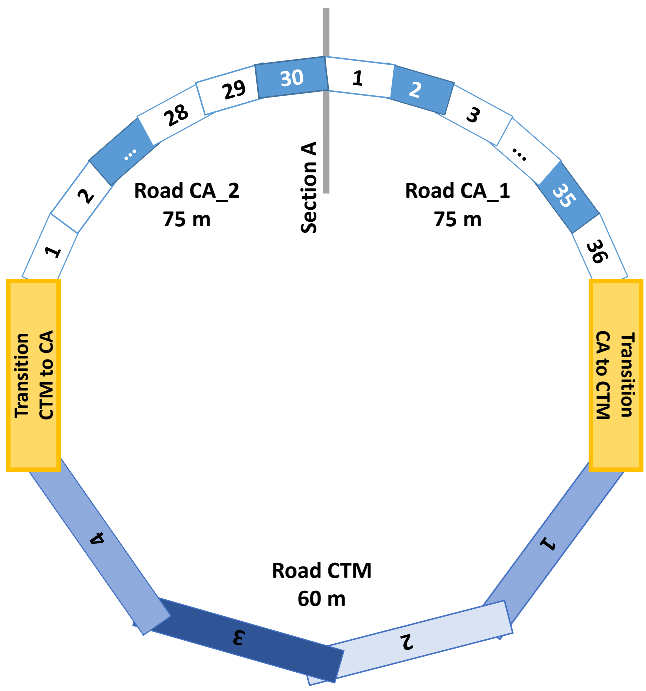


Fig. 4. Hybrid model applied to a close loop layout.

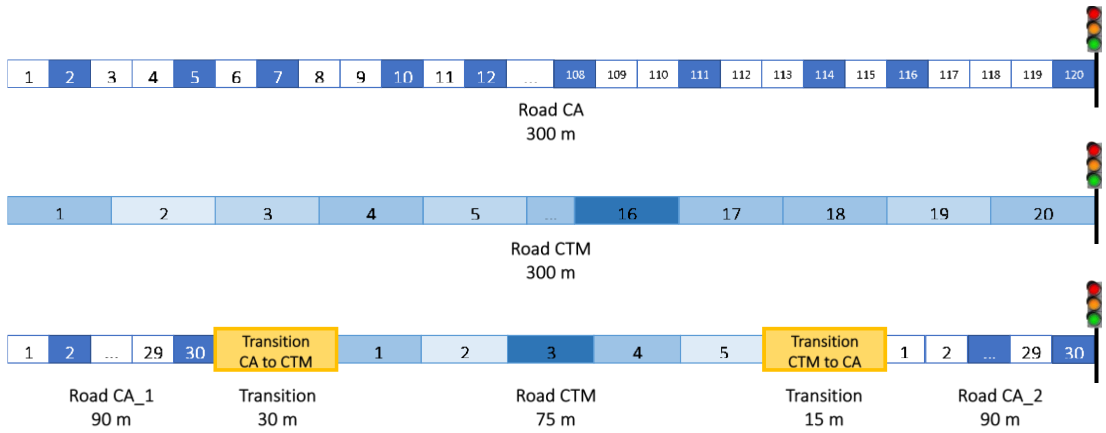


Fig. 5. Layout of an arc with a traffic light downstream, considering only a Celular Automata model, the Cell Transmission Model, and the proposed Hybrid model.

The arc considered was 300 meters long, with the first 90 meters modelled by the CA, then 30 meters of the first transition zone using the LTM to connect the microscopic and the macroscopic model. After this, 75 meters modelled by the CTM, connecting to the second transition zone with a length equal to the CTM cell, and finally 90 meters modelled by the CA.

Four scenarios were tested, where the downstream traffic light was initially red during different intervals, and then it became green in order to dissipate the queue and let decongest the arc. All these scenarios considered the same traffic condition of 900 veh/h with a Poisson law. The minimum and maximum total travel time for the first 200 vehicles considering the initial red light was obtained, and the mean travel time, mean total delay and the standard deviation for 100 vehicles after the green light was on and the queue was fully dissipated (Table 2). The difference between mean travel times can be seen in Fig. 6.

TABLE II: TRAVEL TIME (SECONDS)

Duration of initial red light (seconds)	**Model**	**Travel time considering the initial red light (seconds)**		**Travel time after queue dissipation (seconds)**
		MIN	**MAX**	**MEAN**
50	CA	20,00	46,00	21,96
	CTM	20,00	46,00	20,48
	Hybrid	20,00	45,00	21,79
100	CA	20,00	99,00	22,77
	CTM	20,00	96,00	20,48
	Hybrid	20,00	94,00	21,84
120	CA	20,00	117,00	22,13
	CTM	20,00	116,00	20,48
	Hybrid	20,00	116,00	21,60
145	CA	20,00	141,00	22,12
	CTM	20,00	141,00	20,48
	Hybrid	20,00	142,00	21,77

TABLE III: TOTAL DELAY (SECONDS)

Duration of initial red light (seconds)	Model	Total delay after queue dissipation (seconds)	
		MEAN	ST. DEV.
50	CA	1,96	1,76
	CTM	0,48	0,85
	Hybrid	1,79	1,34
100	CA	2,77	2,79
	CTM	0,48	0,85
	Hybrid	1,84	1,49
120	CA	2,13	1,86
	CTM	0,48	0,85
	Hybrid	1,60	1,17
145	CA	2,12	1,90
	CTM	0,48	0,85
	Hybrid	1,77	1,28

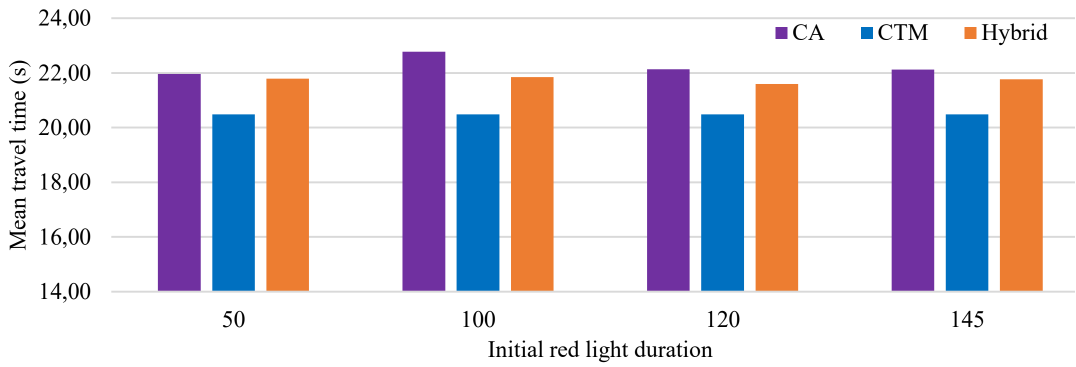


Fig. 6. Mean Travel time after queue dissipation (seconds)

It is possible to observe the deterministic results obtained when the CTM was applied, giving a mean total delay of 0,48 seconds in each scenario, while stochastic results are obtained by the CA model provided by the dawdling parameter p.

IV. CONCLUSIONS

First of all, results highlight that the considered models are able to interact with each other with continuity and are suitable for realistic simulation of traffic flow phenomena. In particular, at the same level of accuracy of phenomena reproduction, there is a strong level of simplification of the model (with a lower number of parameters). Furthermore, the proposed model may be related to two main fields of applications: the first one is about the surrogate measures to be used in terms of objective function starting from the vehicles trajectories; the second one is related to the traffic management and control in presence of connected and autonomous vehicles. Future work will focus about the second topic and different specifications for the CTM and the CA will be considered. It must be highlighted that the study of the mixed traffic flow will require also to verify the global consistency of the model. Finally, it is also worthy of interest the application of the model at larger scale and to the case of signalised urban networks.

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5.2

A Traffic Flow Model Based on Hybrid Deterministic and Stochastic Disaggregation

ABSTRACT

Despite the numerous advances in recent years, traffic flow modelling still offers room for improvement in two main respects: the first concerns the level of realism in analysing and describing traffic flow phenomena, while the second concerns the need to adopt a proper traffic flow model in order to obtain information to be used as input variables for implementing optimisation strategies (prescriptive method). The literature identifies three main approaches to solve the second issue: macroscopic, mesoscopic and microscopic modelling. A further approach has been recently investigated, called hybrid traffic flow modelling, which is also suitable for applications at different scales (multi-scale). This paper proposes a hybrid traffic flow model based on the combination of two sub-models: a macroscopic model (the cell transmission model) and a microscopic model (the cellular automata model). This hybrid model is developed using a transition cell to connect the sub-models in question, and local consistency is discussed and verified. During verification and testing three main layouts are considered: the first is a ring-shaped arc, used to verify the consistency of the model at the local level and with respect to the transition region; the second and third are introduced in order to analyse, respectively, the impact of a different degree of complexity in terms of traffic control strategy and network layout: the second is a signalised arterial, which is analysed considering two optimisation strategies for traffic light decision variables (a fixed plan and using a model predictive control), while the third is a nine-node grid network in which a fixed time control is implemented. All analyses are made in terms of travel times spent, network total delay, queue lengths and degree of saturation. Results provide three main contributions: i) the local consistency is verified; ii) it is suitable also for the applications in presence of enhanced traffic control strategy; iii) in terms of reality reproduction the proposed model outperforms the macroscopic Cell Transmission Model.

Keywords: traffic flow model; Cell Transmission Model; Cellular Automata; hybrid; traffic control; Model Predictive Control.

1. BACKGROUND AND MOTIVATION

In recent decades, many theories have been developed to enhance the level of realism of traffic flow modelling, with a view to explaining traffic phenomena with greater precision, as well as improving its reproduction and prediction capabilities. Traffic flow models have historically been classified according to their level of aggregation of the variables of demand and supply. Thus, three main groups have been identified: macroscopic, mesoscopic and microscopic models (Treiber and Kesting, 2013).

Hybrid traffic flow models, obtained by combining two models, have also been extensively studied. Such models have been generally explored in order to provide traffic analysis at both local and network levels. The main combinations involved are mesoscopic with microscopic models (Burghout, 2004; Burghout et al., 2005; Yang and Slavin, 2002; Yang and Morgan, 2006), and macroscopic with microscopic models (Bourrel , 2003; Bourrel and Henn, 2002).

The matching of the sub models allows two fields of investigation. The first concerns application of the hybrid model at different scales; for instance, macroscopic models can be suitable for the analysis and design of extended macro areas, whilst microscopic models can be applied to study less extensive areas such as sub-networks or specific junctions; this is the multi-scale application context. The second field of investigation entails representation of links and nodes with different levels of detail. For instance, microscopic models can be adopted for links whilst macroscopic models may be adopted to represent nodes. The latter approach is constrained by the different properties of the two models: in the case of dynamic network loading applications, macroscopic models are suitable and simpler for nodes equations specification (Jin and Zhang, 2003; Lebacque and Koshyaran, 2005), whereas microscopic models are needed to model drivers' behaviour along links.

The main focus of this paper lies in hybrid traffic flow modelling between links and nodes, and not in a multiscale application. However, differently from the literature (see for further details section 2), the paper focuses on microscopic node representation and macroscopic link simulation. Indeed, even though microscopic node representation is more complicated than its macroscopic counterpart, it is also intrinsically formalised in microscopic traffic flow modelling and is able to provide specific information about vehicle arrivals in terms, for instance, of speed and trajectories. On the other hand, if information about drivers' behaviour along links is not required but it is sufficient to reproduce properly the main traffic phenomena (such as queue formation, propagation and dissipation and dispersion of vehicles' speed), a macroscopic approach can be adopted. Finally, the proposed model is based on combining a microscopic model for node representation and a macroscopic model for link representation: to be precise, the Cellular Automata model (CA; Nagel and Schreckenberg, 1992) was adopted as a disaggregate microscopic model, and the Cell Transmission model (CTM; Daganzo, 1994) was adopted as an aggregate macroscopic model. It should be pointed out that the macroscopic model adopted represents deterministic behaviour, while the microscopic model considered is intrinsically stochastic. The proposed hybrid model (H – CTMCA; Hybrid Cell Transmission Model Cellular Automata) is thus based on hybrid deterministic and stochastic disaggregation.

The proposed model is appropriate for application with traffic containing connected vehicles approaching signalised junctions since extensive information is required as input data for the optimisation procedure.

Whatever the representation, microscopic on the link and macroscopic at nodes or vice versa, there is a major problem of consistency between the two paradigms consecutively applied. In general, such consistency may be evaluated in two ways: local or global (Joueiai et al., 2014; 2015). Local consistency, which may be formalised in terms of flows and speed variables, aims to describe the conservation of the vehicles through a local interface. Global consistency concerns the conservation of information of vehicles and, since the switching of the modelling paradigm occurs, certain information has to be retained, such as route choice/travel information and driving styles (aggressive or defensive), as well as vehicle class/heterogeneity.

In section 3 is provided an overview of the model in which the analysis of local consistency is heuristically provided.

On the basis of the literature review analysis, the paper proposes a hybrid traffic flow model. The main contribution is fivefold:

- The hybrid model is based on a macroscopic cell transmission model for link representation, and a simplified microscopic cellular automata model for node representation; the combination has not yet been investigated elsewhere, to our knowledge; the usually adopted microscopic model focuses on a sophisticated and computationally complex traffic flow representation;

- With respect to the literature, an alternative approach for transition zone representation is proposed;
- Even though the proposed model is detailed in the case of macroscopic link and microscopic node representation, it may be applied in both cases of microscopic link and macroscopic node representation and vice versa.
- The proposed model is suitable for analysing traffic flow phenomena (descriptive approach);
- The model can also be adopted for traffic control based on optimisation (prescriptive approach) method, especially in the context of multi-objective optimisation (for instance based on surrogate indicators) or in the case of the presence of connected vehicles.

The rest of the paper is organized as follows: in section 2 a literature review about traffic flow modelling is discussed; in section 3 the details of the proposed models are displayed; in section 4 the numerical results with reference to three applications are shown and discussed finally, in section 4 conclusions and future perspectives are discussed.

2. LITERATURE REVIEW

Traffic flow models may be classified into macroscopic, mesoscopic and microscopic models. Macroscopic models may be further classified according to representation in space, continuous or discrete, as well as time. The basic macroscopic continuous traffic flow model is the first order model developed by Lighthill and Whitham (1955) and Richards (1956) (the Lighthill-Whitham Richards – LWR - model), based on the assumption of vehicle conservation between two successive sections in the case of no entrances (sources) or exits (sinks).

Payne (1971), Ross (1988) and Kerner and Konhäuser (1994) proposed second order macroscopic continuous traffic flow modelling to overcome limitations arising in the model: first, as the model does not contain any inertial effects, vehicles adjust their speeds instantaneously; secondly it does not contain any diffusive terms, which would model the ability of drivers to look ahead and adjust to changes in traffic conditions.

The LWR model, which involves a system of partial differential equations, has been solved through discrete representation based on a Godunov family finite difference approximation method for partial differential equations, namely a space discrete - time discrete Cell Transmission model (CTM; Daganzo, 1994). In the CTM each link is partitioned into small sections (cells) and the number of vehicles within each cell is observed as time passes.

Newell (1993) introduced a space discrete model based on a simplified theory of kinematic waves. This theory uses cumulative inflow/outflow curves, and the state of flow at an extreme, according to the traffic conditions of another one, can be predicted without considering traffic conditions on intermediate sections. Consistent with simplified first order kinematic wave theory after Newell, Yperman et al. (2007) present the Link Transmission Model (LTM) in which link volumes and link travel times are obtained from cumulative vehicle numbers.

Mesoscopic models are classified in the literature into headway distribution, cluster and gas kinetic models. The first group is based on the distribution of the headways of individual vehicles (Buckley, 1968; Branston, 1976) whereas cluster models are based on the homogeneous representation of the cluster according to the speed and size of the cluster itself, as proposed by Botma (1978). The third group, namely gas-kinetic traffic flow models, were first proposed by Prigogine (1961) and are based on the analogy between gas flows and traffic flows. Such models provide a representation of dynamic speed distribution (Prigogine and Herman, 1971; Paveri Fontana, 1975; Hoogendoorn and Bovy, 1998).

By contrast, in microscopic models the main attention is on car-following theory which is able to model the interaction between the leading and the following vehicle. Each vehicle reacts to the stimulus of the leading vehicle in terms of driving behaviour by accelerating or decelerating. The basic representation of the dynamic representing the interaction in the car-following models is the stimulus–response approach in which the stimulus may be represented through vehicle speed, acceleration, relative speed and the spacing between vehicles. The General Motors model is the best known stimulus–response model, which was first put forward by Chandler et al. (1958). In this model, the stimulus is specified through the relative speed of vehicles. Each vehicle then tends to move in accordance with the speed of the leading vehicle. Further developments may be found in Gazis et al. (1961) to overcome the main limitation of not explaining the traffic situation in higher density. The collision avoidance model (Gipps, 1981) focuses on a safe distance rather than describing a stimulus-response type function; in accordance with this model, a collision would be unavoidable if the distance is shorter than the safe distance.

However, one of the model's limitations is that the driver might take the behaviour of several preceding vehicles into account and predict to what extent the preceding vehicle might then react by decelerating. Another approach is the physiology-psychology model, also called the Action Point, first introduced by Michaels (1963). The main idea is that driver reacts if he perceives that is now approaching to the vehicle then thresholds must be defined before driver reacts. Further enhancements were proposed by Wiedemann (1974), aiming to define the different regimes in car following based on the driver's relative distance and velocity vis-à-vis the front vehicle. Therefore, the model considers that driving behaviour with larger headways is not influenced or, alternatively, driving behaviour with small headways is influenced only if changes in relative speed and headways are large enough to be perceived. It is assumed that the driver behaves differently in each regime, and thus acceleration is calculated differently. The considered regimes are free driving, closing in, and emergency regimes, corresponding to a set of thresholds. Some of these thresholds use a speed parameter, or the speed difference between the subject vehicle and the lead vehicle. In the class of microscopic models the cellular automata model may also be considered, first introduced by Nagel and Schreckenberg (1992) for traffic flow simulation. This model is based on a space discretisation corresponding to road representation by cells. The model consists of a one-dimensional array of cells with some boundary conditions; each cell may be occupied or empty depending on whether or not there is a car, and may be occupied by no more than one car. Speed is represented by an integer variable in the range between zero and an upper bound corresponding to the maximum speed (equal to 5 in the original research); the number of cells that a vehicle may progress depends on speed (with speed equal to 3 the vehicle may move forward 3 cells).

Finally, the three classes of models may be combined in hybrid traffic flow models. The first studies in this respect concerned the coherence between macroscopic and microscopic models (Gazis et al., 1961) and preliminary discussions of coupling traffic flow models were proposed by Poschinger et al. (2000). Furthermore, some contributions refer to the combinations between mesoscopic and microscopic models (Yang and Morgan, 2006; Burghout et al., 2007) and some concern the combination between macroscopic and microscopic models (Leclercq, 2007; Joueiai et al., 2013, 2014; Joueiai et al., 2015).

Furthermore, such hybrid models require two kinds of analyses regarding local and global consistency, as stated in the introduction. Local consistency aims to simulate accurate wave propagation along two links described through different paradigms; two main approaches may be found in the literature as described below. In the first, the interfaces between the microscopic and macroscopic models have a spatial extend where both models coexist (Magne et al., 2002; Hennecke et al., 2000; Poshinger et al., 2002; Bourrel and Lesort, 2003; Burghout et al., 2005); in the second case, interfaces are located in discrete points in space and are based on a generalisation of demand and supply concepts (Leclercq, 2007).

3. THE PROPOSED MODEL

The general architecture of the proposed hybrid model consists of the combination of a macroscopic CTM with a microscopic CA for each link (see Figure 1). The CA is used to model the traffic flow microscopically at the junction, whereas the CTM models the traffic flow macroscopically along the link. The transitions from CA to CTM and vice versa are based on the introduction of a transition zone.

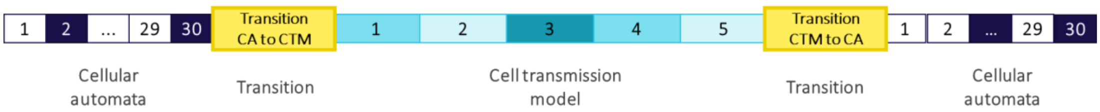


Figure 1: Example of a link with a hybrid approach

Prior to an in/depth description of the transition zone, where the two models coexist at the interfaces, some information about each of the models is provided.

3.1 CTM – Cell Transmission Model

The Cell Transmission Model was introduced to support the solution of the continuous time – continuous space LWR model, and it is based on a *finite-difference method*: the time is divided into constant time intervals, while the road segment is divided into cells of constant length, with an index i increasing in the downstream direction. At each time step, every cell has single values of density and speed (as a function of the speed - density relationship) while the flow between neighbouring cells is constant during the time interval. The most common integration method for LWR models is the *Godunov scheme* (Treiber and Kesting, 2013). This method is based on an exact solution of the continuity equation for one time step, assuming stepwise initial conditions given by the actual densities of the cells. The road is divided into cells of length Δx equal to the distance that a vehicle would travel in a free flow condition during one-time step. Hence it is equal to the free flow speed multiplied by the duration of the time step (also called clock tick), $V_f \Delta t = \Delta x$. It should be pointed out that the relation between the cell length and the time step complies with the *Courant Friedrich-Lewy* condition ($V_f \Delta t \leq \Delta x$) for the stability of explicit solution methods.

Following the Godunov scheme, the densities are initially averaged for each cell (each cell has a constant value of density), and from one time step t, to a successive one, t+Δt, the solution evolution is averaged again in order to obtain a piecewise constant solution. The main variables of the method are

k_i density in cell i;
k_j jam density;
Q_i maximum flow rate in cell i;
V_f free flow speed;
ω shock wave speed in congested traffic;
Δx cell length;
Δt time step;
Y_i flow exiting the boundary of cell i.

The density is then obtained as a function of flows at the cell boundaries as in the following:

$$k_i(t+1) = k_i(t) + [Y_{i-1}(t) - Y_i(t)] \cdot \frac{\Delta t}{\Delta x} \tag{1}$$

Finally, the key quantities of the method can be introduced based on the (trapezoidal) fundamental diagram Figure 2.

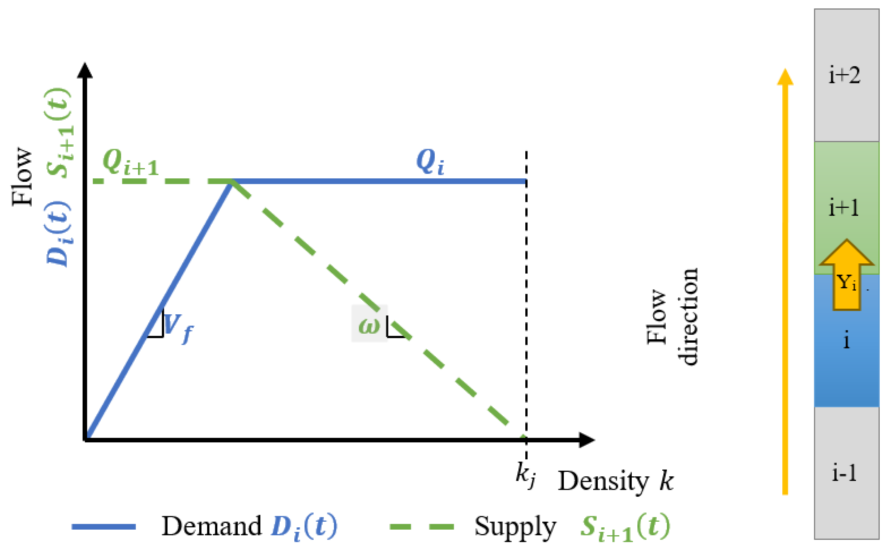


Figure 2: Trapezoidal fundamental diagram – link representation.

The flow of vehicles moving through the boundary between cell i and cell $i+1$ (see Figure 2) is given by the result of a comparison between the maximum flow that can be *sent* (that is the *demand*) by cell i (upstream of the boundary):

$$D_i(t) = \min(Q_i, V_f \cdot k_i) \tag{2}$$

and the maximum flow that can be received (that is the supply) by the downstream cell $i+1$:

$$S_{i+1}(t) = \min\left(Q_{i+1}, \omega \cdot (k_j - k_{i+1})\right) \tag{3}$$

Since every cell has a maximum value of density (k_j), the incoming flow is not only constrained by the maximum value Q_{i+1}, but also by the difference between the maximum density and the current density $(k_j - k_{i+1})$, which allows to describe the spillback phenomena and is able to model the effects of horizontal queuing.

Therefore, in accordance with the *Godunov scheme*, the flow $Y_i(t)$ can be rewritten in accordance with the demand (*sending*)-supply (*receiving*) rule of the cell transmission model as:

$$Y_i(t) = \min(D_i(t), S_{i+1}(t)) \tag{4}$$

3.2 CA - Nagel-Schreckenberg Model

A simplified approach was proposed by Nagel-Schreckenberg (Nagel, K., & Schreckenberg, 1992) who developed a model discrete in time and space, considering a single lane road and dividing it into cells that can have two states: occupied or empty, and a length equal to the length of a vehicle. Every vehicle occupies a cell, which has an "occupied" state. At the next time step, if a vehicle moves to another downstream cell, its speed has integer value (ranging from zero to a maximum value) which represents the number of cells that the vehicle moves downstream, from position $x_i(t)$ to $x_i(t+1)$. Because of this, the behaviour of an upstream vehicle i is influenced by a downstream one $i+1$, if the gap g_i between them is smaller than the speed v_i of the upstream vehicle. The speed can be converted to a dimensional value, multiplying it by the ratio of the cell length and the time step. The acceleration is equal to 1 or 0, thus increasing, or otherwise, the integer value of the speed at each time step.

The model also contains a stochastic component called the *dawdling probability* in which with a probability p a vehicle can remain at the same speed (if it was accelerating) or decelerate. This allows us to model stop-and-go waves in congested traffic, varying the flow-density relation as well.

The model is applied by following four rules. At each time step, and for each vehicle i on the road, their speed $v_i(t)$ and position $x_i(t)$ are updated as:

Slowing down — Obtain the *gap* at time t. If **speed** > *gap*, then slow down.

Acceleration — If **speed** < *gap* and **speed** < **max speed**, then accelerate by one.

$$v_i^*(t+1) = \min\left(v_i(t) + 1, v_0, g_i\right) \quad (5)$$

Randomization (Dawdling rule) — If **speed** > 0, then with probability p (dawdling probability, that is the random term) reduce it by one.

$$v_i(t+1) = \begin{cases} max\left(v_i^*(t+1) - 1\right) & with\, probability\, p \\ v_i^*(t+1) & otherwise \end{cases} \quad (6)$$

Car motion — Update the position

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (7)$$

The Nagel-Schreckenberg Model is not the only type of Cellular Automata. There are also other types, such as the Barlovic Model (Barlovic et al., 1998) which adds a "slow to start" rule, the Kerner Klenov and Wolf model (Kerneret al., 2002) which considers the cell length equal to 0.50 m (thus considering an acceleration of 0.5 m/s2) and adds other parameters to model synchronized traffic in accordance with the three-phase traffic theory proposed by Kerner, and the same model but changing the safe speed rule by using a discretized version of the safe speed of Gipps' model (considering a braking deceleration parameter). In this study, the base model remains the Nagel Schreckenberg, but given that each cell has a length of 2.50 m; the randomization rule is applied only if the speed exceeds a minimum value greater than 0.

3.3 Transition zones

Since a link is modelled with two different aggregation levels, two transition zones have to be specified: from CA to CTM (microscopic to macroscopic) and from CTM to CA (macroscopic to microscopic).

3.3.1 From CA to CTM – Transition 1

This transition receives vehicles from the Cellular Automata upstream, to then insert a flow into the Cell Transmission Model downstream, as can be seen in Figure 3.

The transition zone has two subsections, one for each model:

- The macroscopic CTM section is a single cell with the same properties as the cells of the CTM model, but with a different length. As it has a length Δx_{CTM-T1} equal to $\Delta x_{CTM} \cdot (\Delta t/Q_{CTM})$ a single vehicle can be spread into a cell $(\Delta t/Q_{CTM})$ times the length of the cells of the CTM model.
  In order to have coherence between the length of the CTM section and the cells of the CTM model, the value $(\Delta t/Q_{CTM})$ can be rounded to the next greater integer via a ceiling function $\lceil \Delta t/Q_{CTM} \rceil$. This variation can be seen in **Errore. L'origine riferimento non è stata trovata.**.
- The microscopic CA section is an extension of the upstream CA link, with a number of cells equal to the maximum speed (i.e. the minimum gap between vehicles, hence an upstream vehicle affects a downstream one), and with the same properties, parameters and rules as the CA model.

For each time step, before a vehicle in the CA model upstream can enter the microscopic section of the transition model, it is necessary to calculate the available space of the transition. To this end, the current number of vehicles on the macroscopic section is subtracted from the maximum number of vehicles (considering the jam density). This means that the transition zone is not jammed and has sufficient space to allocate to the

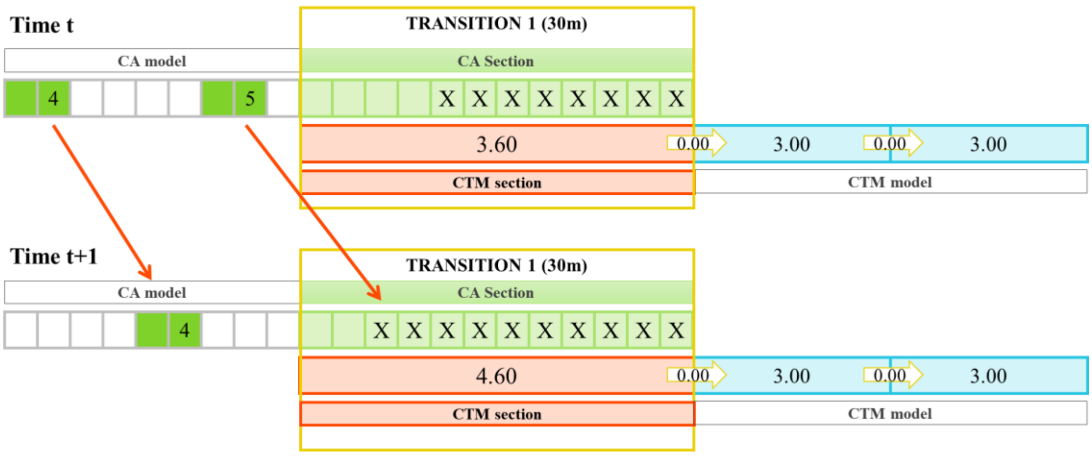


Figure 3: Transition from CA to CTM, considering a vehicle in CA occupies 2 cells. The numbers in the CA cells are the speeds of the vehicles, while the values on the CTM cells are the number of vehicles.

incoming vehicle. The initial cells of the microscopic CA section are then declared "empty" and thus an incoming vehicle from the CA model can enter, calculating the gap (number of empty cells downstream), to then apply the normal procedure of the CA algorithm.

Length of the macroscopic CTM section

$$\Delta x_{CTM-T1} = \Delta x_{CTM} \cdot \lceil \Delta t / Q_{CTM} \rceil \tag{8}$$

Number of vehicles in the transition section

	CA model						Transition 1 (15m)							CTM model - OUTFLOW CAPACITY = 3600 veh/h				
TIME	27	28	29	30	31	32	CA section						CTM section	1	2	3	4	5
1	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
2	0	0	0	6	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
3	0	0	0	0	0	0	0	0	0	6	0	0	1.00	0.00	0.00	0.00	0.00	0.00
4	0	0	0	0	0	0	0	0	0	0	0	0	0.00	1.00	0.00	0.00	0.00	0.00
5	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	1.00	0.00	0.00	0.00
6	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	1.00	0.00	0.00
7	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	1.00	0.00

	CA model						Transition 1 (30m)							CTM model - OUTFLOW CAPACITY = 2700 veh/h				
TIME	27	28	29	30	31	32	CA section						CTM section	1	2	3	4	5
1	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
2	0	0	0	6	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
3	0	0	0	0	0	0	0	0	0	6	0	0	1.00	0.00	0.00	0.00	0.00	0.00
4	0	0	0	0	0	0	0	0	0	0	0	0	0.50	0.50	0.00	0.00	0.00	0.00
5	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.50	0.50	0.00	0.00	0.00
6	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.50	0.50	0.00	0.00
7	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.50	0.50	0.00

	CA model						Transition 1 (45m)							CTM model - OUTFLOW CAPACITY = 1800 veh/h				
TIME	27	28	29	30	31	32	CA section						CTM section	1	2	3	4	5
1	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
2	0	0	0	6	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
3	0	0	0	0	0	0	0	0	0	6	0	0	1.00	0.00	0.00	0.00	0.00	0.00
4	0	0	0	0	0	0	0	0	0	0	0	0	0.67	0.33	0.00	0.00	0.00	0.00
5	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0.33	0.33	0.00	0.00	0.00
6	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.33	0.33	0.33	0.00	0.00
7	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.33	0.33	0.33	0.00

	CA model						Transition 1 (60m)							CTM model - OUTFLOW CAPACITY = 900 veh/h				
TIME	27	28	29	30	31	32	CA section						CTM section	1	2	3	4	5
1	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
2	0	0	0	6	0	0	0	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
3	0	0	0	0	0	0	0	0	0	6	0	0	1.00	0.00	0.00	0.00	0.00	0.00
4	0	0	0	0	0	0	0	0	0	0	0	0	0.75	0.25	0.00	0.00	0.00	0.00
5	0	0	0	0	0	0	0	0	0	0	0	0	0.50	0.25	0.25	0.00	0.00	0.00
6	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.00	0.00
7	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.25	0.25	0.25	0.25	0.00

Figure 4: variation of the length of the Transition 1 depending on the outflow capacity. The cell length on the CA is 2.50 m and on the CTM is 15 m. the free flow speed is set to 15 m/s. The numbers in the CA cells are the speeds of the vehicles, while the values on the CTM cells are the number of vehicles.

$$n_{veh-T1} = k_{CTM-T1} \cdot \Delta x_{CTM-T1} \tag{9}$$

Number of vehicles that can enter the transition section

$$n_{veh-T1}^{enter} = (k_j - k_{CTM-T1}) \cdot \Delta x_{CTM-T1} \tag{10}$$

Number of cells available in the microscopic CA section ("empty" cells):

$$n_{cellsCA-T} = \frac{n_{veh-T}^{enter}}{\Delta x_{CA}} \tag{11}$$

Space gap of the vehicle upstream to the transition:

$$g_i(t) = x_{last\ cell\ of\ CA\ model} - x_i(t) + n_{cellsCA-T} \tag{12}$$

After this procedure, the rules of the CA model are applied to the vehicle upstream, considering the gap with the available cells of the CA section of the transition. Then, if the position of the vehicle $x_i(t+1)$ lies within the CA section of the transition, the CTM section of the transition of the successive time step is updated.

The flow of vehicles moving through the boundary between the cell of the CTM section of the transition and the first cell of the CTM model is obtained following the same procedure as in the CTM model as described above.

3.3.2 From CTM to CA – Transition 2

The transition from the Cell Transmission Model to the Cellular Automata has a similar layout to the first, as it has two subsections:

- A macroscopic CTM cell, with the same characteristics as the CTM model, which acts as a cell to accumulate flow.
- A microscopic CA section, with as many cells as to cover the entire length of the CTM cell, being the initial segment of the CA model downstream.

A scheme of the transition cell in question can be seen in Figure 5.

The flow $Y_{end}(t)$ of the boundary between the last cell of the CTM upstream and the macroscopic CTM cell of the transition, is calculated following the same procedure described above for the CTM model, but bearing in mind that the maximum flow that can be received (the *supply*) is also conditioned by the number of vehicles n_{CA-T2} located in the microscopic CA section:

$$S_{CTM-T2}(t) = \min\left(Q_{CTM}, \omega \cdot \left(k_j - (k_{CTM-T2} + n_{CA-T2}/\Delta x_{CTM})\right)\right) \qquad (13)$$

$$Y_{end}(t) = \min\left(D_{end}(t), S_{CTM-T2}(t)\right) \qquad (14)$$

The density of the macroscopic CTM cell of the transition is then updated, considering only the incoming flow.

$$k_{CTM-T2}(t+1) = k_{CTM-T2}(t) + [Y_{end}(t)] \cdot \frac{\Delta t}{\Delta x} \qquad (15)$$

If the macroscopic CTM cell of the transition has a density such that an entire vehicle is located within the cell, then it is transferred towards the microscopic CA section. To this end, the density of the CTM cell is reduced, and the status of the last available cell of the microscopic CA section i changed to “occupied”, initially considering a speed equal to the desired free flow speed v_0. The same rules as in the CA model are then applied to this vehicle. Thus, its speed and position are updated for the following time step considering the gap with an eventual vehicle downstream.

$$if\ (k_{CTM-T2}(t) \cdot \Delta x_{CTM} \geq 1) \qquad (16)$$

$$n_{transferring}(t) = int(k_{CTM-T2}(t) \cdot \Delta x_{CTM}) \qquad (17)$$

$$k_{CTM-T2}(t) = k_{CTM-T2}(t) - n_{transferring}(t) \cdot \Delta x_{CTM} \qquad (18)$$

$$n_{CTM-T2}(t) = n_{CTM-T2}(t) - n_{transferring}(t) \qquad (19)$$

$$n_{CA\_T2}(t) = n_{CA\_T2}(t) + n_{transferring}(t) \qquad (20)$$

With regard to the example shown in Figure 5, the total number of vehicles in the

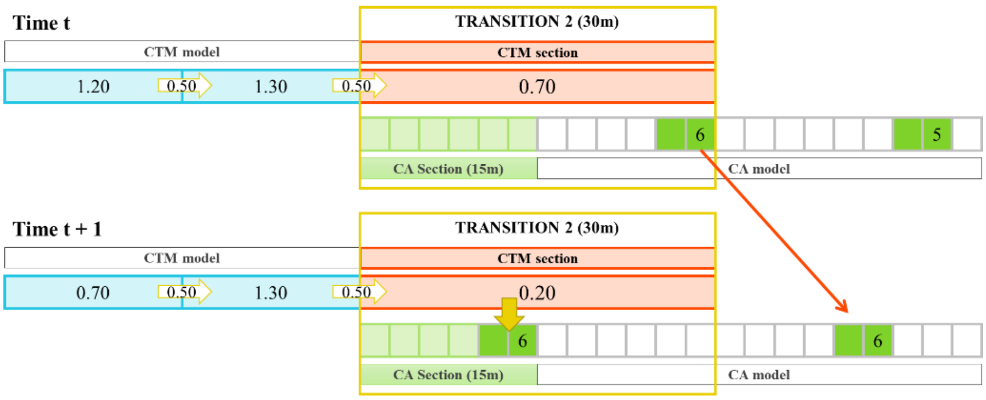


Figure 5: Transition from CTM to CA with a cumulative transition cell. The numbers in the CA cells are the speeds of the vehicles, while the values on the CTM cells are the number of vehicles.

transition zone at time t is equal to 1.70, obtained by adding one vehicle in the CA model (which has a speed of 6 cells/s) to 0.7 vehicles in the macroscopic transition cell.

4. CASE STUDIES AND NUMERICAL RESULTS

The proposed model was tested using several numerical applications. The case studies are summarised in Table 1, in which they are named according to: i) the layout of the network (layout), ii) the traffic flow model considered (TFM), iii) application of a traffic control strategy (with/without), iv) a capacity reduction according to the traffic flow model (a reduction in the outflow capacity for the CTM, or the dawdling probability p for the CA), v) the value of the entry flows (constant or variable over time) and the degree of saturation (undersaturated or oversaturated).

The test networks have three different layouts:

- a ring-shaped link (see Figure 6),
- an arterial with three intersections (see Figure 13),
- and a nine-node grid (see Figure 21).

Table 1: Summary of case studies considered

STRATEGY	**LAYOUT**	**TRAFFIC FLOW MODEL**			**TRAFFIC CONTROL**		**CAPACITY REDUCTION**	**ENTRY FLOWS**
		CTM + CA	**CTM**	**CA**	**WITHOUT**	**WITH**		
A $_{1,1,1,1}$		X					-	
A $_{1,1,2a,1}$		X					X (outflow capacity)	
A $_{2,1,2a,1}$	RING		X		X	-	X (outflow capacity)	NO ENTRIES
A $_{1,1,2b,1}$		X					X (p-dawdling)	
A $_{3,1,2b,1}$				X			X (p-dawdling)	
B $_{1,2,1,1}$		X				X - FIXED		Constant/Undersat.
B $_{1,2,1,2}$		X						Variable/Oversat.
B $_{1,3,1,1}$	ARTERY	X			-		-	Constant/Undersat.
B $_{1,3,1,2}$		X				X – MPC		Variable/Oversat.
B $_{2,3,1,1}$			X					Constant/Undersat.
B $_{2,3,1,2}$			X					Variable/Oversat.
C $_{1,2,1}$	9 NODE GRID	X			-	X – FIXED	-	Constant/Undersat
C $_{2,2,1}$			X					

**For each strategy identified as $S_{w,x,y,z}$, S is the layout, w is the traffic flow model, x is the traffic control strategy, y is the (endogenous) capacity reduction, z is the profile of traffic flow values (constant/variable over time) and the saturation degree (undersaturated/oversaturated).*

The ring serves to verify the local consistency of the transition zones of the hybrid model, and the effects of the capacity reduction on the CA, on the CTM, and on the hybrid model (H – CTMCA). The arterial is used to test the influence of a traffic control strategy on the hybrid traffic flow model. To this end, two methods are used: a pre-timed traffic control method (Robertson, 1969) and an enhanced traffic control strategy based on the model predictive control (Lin, 2011; Zegeye, 2011). Finally, the nine node grid is used to test the effect of a more complex network layout, without implicit path choice modelling and a fixed signal setting implementation.

The results of the various tests are analysed with respect to different indicators:

- *Maximum and mean queue (MMQ):* obtaining the queue length at each time step for each link, counting the number of vehicles stopped in the CA and the stopped flow in the CTM, to then calculate the maximum and the mean value on the whole simulation interval for each road.
- *Saturation degree (SD)***:** considering the ratio between the number of incoming vehicles on each road, and the maximum number of vehicles that could exit each link during the green time of the traffic signal.
- *Total time spent (TTS):* the sum of the number of vehicles on each link for each time step, for the whole simulation interval. It is equivalent to adding the total time spent by each vehicle on each link. By adding the TTS on each link a single value for the whole network may be obtained.
- *Total delay (TD):* the extra time spent by each vehicle on a link, due to congestion or the presence of traffic lights, obtained as the total time spent by each vehicle on each link minus the time it would have taken to cross the link on a free-flow condition without traffic lights.

For the scenarios with entry flows, the layouts are initially empty, and are subsequently loaded with uniform traffic flow through the source nodes during a “warm-up” interval. This is the minimum interval required for vehicles to cross the entire layout. In terms of simulation settings in our model it was considered equal to 15 minutes.

Finally, the computer used to run these tests had an Intel(R) Core(TM) i7-4510U CPU @ 2.00GHz (4 CPUs), ~2.6GHz with 8192MB RAM, and an OS Windows 10 Home 64-bit. The code was written on MATLAB R2019b.

4.1 Ring

Hybrid traffic flow models need to be analysed in terms of *local* consistency (Joueia iet al., 2013; 2014), which describes conservation of vehicles through a local interface. With this aim, this subsection provides an analysis of the results obtained by applying the H – CTMCA model on the ring layout (see Figure 6) to check its continuity.

The ring is 5000 m long which, considering a jam density of 200 vehicles per kilometre, which means that the ring can allocate up to 1000 vehicles. The main settings of the model parameters are displayed in Table 2.

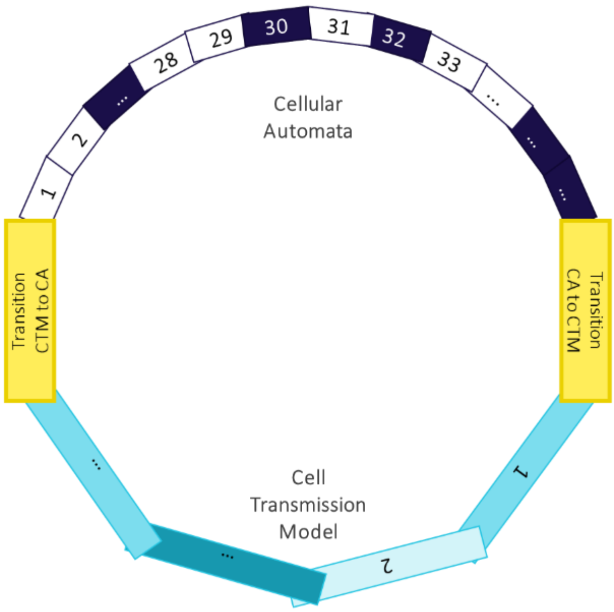
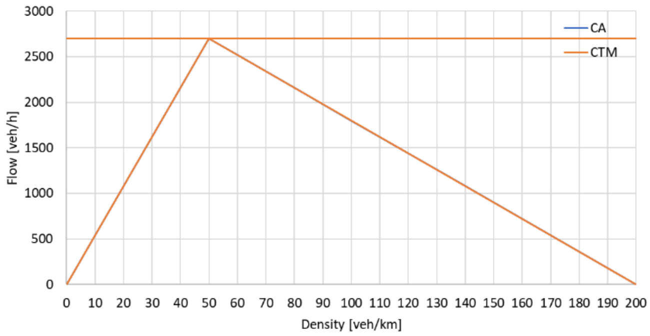


Figure 6: Scheme of the ring layout

Table 2: Parameter values for the ring application

Parameter	**CTM**	**CA**
Δt time step	1 s	
k_{jam} jam density	200 PCU/km	
Cell length	15.00 m	2.50 m
Vehicle length	-	2 cells
v_f free flow speed	15 m/s	6 cells/s
w shock wave speed	5 m/s	-
q_i maximum flow rate	variable	-
p dawdling probability	-	variable
Min speed to apply dawdling	-	variable

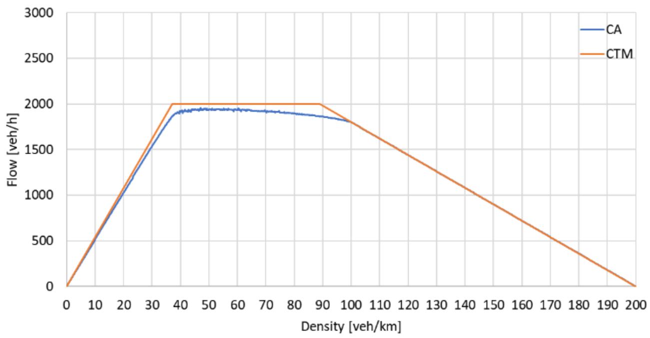
The maximum flow rate for the CTM model, and the dawdling probability and minimum speed to apply the dawdling rule on the CA model were varied in order to consider three types of flows, producing a different flow-density relationship. The setting of these parameters for each sub - model is summarised in the following Figure 7.



Type of flow 1
CTM:
q$_i$ maximum flow rate = 2700 [PCU/h]

CA
p dawdling probability = 0
Min speed to apply dawdling = 0

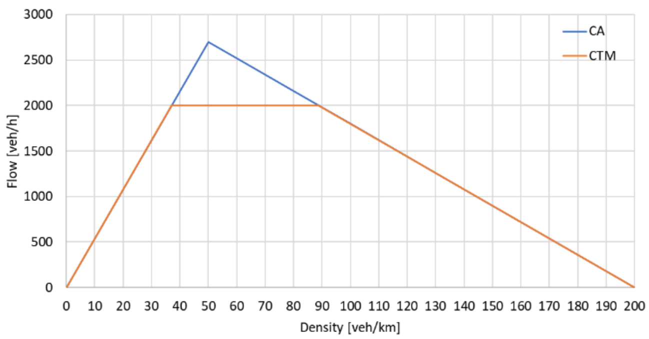
Deterministic behaviour of the CA- (no dawdling)



Type of flow 2
CTM:
q$_i$ maximum flow rate = 2000 [PCU/h]

CA
p dawdling probability = 0.266
Min speed to apply dawdling = 2

Stochastic behaviour of the CA- (dawdling applied)



Type of flow 3
CTM:
q$_i$ maximum flow rate = 2000 [PCU/h]

CA
p dawdling probability = 0
Min speed to apply dawdling = 0

Deterministic behaviour of the CA- (No dawdling)

Figure 7: parameter settings for each type of flow considered.

The proportion of CA vs CTM varies considering two alternatives:

- 1/3 of the ring modelled with CA - 2/3 of the ring modelled with CTM (see Figure 8);
- 2/3 of the ring modelled with CA - 1/3 of the ring modelled with CTM (see Figure 9).

The results of the numerical applications are shown and discussed with reference to the impact on the traffic flow-density relationship of the proposed hybrid traffic flow model, considering:

a) **Flow type 1**, in which the CA sub- model behaves deterministically since the dawdling probability is set to 0, and the CTM sub- model has the same maximum outflow of 2700 PCU/h;
b) **Flow type 2**, in which the CA sub- model behaves stochastically, and the maximum outflow capacity of the CTM model is slightly above the maximum flow of the CA sub- model;
c) **Flow type 2** as in scenario 2, but with a **restriction** (increase) of the **dawdling probability p** on a section of the CA sub- model on cells 94 to 99 (of the CA), increasing to 0.50;
d) **Flow type 2** as in scenario 2, but with a **restriction** (decrease) of the **outflow capacity** on a single cell of the CTM sub- model on cell 99 (of the CTM), decreasing to 1000 PCU/h;
e) **Flow type 3**, in which the CA behaves deterministically since the dawdling probability is set to 0, but the CTM sub- model has a lower maximum outflow of 2000 PCU/h;

It should also be specified that scenarios 3 and 4 are introduced to test model resilience in the case of a bottleneck generation. The flow-density relation of each scenario was obtained considering:

i. Mean flow density on a section after cell 100 of the CA sub- model;
ii. Mean flow density on cell 100 of the CTM sub- model;
iii. Mean flow density for the whole ring.

The results of applications highlight the model’s consistency in terms of continuity between the CA and CTM as can be directly observed.

The analysis shows that other major differences lie in the dawdling probability which is required to observe the fluctuations in the density transitions. Finally, with regard to the CTM, the capacity restriction underlines the model’s resilience.

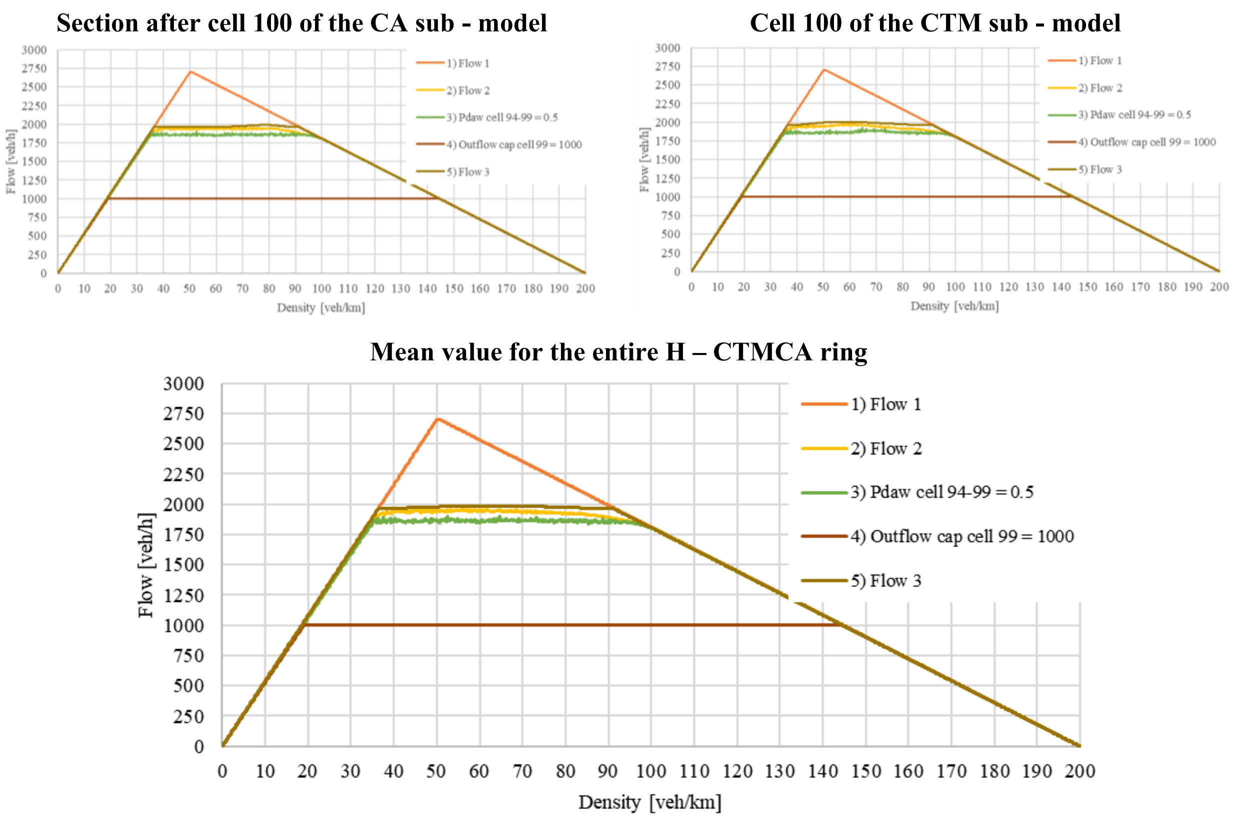


Figure 8: Results of 1/3 of the ring modelled with CA - 2/3 of the ring modelled with CTM

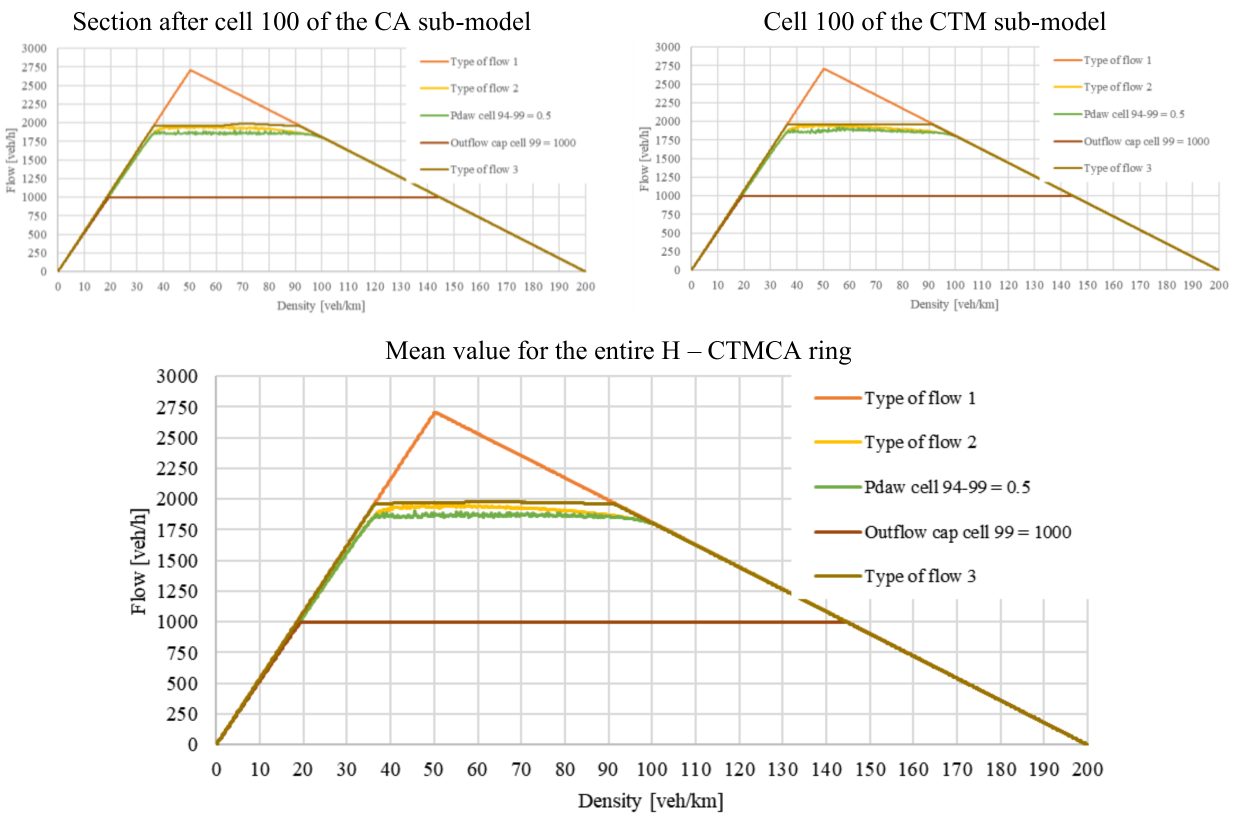


Figure 9: Results of 2/3 of the ring modelled with CA - 1/3 of the ring modelled with CTM

After these considerations, the most important scenario to be analysed in more detail is flow type 2, in which the CA sub - model has a stochastic behaviour due to the dawdling parameter, and the CTM has an outflow capacity of 2000 PCU/h. A final comparison is shown, considering the two proportions of the CA and CTM on the H – CTMCA model (1/3 CA - 2/3 CTM and vice versa) as displayed in Figure 10, showing that very similar results are achieved.

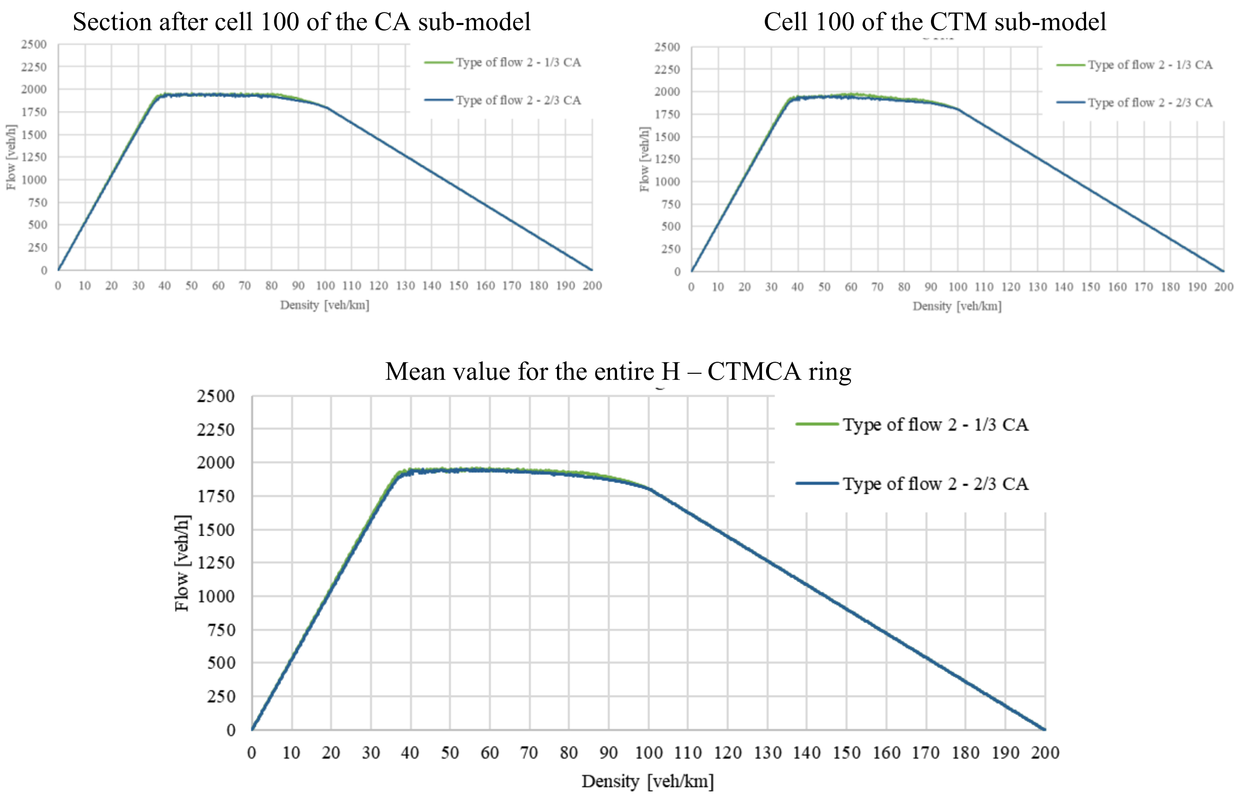


Figure 10: Flow - Density diagram for Flow Type 2.

A similar analysis was carried out in the cells upstream and downstream of the transition zones to verify local consistency. The results are displayed in the following figures: transition from CA to CTM (see Figure 11) and from CTM to CA (see Figure 12).

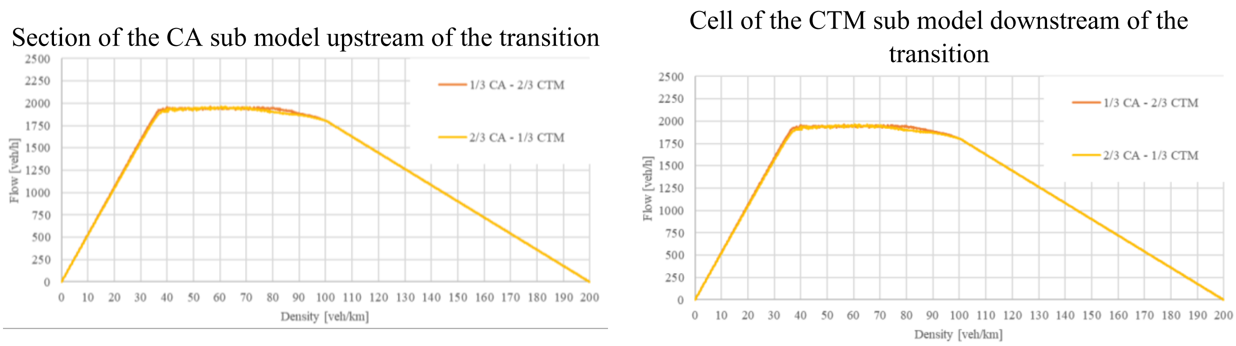


Figure 11: Flow - Density diagram for transition 1 (from CA to CTM).

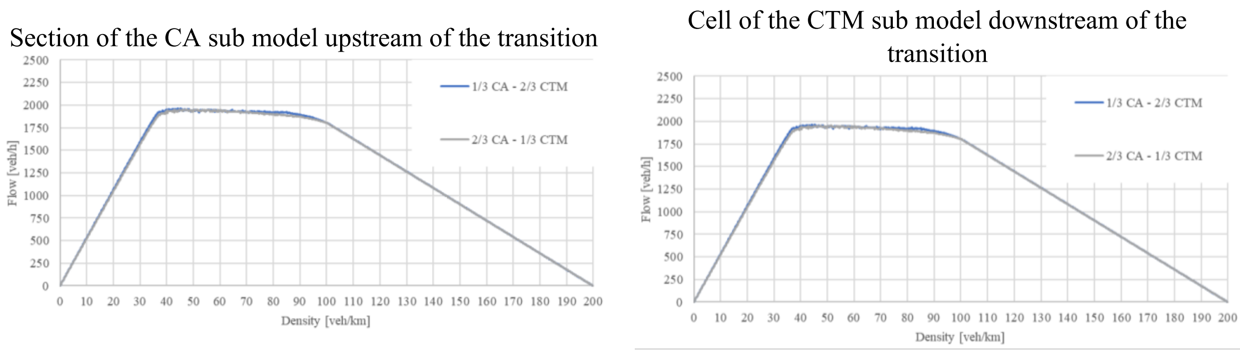


Figure 12: Flow - Density diagram for transition 2 (from CTM to CA).

4.2 Arterial

This section contains the results of a numerical application of a two-way arterial with three intersections. This layout was used to test two main applications via optimisation of green times and offsets: the first application is a fixed time strategy and the second is an enhanced strategy based on Model Predictive Control (MPC; Lin, 2011; Zegeye, 2011) approach.

The fixed time strategy is based on a synchronisation method (Cantarella et al; 2015) aiming to minimise network total delay. MPC may be applied as a centralised, decentralised, or distributed control structure. In the first type of structure, the entire system is managed by a single controller who receives information about the whole system as input signals, and makes decisions for the entire system, which are sent back to it as output signals. It is thus possible to achieve on-line synchronisation of the network which includes the simultaneous optimisation of green timings and offsets (see Cantarella et al; 2015). In the case of a decentralised control structure, the whole network is divided into subsystems with their own local controller, who optimises green timings and offsets through local measurements and following a local optimisation procedure (for example, the coordination approach in which the decision variables optimisation is sequential). In this case, the output signals of each controller are based on the information obtained for each subnetwork with no interaction between controllers. Finally, the distributed control structure is similar to the decentralised one since the system is divided into subsystems with independent local controllers, but they can communicate between each other, sharing information and coordinating.

Each control structure may be properly applied depending on the network size considered. For instance, the centralised approach may not be easily implemented in the case of large–scale networks. However, given the focus of this paper, centralised MPC was implemented. The objective function considered by the controller, in accordance with the literature (Lin, 2011; Zegeye, 2011), is total time spent (TTS). Since the aim of this application is to test the H – CTMCA model, this traffic model was used to simulate the system, and also as a prediction model on the MPC controller.

The test layout is a two-way arterial with three successive signalised junctions (A, B and C), as can be observed in Figure 13. It has five entry/exit links 90 metres long; the distance between junctions A and B is around 810 metres, as is the distance between junctions B and C.

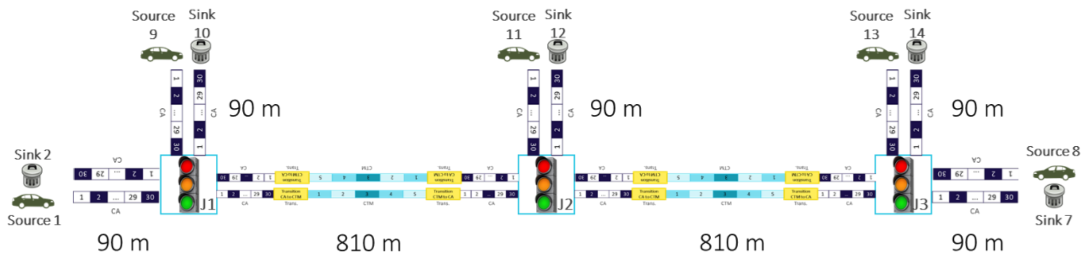


Figure 13: Layout of the two-way arterial.

The entry/exit flows considered between entry and exit links are displayed in detail in Table 3.

Table 3: Base Entry - Exit flows of the arterial application

		Exit [PCU/h]					
		2	**7**	**10**	**12**	**14**	**TOTAL**
Entry [PCU/h]	**1**		200		100	100	400
	8	400		100	100		600
	9	100	100				200
	11	100	100				200
	13	100	100				200
	TOTAL	700	500	100	200	100	1600

These values were considered constant over time as uniform traffic flows (see Figure 14), and then were increased to a peak value as a variable traffic flow (see Figure 15):

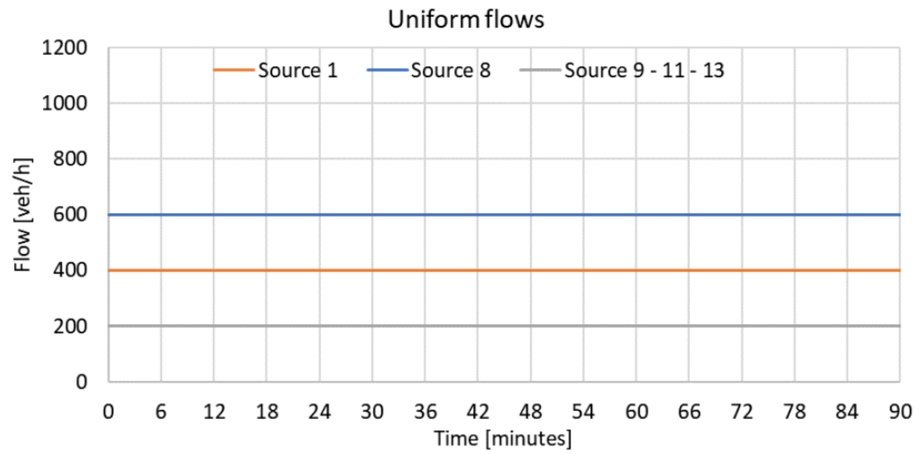


Figure 14: Uniform flow values over time.

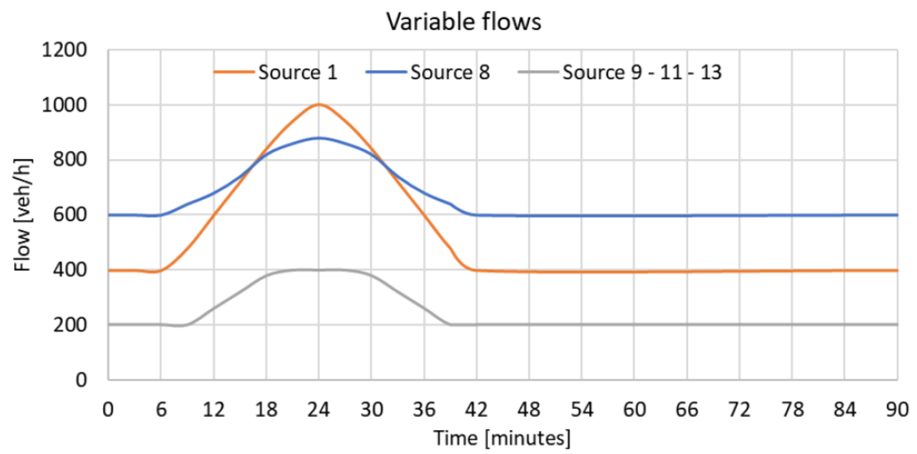


Figure 15: Variable flow values over time.

Before comparing the fixed timing strategy and MPC application, it is necessary to analyse the parameters set on the controller. MPC is able to adapt the optimisation of the traffic signal settings to the system prediction starting from the current state of the system. To this end, the controller receives information (measurements) from the system and via a control loop applies an optimisation procedure on a prediction model over a prediction horizon. During this prediction horizon, several control inputs may be obtained (solutions of the optimisation procedure) for a control horizon. Only the first sample is implemented, and the horizon is thus shifted one sample, restarting the optimisation with new measurements.

The main MPC settings are:

- the prediction horizon N_p: the time over the controller would predict future states of the system on a prediction model if the set of control inputs of the optimisation procedure were applied to the system. This value should be long enough to consider all the dynamics of the system, but at the same time not so long as to increase computational complexity. It is expressed in controller time steps;
- the control horizon N_c: it is the number of controller time steps for which the control inputs are optimised. The setting of this parameter is a trade-off between low computational complexity (a shorter control horizon) and better controller performance (a longer control horizon). After the control horizon has passed, the control signal is assumed constant over the rest of the prediction horizon.
- parameters of the objective function: as stated above, the single objective function to be minimised is the total time that all vehicles spend on the network, as a unique value. However, it is possible to consider a more complex objective function – using a weighted sum approach – or several functions that could be in conflict. In this case, it is necessary to properly choose a set of weights to consider the trade-off between different objectives.

Other important parameters are:

- T simulation time interval for the prediction model: this is the time interval in which the prediction model (i.e. the H – CTMCA model) yields an estimate of the system state. In this case, it is equal to 1 s. Its step counter is denoted as k;
- T_c control time interval: this is the time interval in which intersections within the subnetwork can communicate with each other and be synchronous. The first sample of the optimisation procedure is implemented during this interval. Its step counter is denoted as k_c.

The relation between T and T_c is given by:

$$T_c = M \cdot T \tag{21}$$

where M is a constant integer.

Since there is a difference between the simulation time interval T and the control time interval T_c, the traffic states are estimated M times more than the variation in the control inputs. The optimisation strategy uses a metaheuristic procedure as a solution algorithm;

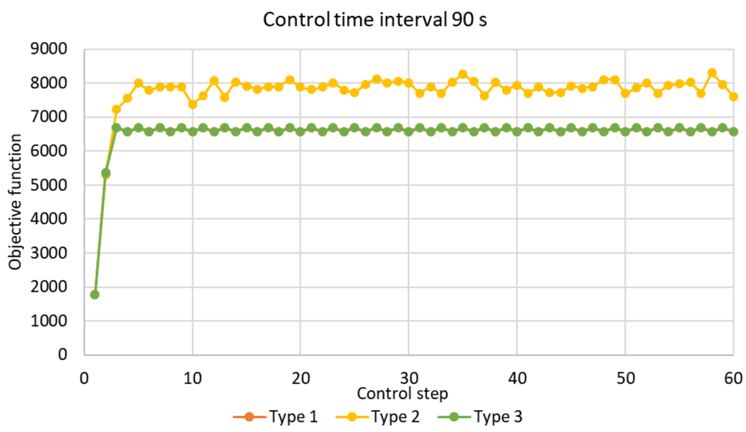
in this case the Differential Evolution method (DE; Price, 2013; Brabazon et al., 2006). There is no proof of convergence for DE, however it has been shown to be effective on a large range of classic optimization problems. In a comparison by Storn and Price (1997) DE was more efficient than simulated annealing and genetic algorithms. Ali and Torn (2004) found that DE was both more accurate and more efficient than controlled random search and another genetic algorithm. In Lampinen and Storn (2004) demonstrated that DE was more accurate than several other optimization methods including four genetic algorithms, simulated annealing and evolutionary programming. DE was applied with the following setting of the parameters:

- Population size: variable depending on each scenario
- Combination probability: 0.90
- Mutation factor: $0.50 \cdot (1 + rand)$
- Maximum iterations: 1000

With regard to the H – CTMCA traffic flow model, the parameters set are equal to the ring application (see section 4.1). That is, three types of flow were considered depending on the combination between the outflow capacity of the Cell Transmission Model (equal to 2700 or 2000 PCU/h) and the dawdling probability of the Cellular Automata (CA deterministic or stochastic).

A first implementation of MPC was considered, with a uniform entry flow, considering each of the three flow types. The results are displayed for two combinations of MPC settings (control time interval, control horizon and prediction horizon) in the following figures (see Figure 16) in which the landscape of the objective function against the control step is displayed. In both cases, the cycle length of the junctions is equal to 90 s, and the total simulation period of the system is set at 90 minutes (i.e., 5400 s equal to 60 cycles). For this implementation, as optimisation variables three green times (the same for the three junctions) and two independent absolute offset values were selected.

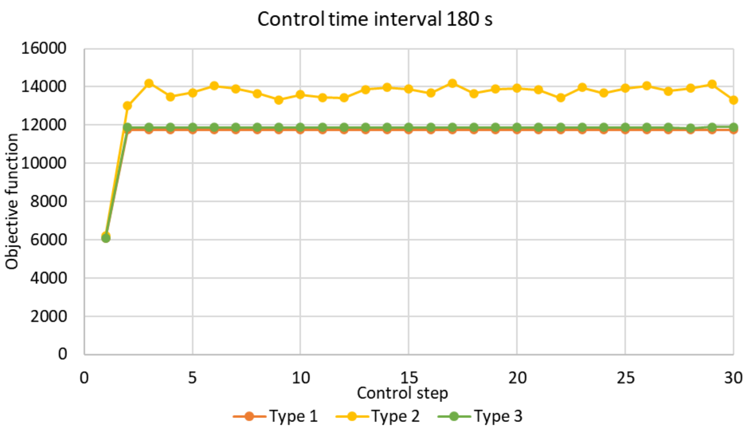
The first consideration to be made is that, since the entry flow considered is uniform over time, a constant trajectory of the objective function is expected, independently of MPC settings. Both figures show a variable trajectory for flow type 2, which is consistent with the endogenous stochastic setting of the CA. It is worth noting that when a deterministic behaviour is set, the difference between the value of the objective function in two consecutive control steps for the smaller control time interval is given by the small difference between the number of vehicles that entered through the sources, as they are inserted via the discrete CA model.



MPC settings
Simulation horizon: 5400 s
Control time interval: 90 s

Prediction horizon: 6 (i.e., 540 s)
Control horizon: 1

Solution Algorithm settings
Variables: 5
Population size: 25



MPC settings
Simulation horizon: 5400 s
Control time interval: 180 s

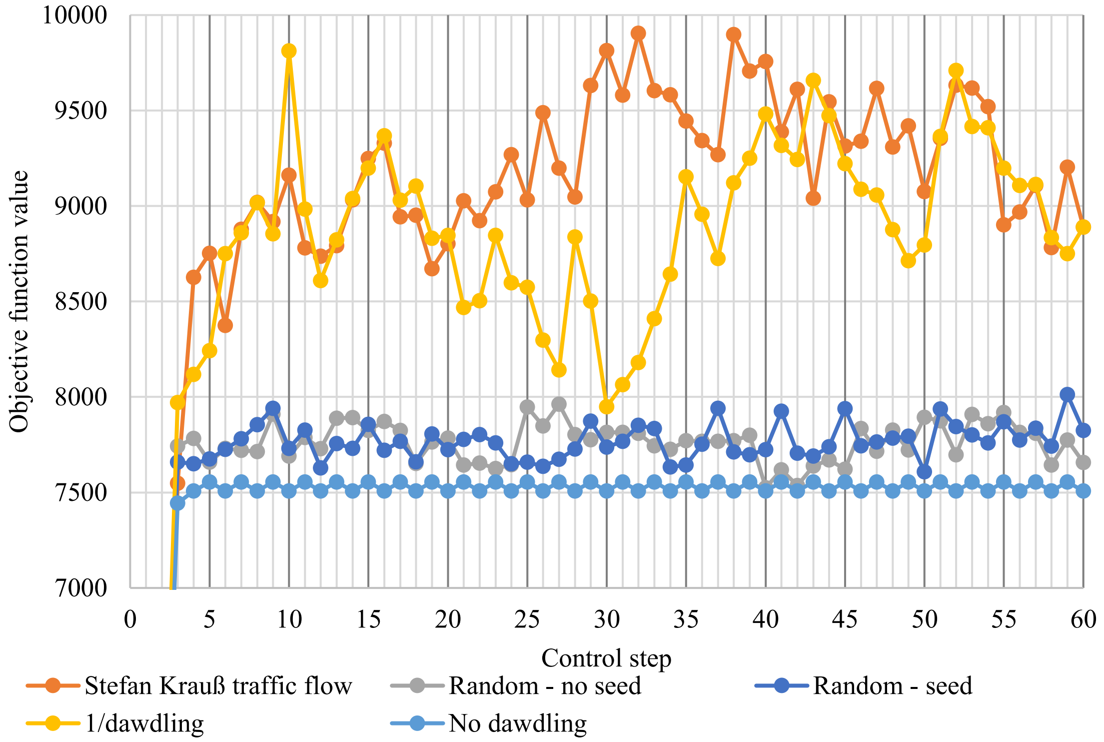
Prediction horizon: 4 (i.e., 720 s)
Control horizon: 1

Solution Algorithm settings
Variables: 5
Pop size: 25

Figure 14: Values of the objective function (Total Time Spent) with respect to two different MPC settings

With regard to the stochastic nature of the traffic flow models and how it may affect the objective function of the MPC, a further analysis was made. The results with the Stefan Krauß traffic flow model (see Krauss 1998), were compared with the deterministic and stochastic CA. Finally, regarding the stochastic CA three further applications were considered: without setting a seed at each control step to generate the random number to apply the dawdling rule (random – no seed scenario), by setting a seed at each control step (random – seed fixed scenario) and by applying the rule every 1/(dawdling probability) vehicle (for instance if p = 0.266 the rule is applied every 3.759 = 1/0.266 vehicles). The results are displayed in the following Figure 17 in which two different clustered behaviours may be observed: the first with high stochastic nature consists of the Krauß traffic flow model and the 1/(dawdling probability) implementation, while the second is composed by the deterministic scenario and the two "seed/no seed" scenarios.

In the same Figure 17 the values of the mean and standard deviation (St. Dev.) are also displayed for each of the simulations; therefore, it is evident that the random – seed fixed scenario has to be considered.

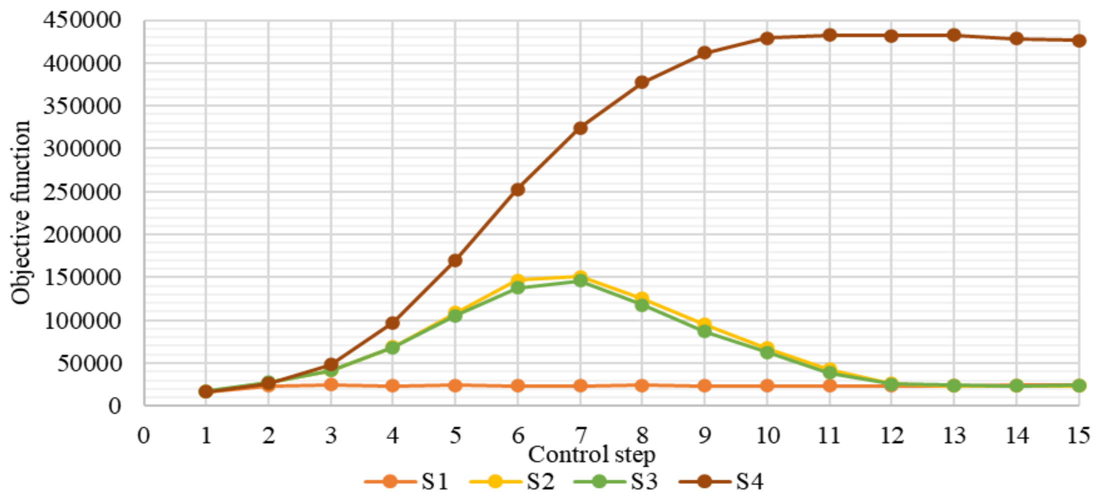


	SUMO Stefan Krauß traffic flow	stochastic			deterministic
		rand – no seed	***rand – seed fixed***	*1/(dawdling probability)*	*no dawdling*
Mean	9214.82	7762.79	**7768.28**	8902.30	7530.58
St. Dev.	354.40	100.73	**91.62**	424.56	24.21

Figure 17: Values of the objective function (Total Time Spent) considering different settings of the H – CTMCA model, and applying the Kraub traffic flow model

Fixing the seed of the random number generator allows the same result to be obtained within a control step, given the same conditions (same initial state and equal set of control inputs) when the controller is testing several control inputs to find the optimum set.

After choosing the fixed seed strategy considering flow type 2 (stochastic behaviour of the CA), four scenarios S1, S2, S3 and S4 were specified as displayed in Figure 18 below. The first two scenarios have as decision variables nine green times and two absolute offsets on one control horizon, considering uniform and variable entries of flows. The third scenario considers two control horizons, therefore improving the objective function for the variable entry flow. Finally, the fourth scenario evaluates the objective function considering a fixed timing strategy but with a variable entry of flow.



Scenario	S1	S2	S3	S4
Flow entry	Uniform	Variable	Variable	Variable
Simulation horizon	5400 s			
Control time interval	360 s			
Prediction horizon	2 (i.e. 720 s)			Fixed
Control horizon	1	1	2	
Variables	11	11	22	
Pop size	110	110	220	

Figure 18: Values of the objective function (Total Time Spent) considering different scenarios (varying the flow, the parameters of the MPC controller, and considering a fixed value of the green times and offsets)

As expected, the objective function (Total Time Spent) grows as the flow increases for scenario S3, but the controller adjusts the green timings and the offsets, reacting to this variation. If the green timings and the offsets were fixed (scenario S4), the total time spent would increase since some initially uncongested links would become congested.

The results of the green timings for junction J1 (Figure 19) and the absolute offsets (Figure 20) are shown for each of the four scenarios. The first observation to be made is that the traffic light decision variables are more stable in the case of uniform flows than that of variable flows. However, since a metaheuristic procedure is used, a variation in green times may also be seen for uniform entry flow.

Finally, the results of a fixed strategy are compared with those of an MPC strategy.

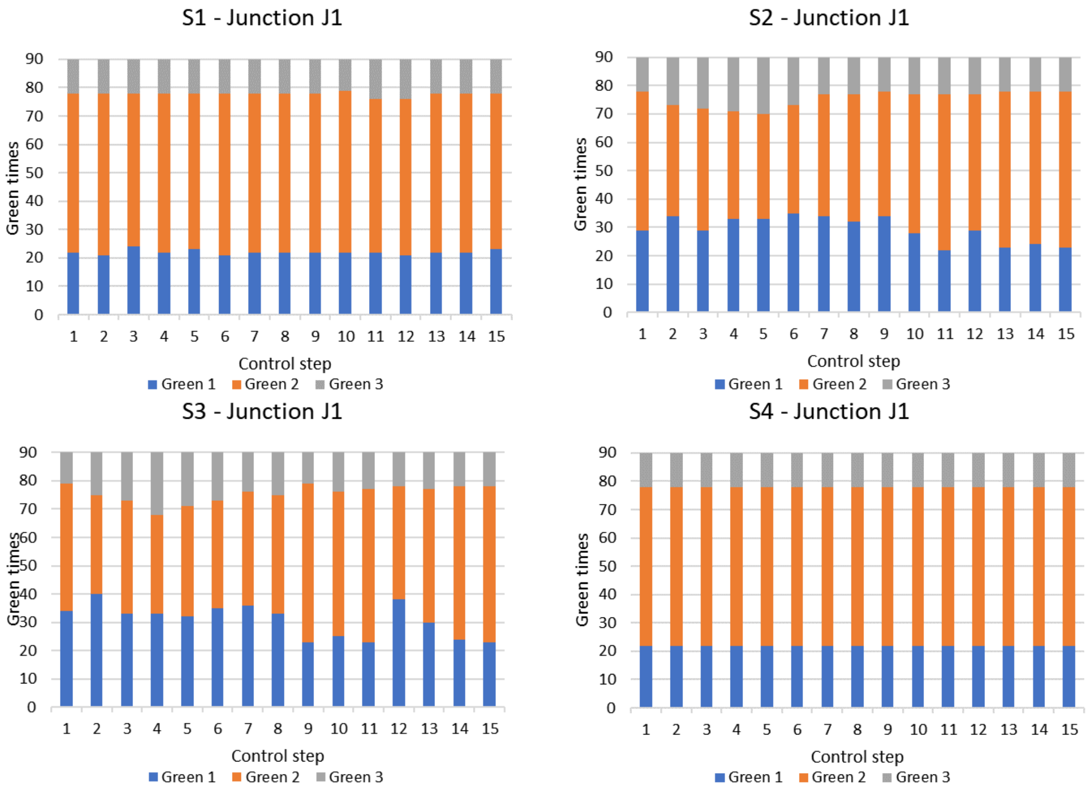


Figure 19: Green timings for the junction J1 for each scenario considered

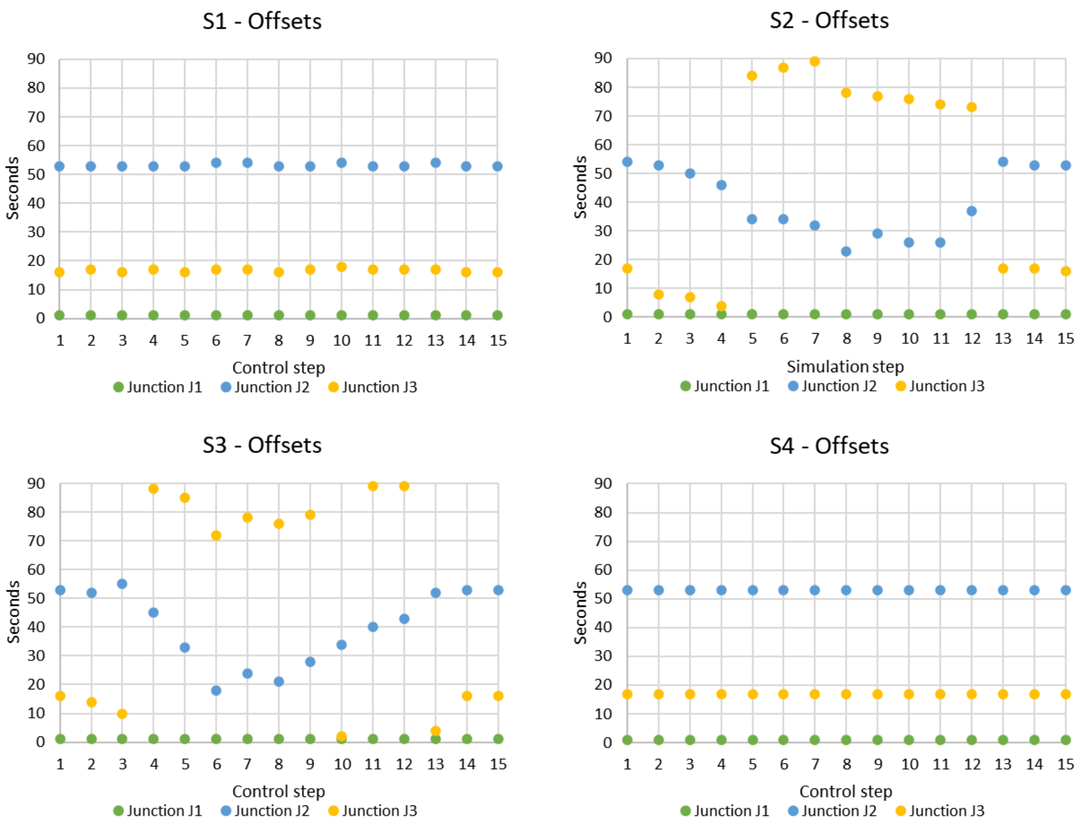


Figure 20: Absolute offsets for the three junctions, for each scenario considered.

The results are summarised in the following tables (from Table 4 to Table 6), and for MMQ and SD the values refer to the four internal hybrid links, without considering the sources and sinks whilst for TTS the sources and sinks are also included.

In general, the main focus of the application is on the comparison between two different traffic control strategies, the fixed and the MPC strategy, and the comparison between two traffic flow models, the CTM and the proposed hybrid traffic flow model, considering the same traffic control method. All numerical applications were performed twice, considering two different traffic flow trajectories, uniform and variables.

First of all, with respect to the traffic flow representation it may be observed that in all cases the H – CTMCA model is able to properly incorporate the different traffic flow landscape and higher values of the indicators are displayed. Concerning the comparison between two traffic control strategies, it may be concluded that in the case of uniform flows the indicators are slightly different, whilst in the case of variable flows, the MPC indicators, which are not considered on the optimisation procedure, that is MMQ and SD, are slightly higher in scenario $B_{1,3,1,2}$ than in $B_{1,2,1,2}$ whilst the TTS indicator considered for the MPC optimisation procedure is lower than 57%. The results confirm that the traffic flow model is also suitable in the case of more complex traffic signal optimisation.

Table 4: Indicators for a fixed green times and offsets strategy on the H – CTMCA model.

B $_{1,2,1,1}$ – Uniform entry flow – Fixed strategy		
MMQ [PCU]	SD [%]	TTS [PCU h]
5.47	77.30	89.89
B $_{1,2,1,2}$– Variable entry flow – Fixed strategy		
MMQ [PCU]	SD [%]	TTS [PCU h]
5.85	79.84	495.68

Table 5: Indicators applying an MPC controller on the H – CTMCA model.

B $_{1,3,1,1}$ – Uniform entry flow – MPC strategy		
MMQ [PCU]	SD [%]	TTS [PCU h]
5.57	77.27	91.02
B $_{1,3,1,2}$– Variable entry flow – MPC strategy		
MMQ [PCU]	SD [%]	TTS [PCU h]
11.07	88.30	213.44

A further and final analysis was also provided in terms of comparison between the two traffic flow models, the usually adopted CTM and the proposed H – CTMCA model. The results shown in the following table highlight the fact that higher realism is provided by the proposed model. Indeed, all indicators considered for queue estimation, network capacity representation and finally travel time estimation are higher in the H – CTMCA model than the case of CTM.

Table 6: Indicators for a fixed green times and offsets strategy on a CTM only model.

$B_{2,3,1,1}$– CTM model - Uniform entry flow – Fixed strategy		
MMQ [PCU]	SD [%]	TTS [PCU h]
4.5	77.58	85.72
$B_{2,3,1,2}$– CTM model – Variable entry flow – Fixed strategy		
MMQ [PCU]	SD [%]	TTS [PCU h]
4.88	82.17	484.97

4.3 Network

In this section, the H – CTMCA traffic flow model was used on a more complex layout, consisting of a grid network with 4 origins, 4 destinations, 4 o-d pairs, 9 inner nodes and 12 bidirectional links (or 17 nodes and 32 links if the connectors to the origins and destinations are considered). Each inner link was modelled with the H – CTMCA traffic flow model, while the connectors were modelled with a Cellular Automata model. All links have one lane in each direction; the saturation flow of each lane is assumed equal to 2000 PCU/h. Their length varies, since links connecting node 5 with other nodes (2-5, 4-5, 5-6, 5-8) are equal to 405 (equal to 27 cells, each 15 m long in the CTM), the other links on the network are 810 m long (equal to 54 cells, each 15 m long in the CTM), and the connectors are 90 m long. A scheme of the network layout is shown in Figure 21 and the details of the entry-exit matrix are displayed in Table 7.

Table 7: Entry-exit matrix of the OD pairs for the network layout.

		Exit [PCU/h]				**TOTAL**
		2	**4**	**6**	**8**	
Entry [PCU/h]	**1**	-	480	382	336	1198
	3	433	-	288	382	1103
	5	480	624	-	422	1526
	7	336	575	433	-	1344
TOTAL		1249	1679	1103	1140	**5171**

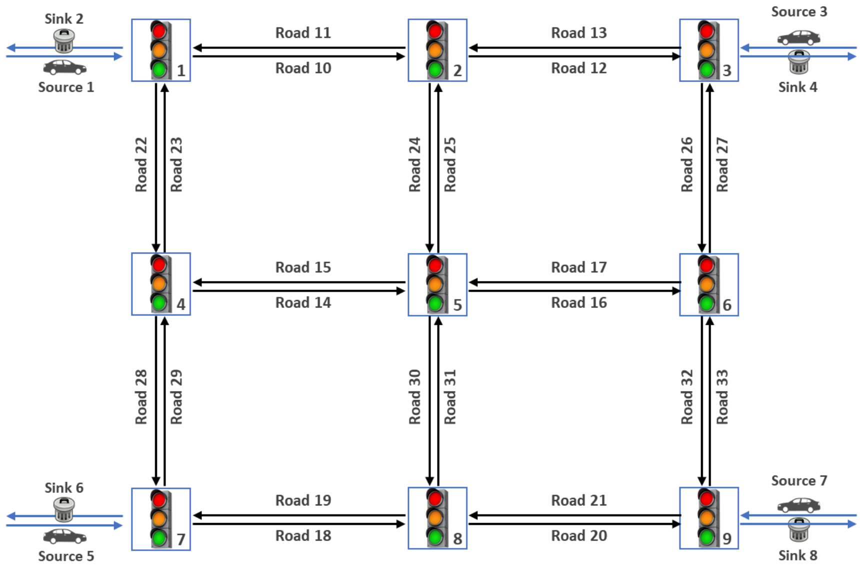


Figure 21: representation of the nine-node grid network layout modelled with the H – CTMCA model.

The network has signalised junctions at each node, while the solution for the optimisation control problem is based on the criterion of minimising total delay, considering green times and offsets as network decision variables. For this application, path choice modelling has an explicit (enumeration) approach (see Cascetta, 2009), detailed in Table 8, indicating for each origin destination pair the instantaneous travel time (i.e. the travel time without considering the impact of congestion).

The model was analysed considering two traffic flow conditions: uniform or variable arrivals, depending on whether the time-gap between two vehicles on the same path for the same OD pair was constant or variable. The results are preliminarily analysed with respect to the total time spent (TTS); as can be observed in Figure 22, in which the trend of total time spent for both types of arrival condition may be identified, showing that the proposed model is able to reproduce the traffic flow independently of the arrival law of vehicles at the source nodes.

Table 8: Link sequence and flow for each path, considering each single OD pair.

Origin	Destination	Sub-path ID	Path ID	Instantaneous travel time [s]	Link sequence	Flow OD [PCU/h]	Flow rates (%)	Flow on each path [PCU/h]
1	4	1	1-4/1	120	{1 10 12 4 0 0}	480	90.46	435
1	4	2	1-4/2	174	{1 10 24 16 27 4}		3.18	15
1	4	3	1-4/3	174	{1 22 14 16 27 4}		3.18	15
1	4	4	1-4/4	174	{1 22 14 25 12 4}		3.18	15
1	6	1	1-6/1	120	{1 22 28 6 0 0}	382	90.46	346
1	6	2	1-6/2	174	{1 10 24 15 28 6}		3.18	12
1	6	3	1-6/3	174	{1 10 24 30 19 6}		3.18	12
1	6	4	1-6/4	174	{1 22 14 30 19 6}		3.18	12
1	8	1	1-8/1	174	{1 10 24 16 32 8}	336	25.00	84
1	8	2	1-8/2	174	{1 10 24 30 20 8}		25.00	84
1	8	3	1-8/3	174	{1 22 14 16 32 8}		25.00	84
1	8	4	1-8/4	174	{1 22 14 30 20 8}		25.00	84
3	2	1	3-2/1	120	{3 13 11 2 0 0}	433	90.46	391
3	2	2	3-2/2	174	{3 13 24 15 23 2}		3.18	14
3	2	3	3-2/3	174	{3 26 17 15 23 2}		3.18	14
3	2	4	3-2/4	174	{3 26 17 25 11 2}		3.18	14
3	6	1	3-6/1	174	{3 13 24 15 28 6}	288	25.00	72
3	6	2	3-6/2	174	{3 13 24 30 19 6}		25.00	72
3	6	3	3-6/3	174	{3 26 17 15 28 6}		25.00	72
3	6	4	3-6/4	174	{3 26 17 30 19 6}		25.00	72
3	8	1	3-8/1	120	{3 26 32 8 0 0}	382	90.46	346
3	8	2	3-8/2	174	{3 13 24 16 32 8}		3.18	12
3	8	3	3-8/3	174	{3 13 24 30 20 8}		3.18	12
3	8	4	3-8/4	174	{3 26 17 30 20 8}		3.18	12
5	2	1	5-2/1	120	{5 29 23 2 0 0}	480	90.46	435
5	2	2	5-2/2	174	{5 18 31 15 23 2}		3.18	15
5	2	3	5-2/3	174	{5 18 31 25 11 2}		3.18	15
5	2	4	5-2/4	174	{5 29 14 25 11 2}		3.18	15
5	4	1	5-4/1	174	{5 18 31 16 27 4}	624	25.00	156
5	4	2	5-4/2	174	{5 18 31 25 12 4}		25.00	156
5	4	3	5-4/3	174	{5 29 14 16 27 4}		25.00	156
5	4	4	5-4/4	174	{5 29 14 25 12 4}		25.00	156
5	8	1	5-8/1	120	{5 18 20 8 0 0}	422	90.46	383
5	8	2	5-8/2	174	{5 18 31 16 32 8}		3.18	13
5	8	3	5-8/3	174	{5 29 14 16 32 8}		3.18	13
5	8	4	5-8/4	174	{5 29 14 30 20 8}		3.18	13
7	2	1	7-2/1	174	{7 21 31 15 23 2}	336	25.00	84
7	2	2	7-2/2	174	{7 21 31 25 11 2}		25.00	84
7	2	3	7-2/3	174	{7 33 17 15 23 2}		25.00	84
7	2	4	7-2/4	174	{7 33 17 25 11 2}		25.00	84
7	4	1	7-4/1	120	{7 33 27 4 0 0}	575	90.46	521
7	4	2	7-4/2	174	{7 21 31 16 27 4}		3.18	18
7	4	3	7-4/3	174	{7 21 31 25 12 4}		3.18	18
7	4	4	7-4/4	174	{7 33 17 25 12 4}		3.18	18
7	6	1	7-6/1	120	{7 21 19 6 0 0}	433	90.46	391
7	6	2	7-6/2	174	{7 21 31 15 28 6}		3.18	14
7	6	3	7-6/3	174	{7 33 17 15 28 6}		3.18	14
7	6	4	7-6/4	174	{7 33 17 30 19 6}		3.18	14

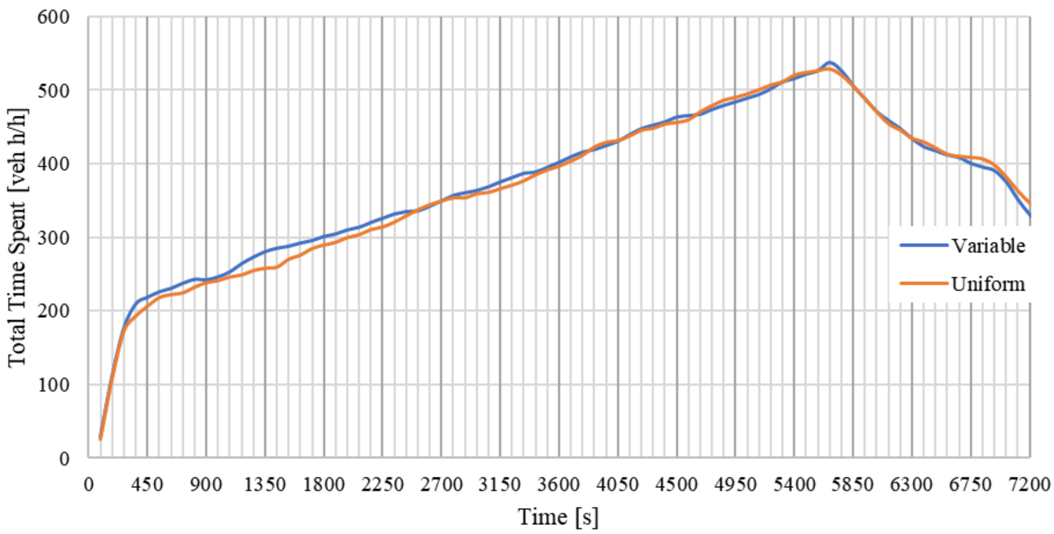


Figure 22: Total Time Spent with respect to the simulation time, considering Variable and Uniform arrival law for incoming vehicles.

The proposed model was compared numerically with the two cases of uniform and variable arrivals. The results are displayed in table 9 which includes the Mean Maximum Queue (MMQ), Saturation Degree (SD), Total Delay (TD[3]), and Total Time Spent (TTS) as performance indicators, confirming model feasibility in both cases of uniform and variable arrivals. The results are obtained for five intervals of 15 minutes, since the first interval was considered as a warm-up period to preload the network. Applying the entry-exit matrix of Table 7, the network has a mean saturation degree close to 74%, but some links are oversaturated, yielding an increasing value of Total Delay (TD) and Total Time Spent (TTS) for each time interval.

Table 9: Performance indicators of the network modelled with the H – CTMCA traffic flow model.

		H – CTMCA model – Uniform arrivals – Fixed strategy		
TIME	MMQ [PCU]	SD [%]	TD[PCU-h/h]	TTS [PCU-h/h]
0-900	11.00	64.49%	79.77	182.19
901-1800	13.04	73.32%	148.17	261.50
1801-2700	15.29	75.12%	210.46	319.25
2701-3600	16.33	73.31%	284.14	376.17
3601-4500	17.42	74.51%	355.97	430.70
901-4500	15.52	74.06%	249.68	346.91
		H – CTMCA model – Variable arrivals – Fixed strategy		
TIME	MMQ [PCU]	SD [%]	TD[PCU-h/h]	TTS [PCU-h/h]
0-900	11.79	66.83%	90.40	195.94
901-1800	14.50	74.42%	180.73	293.81
1801-2700	16.04	74.18%	253.72	354.56
2701-3600	16.96	73.35%	318.25	400.58
3601-4500	18.08	74.68%	388.30	455.97
901-4500	16.40	74.16%	285.25	376.23

[3] This is the network total delay (see Cantarella et al., 2015)

Finally, in order to evaluate the ability of the H – CTMCA model to reproduce traffic phenomena, it was compared with the existing Cell Transmission Model with respect to the performance indicators (MMQ, SD, TD and TTS), which are displayed in Table 10 below.

Table 10: Performance indicators of the network modelled with a Cell Transmission Model on TRANSYT.

CTM – Uniform arrivals – Fixed strategy CTM				
TIME	MMQ [PCU]	SD [%]	TD[PCU-h/h]	TTS [PCU-h/h]
0-900	9.64	78.17%	116.07	332.51
901-1800	11.17	78.17%	155.64	369.00
1801-2700	12.41	78.17%	186.04	398.78
2701-3600	13.55	78.17%	213.79	426.18
3601-4500	14.63	78.17%	240.19	452.24
901-4500	12.94	78.17%	198.92	411.55

Comparing the indicators for both models, it may be seen that the values of MMQ and TD are higher for the H – CTMCA model (around 20% more for MMQ and 26% more for TD). These indicators are expected to exhibit the same trend over different time intervals within each model, and it may be concluded that the hybrid model is able to predict the traffic flow phenomenon and the queue propagation more realistically, due to the disaggregation of the vehicles.

The SD and TTS of the CTM are both higher (around 5% for SD, and 16% for TTS). The result may be justified on the basis of a different modelling discretization of vehicles close to the intersections with respect to the CTM, since the hybrid model uses a discrete Cellular Automata in which every vehicle has a certain acceleration (and not an instant outflow capacity as the CTM), which induces a sort of (macroscopic) capacity drop endogenously depending on the model representation.

5. CONCLUSIONS

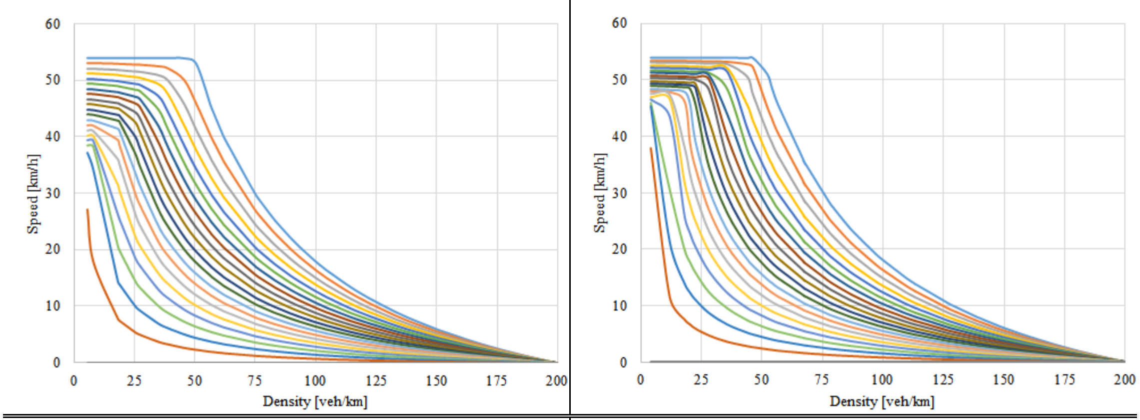
This paper developed a hybrid traffic flow model (H – CTMCA) by combining a macroscopic approach to model links with a microscopic approach to model nodes. To this end, two traffic flow models were adopted: a Cellular Automata model (CA; Nagel and Schreckenberg, 1992) as the microscopic model, and a Cell Transmission Model (CTM; Daganzo, 1994) as the macroscopic model.

The contribution of the paper may be seen as fivefold:

- it is based on a macroscopic Cell Transmission Model for link representation, and a simplified microscopic Cellular Automata model for node representation; to our knowledge, the combination has not yet been investigated;
- within the model, an alternative approach to the representation of the transition region is described;
- the model is detailed in the case of macroscopic link and microscopic node representation, however it may be applied in both cases of microscopic link and macroscopic node representation and vice versa;
- the proposed hybrid model is suitable for analysing traffic flow phenomena;
- the model can also be adopted for traffic control in both cases: in the context of multi objective optimisation (for instance based on surrogate indicators) and with the presence of connected vehicles.

To provide further details about the hybrid model, it should be emphasized that the macroscopic model is deterministic, while the microscopic model behaves stochastically due to the dawdling effect given by the dawdling probability of the CA. To highlight the impact of such stochasticity in the microscopic model, the following analyses are provided with respect to the speed – density relation considering different parametric values of the dawdling probability. The settings of the general model are shown in the tables below the figures that display the results obtained for two different cell lengths. This analysis shows the effect of cell length in terms of modelling realism. Since the dawdling rule induces a deceleration of a vehicle of 1 cell/(time_step)^2, if the length of the cell is large, then the speed has a large variation as well. This can be seen in the Figure 23 below which show that, even in a free flow condition, vehicles with a large cell length are wide apart from the desired speed (15 m/s = 54 km/h) than those with a smaller cell length when the dawdling probability increases, since deceleration in a free flow condition is only caused by the dawdling rule. Therefore, to obtain more realistic deceleration without a higher computational effort, the cell length of 2.50 metres was chosen. Finally, the flow-density and the speed-density relationship for this cell length are also displayed (see Figure 24), varying the dawdling probability.

CA-1 model		**CA-2 model**	



Time step	1 s	Time step	1 s
Max speed	15 m/s	Max speed	15 m/s
Jam density	200 PCU/km	Jam density	200 PCU/km
Cell length	5.00 m	Cell length	2.50 m
Max speed (CA)	3 cells/s	Max speed (CA)	6 cells/s
Vehicle length	1 cell	Vehicle length	2 cells

Figure 23: Diagrams for two Cellular Automata models, considering different cell lengths.

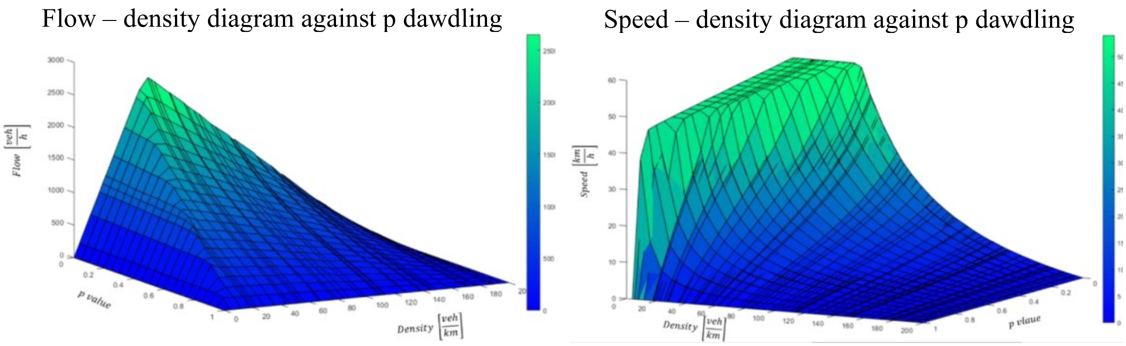


Figure 24: Flow-density and speed-density diagrams against p dawdling, for the CA-2 model (cell length= 2.50 m).

With regard to the numerical results of tests applying the hybrid traffic flow model, three main applications were considered:

1. a ring layout, to test and verify the local consistency of the model;
2. an arterial with two traffic control strategies: a simple fixed optimisation procedure and a model predictive control strategy. The latter was used to test the impact of a

different and more complex procedure using traffic light timings and offsets as optimisation variables;

3. a nine-node signalised network, to test the impact of a different and more complex network layout.

The ring layout was used to verify the local consistency of the model, describing the conservation of the vehicles through local interfaces. An overview of the model can be found below, in which the analysis of local consistency is heuristically displayed for the two transition zones: from the microscopic CA model to the macroscopic CTM and vice versa (see Figure 25). The space is shown on columns, while time steps are displayed on rows. Vehicles in CA are displayed as ones (zero if the cell is empty), while the cells of the CTM model shows the value of the number of vehicles in each cell. As described in section 3.3, the CA and CTM sections of the transitions are synchronised: for transition 1 this means that the distance that a vehicle can travel in the CA section depends on the number of vehicles in the transition, affecting the vehicles upstream of the transition zone, while for transition 2 the supply of the cell of the CTM section depends on the total number of vehicles in this transition zone, affecting the incoming flow from the last cell of the CTM model. As detailed above, there is a space overlapping the CA section and CTM section in both transition zones, but for better visual comprehension, they are displayed next to each other.

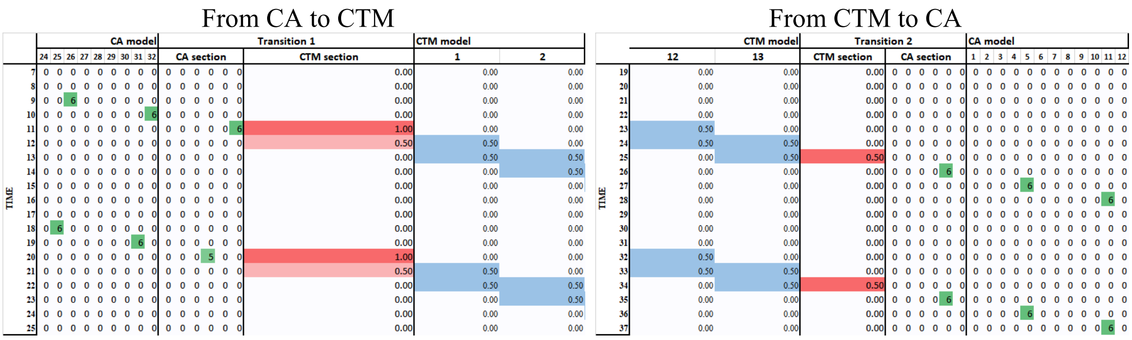


Figure 25: Transition zones on a free-flow condition.

The second application was an arterial. In this case, two main results were achieved: first the model suitability with a simple fixed-time strategy and a more complex MPC for traffic signal design was demonstrated; second, the two traffic flow models, the CTM and the proposed H – CTMCA model, were compared. For the second case, a table is displayed below to compare the computational effort of both models (a CTM only and a hybrid traffic flow model) with respect to the running time over 50 control steps. The values shows that despite the greater realism of the hybrid model with respect to the CTM, the time for 1000 executions is still comparable, independently of the values of the dawdling probability (deterministic if the dawdling probability is set to 0, or stochastic if the dawdling probability is greater than 0). The last two columns were tested with a lower population size on the Differential Evolution method, which shows a lower total elapsed time compared to the other tests.

Table 11: Execution times considering different traffic flow models, and parameter settings.

Flow model	CTM	H – CTMCA	CTM	H – CTMCA			
	Det.	Det.	Det.	Stoch.	Det.	Det.	Det.
Simulation horizon [s]				4500			
Control time interval [s]				90			
Prediction horizon				6			
Control horizon				1			
Outflow capacity [PCU/h]	3600				1800		
N variables	4				4		
Population size	22			22		11	
Total number of iterations	4847	4429	3802	6703	4389	3622	2869
Total number of executions	106634	97438	83644	147466	96558	39842	31559
Total elapsed time [s]	11363.8	8759.6	9824.8	13872.2	9733.5	4739.3	3890.1
Time for 1000 executions [s]	106.568	89.899	117.459	94.070	100.804	118.951	123.264

On the same layout, the network throughput (vehicle in – out) was also analysed with respect to the different demand profiles and signal setting design strategy. The results are summarised in Table 12 and Figure 27 which confirm the model's effectiveness with respect to the throughput in both cases: an increase in demand, and the impact of a more complex traffic control strategy.

Table 12: Throughput analysis for the arterial case study modelled with the H – CTMCA model.

ARTERIAL With a H – CTMCA model		Total vehicles trying to enter	Total vehicles that have entered	Total vehicles that have exited	Number of vehicles waiting to enter at the end of the simulation	Number of vehicles in the network at the end of the simulation
Uniform flows	fixed time	2400	2385	2343	15	42
Uniform flows	with MPC	2400	2385	2339	15	46
Variable flow	fixed time	2874	2523	2480	351	43
Variable flow	with MPC	2874	2859	2816	15	43

Finally, the same analysis was made on the third scenario, a nine-node grid network, to test the hybrid model on a more complex layout. The value of the number of vehicles trying to enter, that entered, and that exited the network were obtained every five cycles (450 s). The numerical results were computed with respect to the interval from 900 to

4500 seconds (the interval from 0 to 900 was considered as a warm-up period). Their values are displayed in the following diagrams (see Figure 26) and are summarised in Table 13. In this analysis, two types of arrivals were considered for each OD pair: uniform arrivals with a constant time gap between two vehicles, or variable arrivals, considering a variable time gap.

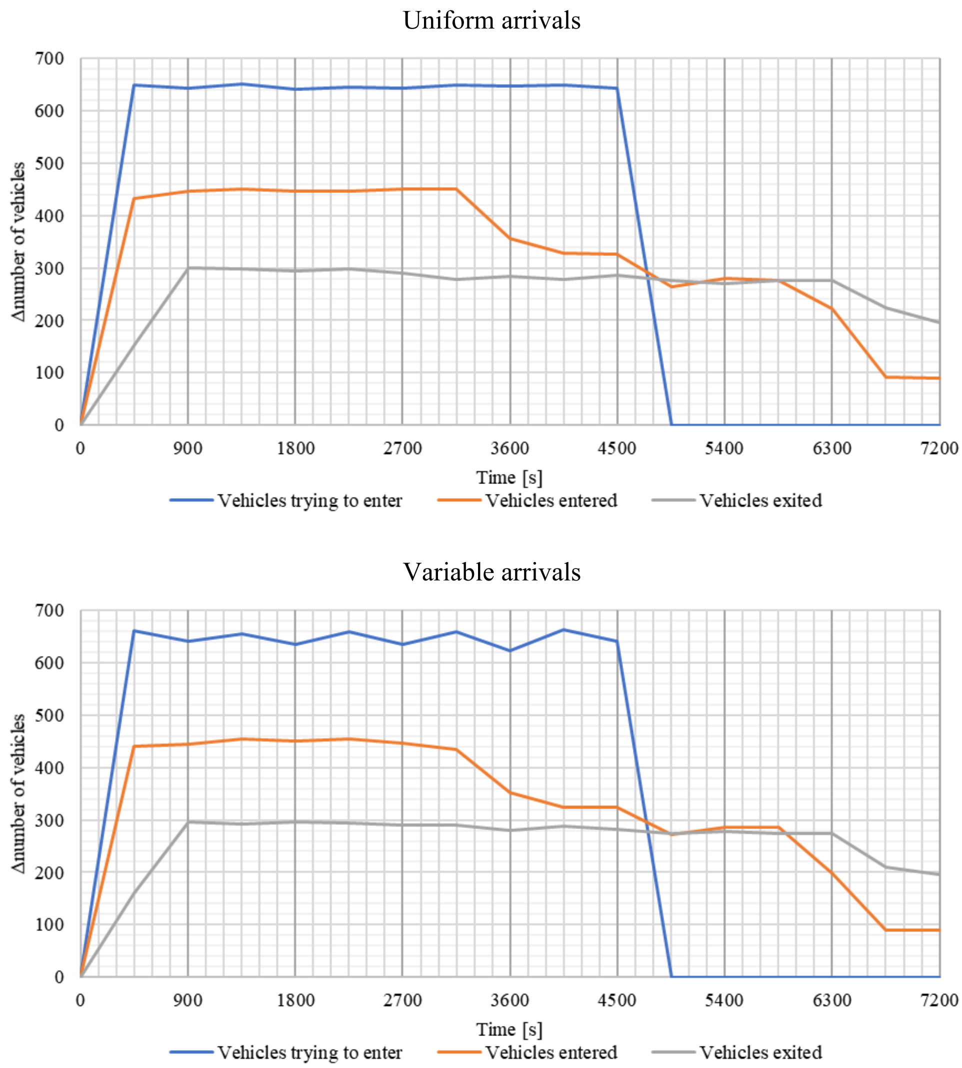


Figure 26: Delta values of vehicles every 450 s, considering different flow trends and control strategies on the network modelled with the hybrid traffic flow model.

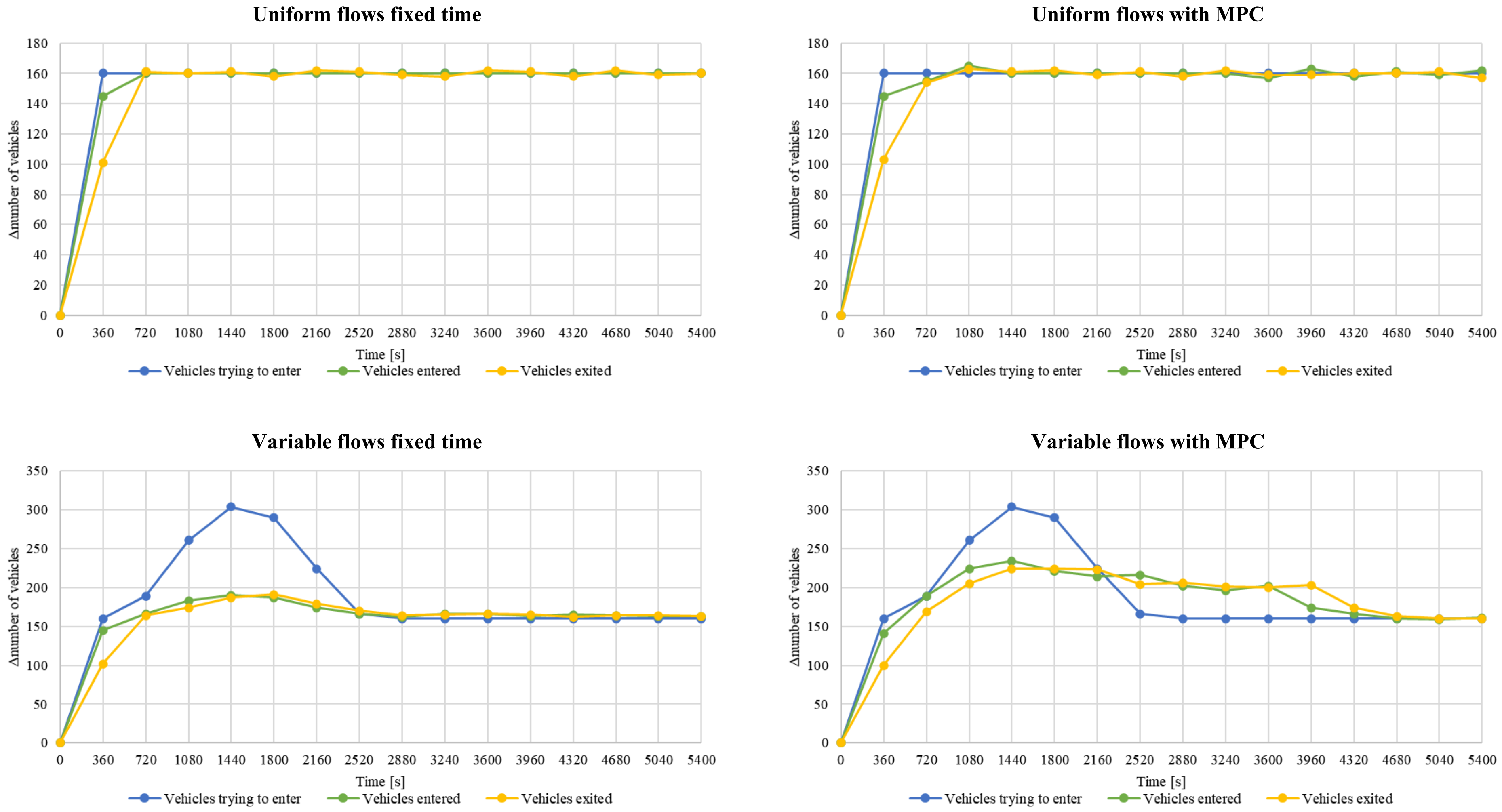


Figure 27: Delta values of vehicles every 360 s, considering different flow trends and control strategies on the arterial modelled with the hybrid traffic flow model.

In this layout, the model's effectiveness regarding the network throughput is confirmed, as it was in the arterial application.

Table 13: Throughput analysis for the network case study modelled with the hybrid model.

NETWORK With a hybrid model	Total vehicles trying to enter	Total vehicles that have entered	Total vehicles that have exited	Number of vehicles waiting to enter at the end of the simulation	Number of vehicles in the network at the end of the simulation
Uniform arrivals	5171	3257	2310	1914	947
Variable arrivals	5173	3242	2316	1931	926

In terms of future perspectives, the model will be compared with different approaches and the validation against real data or data gathered from microsimulation will be considered. Furthermore, the proposed model will be tested on an application of traffic modelling which considers the presence of connected and electric vehicles, taking advantage of the information they provide for the optimisation procedure of the network.

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5.3

Analysis and comparison of traffic flow models: a new hybrid traffic flow model vs benchmark models

ABSTRACT

This paper compares a hybrid traffic flow model with benchmark macroscopic and microscopic models. The proposed hybrid traffic flow model may be applied in the context of mixed traffic flow in which connected vehicles may provide relevant disaggregated information in order to support the efficiency and effectiveness of traffic signal optimisation. However, to reduce the computational effort, macroscopic traffic flow modelling along the link should be performed. The model is based on the combination of the macroscopic cell transmission model and the microscopic cellular automata. The hybrid is compared with three microscopic models, namely the Krauss model, the intelligent driver model and the cellular automata, and with two macroscopic models, namely the cell transmission model and the cell transmission model with dispersion. To this end, three main applications were considered: a link with a signalised junction at the end, a signalised artery, and a grid network with signalised junctions. Since traffic signal optimisation is not the focus of the paper, all signalised junctions were optimised with a pre-timed approach and on the basis of the total delay minimisation criterion. Our results show that the model provides realistic results. Especially in terms of travel times, it shows similar behaviour with respect to the microscopic model. By contrast, it provides less overestimated values of queue propagation than do microscopic models (intrinsically dominated by stochastic phenomena), which are closer to the values shown by the enhanced macroscopic cell transmission model and the cell transmission model with dispersion.

Keywords: macroscopic traffic flow models; microscopic traffic flow models; hybrid traffic flow models.

1. BACKGROUND AND MOTIVATION

Although three main groups of traffic flow models have been identified in the literature, namely macroscopic, mesoscopic and microscopic models (Treiber and Kesting, 2013), hybrid traffic flow models obtained by combining models from two of the above groups have more recently been explored. This paper aims to compare a proposed hybrid traffic flow model (CTM & CA; Storani et al., 2020) with some benchmark macroscopic and microscopic models.

Macroscopic models are based on aggregate variables representing user behaviour as flows, density, and aggregate variables describing supply, such as speed. They can be classified in accordance with the literature depending on the continuous or discrete representation of space and time. The basic model, formulated in the case of continuous space and time, was the first-order model developed by Lighthill and Whitham (1955) and Richards (1956) (the Lighthill-Whitham-Richards – LWR - model). Subsequently, Payne (1971), Ross (1988), and Kerner and Konhäuser (1994) proposed second-order models in order to overcome limitations such as the instantaneous driver's reaction and the impact of the inertial effect, as well as drivers' reactions to the conditions of the traffic context. Finally, within the same group of models, the third-order model was proposed by Helbing (1996), based on three states: vehicle density, mean speed and mean speed dispersion.

In order to solve the first-order model, the cell transmission model (CTM; Daganzo, 1994), a discrete space and time model was introduced. In the class of space-discrete and time-continuous models is the model introduced by Newell (1993), based on a simplified theory of kinematic waves focusing on the representation of inflow/outflow curves, and the state of flow at an extreme. Consistent with simplified first-order kinematic wave theory after Newell, Yperman et al. (2007) proposed the link transmission model (LTM) in which link volumes and link travel times are obtained starting from cumulative vehicle numbers.

In the family of microscopic models there is also a discrete space-based model, namely the cellular automata model (Nagel and Schreckenberg, 1992). In this model each cell (whose size is equal to one car) may be occupied or empty depending on whether or not there is a car. Speed may be represented as an integer variable and the number of cells that a vehicle may advance depends on speed. Microscopic traffic flow models aim to reproduce single vehicle behaviour by considering the disaggregate representation of the position as well as the disaggregate representation of speeds. This class of models has been widely studied by researchers and four main groups may be identified: stimulus–response models, safety distance models, optimal velocity models and physiology-psychology models.

In the case of stimulus-response models, the leading vehicle and follower are analysed as a pair and it is supposed that each vehicle reacts to the stimulus of the leading vehicle. Preliminary studies may be found in Chandler et al. (1958) and Gazis et al. (1961). Although the latter model was better able to model the case of high density by considering the stimulus not only a function of the leader vehicle as in the former model but also as a function of the speed difference between the leader and the follower, this class of model is not reliable in the case of free flow conditions. This shortcoming has given rise to other approaches in the literature (Lee, 1966; Ahmed, 1999; Koutsopoulos and Farah, 2012).

The second group of models was primarily introduced by Gipps (1981) and focused on the safe distance to ensure collision avoidance. Further refinements of the model were subsequently proposed especially by Leutzbach (1988) who took account of different steps in driver behaviour (i.e. perception, decision and braking). Other enhancements of the Gipps model are proposed by the Krauss model (Krauß,, 1998) through the introduction of stochasticity.

The optimal velocity model (Bando et al., 1995) is based on the discrepancy between desired speed and actual speed. The model has been further developed by several authors (Helbing and Tilch, 1998; Jiang et al., 2001; Davis, 2003; Gong et al., 2008; Peng and Sun, 2010). In particular, Treiber et al. (2000) proposed the intelligent driver model (IDM) which takes into account the desired space headway and desired speed.

Finally, there are the action point models first introduced by Michaels (1963), generally referred to as physiology-psychology models. Further developed by Wiedemann (1974), the models are based on different regimes (i.e. free driving, closing in and emergency) depending different thresholds piloting the behaviour of the follower when approaching to the leading vehicle.

Additionally, among microscopic models is the Cellular Automata model (van Wageningen-Kessels et al., 2015), which was introduced by Nagel and Schreckenberg (1992) for traffic flow simulation. The model is based on space discretisation. As regards the movement rule, each cell may be occupied or empty depending on whether or not there is a car and may be occupied by no more than one car, and the number of cells that a vehicle may advance depends on speed (with speed equal to 3 the vehicle may move forward 3 cells).

Finally, mention must be made of hybrid traffic flow models which are based on a combination of two traffic flow models (Burghout, 2004 and Burghout et al., 2005; Burghout et al., 2005; Bourrel (2003) and Bourrel and Henn (2002)). Hybrid traffic flow models were introduced in order to obtain properties of different models at different levels of network layouts. For instance, macroscopic modelling is more suitable than microscopic modelling for simple node representation whereas the latter may be better applied along links in order to appropriately reproduce vehicle interactions and drivers' mutual influences). The proposed hybrid model is based on the combination of the macroscopic cell transmission model (CTM; Daganzo, 1995) and the microscopic cellular automata model (CA; Nagel and Schreckenberg; 1992). The hybrid model (CTM & CA; Storani et al., 2020) appropriately reproduces the queue propagation phenomena and drivers' behaviour in order to be applied in the presence not only of human-driven vehicles but also in the presence of connected and autonomous vehicles supporting the vehicles to infrastructure communication at node networks particularly in the case of traffic control. It should be pointed out that the CA is a disaggregate model for basic microscopic traffic flow analysis, significantly reducing computational effort. As for the CTM, although the model considered is the basic application, several enhancements may be found in the literature. For instance, the CTM with dispersion (CTM – PDM; Cantarella et al., 2015) could be an affordable extension to be considered.

The rest of the paper is organised as follows: in section 2 the models in question are outlined; in section 3 the numerical results with reference to three applications are discussed, and in section 4 conclusions and future perspectives are summarised.

2. DESCRIPTION OF MODELS

In this section the mathematical details of each macroscopic and microscopic model is discussed. In the former class, the cell transmission model (Daganzo, 1995) and the cell transmission model with dispersion (Cantarella et al., 2015) are discussed, whilst in terms of microscopic models our analysis covers the Krauss model (Krauß, 1998), the IDM (Treiber and Helbing, 2002) and the cellular automata (Nagel and Schreckenberg; 1992).

2.1. Macroscopic Models

In this section the analytical details of macroscopic traffic flow models are discussed in greater detail. The following models are considered: the platoon dispersion model (Robertson, 1969) which is adopted in several applications and benchmark tools (TRANSYT, Robertson, 1969) and SCOOT (Hunt et al., 1981).

2.1.1 Cell Transmission Model (CTM)

The cell transmission model was introduced to support the solution of the continuous time – continuous space LWR model, and is based on a finite difference method: the time is divided into constant time intervals, while the road segment is divided into cells of constant length, with an index i increasing in the downstream direction. At each time step, every cell has single values of density and speed (as a function of the speed-density relationship) while the flow between neighbouring cells is constant during the time interval. The most common integration method for LWR models is the *Godunov scheme* (Treiber and Kesting, 2013). This method is based on an exact solution of the continuity equation for one time step, assuming stepwise initial conditions given by the actual densities of the cells. The road is divided into cells of length □x equal to the distance that a vehicle would travel in a free flow condition during one time step. Hence it is equal to the free flow speed multiplied by the duration of the time step (also called clock tick), $V_f \Delta t = \Delta x$. It should be pointed out that the relation between the cell length and the time step complies with the *Courant Friedrich-Lewy* condition ($V_f \Delta t \leq \Delta x$) for the stability of explicit solution methods.

Following the Godunov scheme, the densities are initially averaged for each cell (each cell has a constant density), and from one time step t, to a successive one, t+Δt, the solution evolution is averaged again in order to obtain a piecewise constant solution. The main variables of the method are

k_i density in cell i;
k_j jam density;
Q_i maximum flow rate in cell i;
V_f free flow speed;
ω shock wave speed in congested traffic;
Δx cell length;
Δt time step;
Y_i flow exiting the boundary of cell i.

The density is then obtained as a function of flows at the cell boundaries as in the following:

$$k_i(t+1) = k_i(t) + [Y_{i-1}(t) - Y_i(t)] \cdot \frac{\Delta t}{\Delta x} \tag{1}$$

Finally, the key quantities of the method can be introduced based on the (trapezoidal) fundamental diagram (Figure 1).

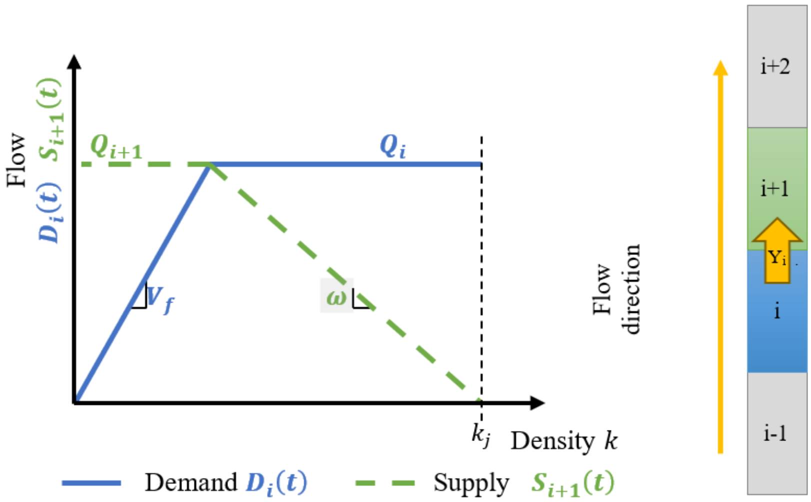

Figure 1: Trapezoidal fundamental diagram – link representation.

The flow of vehicles moving through the boundary between upstream cell i and downstream cell $i+1$ (see Figure 2) is given by the result of a comparison between the maximum flow that can be sent (that is the demand) by cell i (upstream of the boundary):

$$D_i(t) = \min(Q_i, V_f \cdot k_i) \tag{2}$$

and the maximum flow that can be received (that is the supply) by the downstream cell $i+1$:

$$S_{i+1}(t) = \min\left(Q_{i+1}, \omega \cdot (k_j - k_{i+1})\right) \tag{3}$$

Since every cell has a maximum density (k_j), the incoming flow is not only constrained by the maximum value Q_{i+1}, but also by the difference between the maximum density and the current density $(k_j - k_{i+1})$, which captures the spillback phenomena and is able to model the effects of horizontal queuing.

Therefore, in accordance with the *Godunov scheme*, the flow $Y_i(t)$ can be rewritten in accordance with the demand (sending)-supply (receiving) rule of the cell transmission model as:

$$Y_i(t) = \min(D_i(t), S_{i+1}(t)) \tag{4}$$

2.1.2 CTM with dispersion

First of all, some details about the platoon dispersion phenomenon should be supplied. Let

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

Robertson's model takes the following mathematical form:

$$q_d(j) = Fq_0(j-t) + (1-F)q_d(j-1) \quad (5)$$

where F, the smoothing factor, is given by

$$F = (1 + \alpha\beta T)^{-1} \quad (6)$$

Two main conditions may arise depending on the F values: i) if the distance between two successive junctions is high, the travel time is high and F tends to zero; in this case uniform flow profiles are observed and the two successive junctions are not interacting; ii) otherwise, when the distance between them is low they are interacting; suppose that the travel time tends to zero, the smoothing factor tends to 1 and then $q_d(j) = q_d(j-1)$.

The cell transmission model with dispersion was modified to include the Drake speed-density relationship, modelling the dispersion of the platoon formed upstream of a traffic light.

Let:

t be the time step
Δt, the duration of the time step
Δx, the length of the cells
Q_i, the maximum flow rate in cell i
$k_i(t)$, the density in cell i at time step t
k_j, the jam density
k_m, the traffic density at maximum flow
V_f, the free flow speed and
ω, the shock wave speed in congested traffic.

For each cell, at each time step, the demand flow is given by:

$$D_i(t) = \min\left(Q_i, V_f \cdot k_i(t)\right) \tag{7}$$

The supply flow from the immediate downstream cell is given by:

$$S_{i+1}(t) = \min\left(Q_{i+1}, \omega \cdot \left(k_j - k_i(t)\right)\right) \tag{8}$$

The speed of the outgoing flow at each cell is given by the Drake speed-density relationship as:

$$v_i(t) = V_f \cdot e^{-0.5\left(\frac{k_i(t)+k_{i+1}(t)}{2\,k_m}\right)^2} \tag{9}$$

The flow from each cell derived from the Drake speed-density relationship is given by:

$$X_i(t) = k_i(t) \cdot v_i(t) \tag{10}$$

The flow to the downstream cell is then calculated as:

$$Y_i(t) = \min\left(D_i(t), S_{i+1}(t), X_i(t)\right) \tag{11}$$

To update the density at the next time step, for each cell i:

$$k_i(t+1) = k_i(t) + [Y_{i-1}(t) - Y_i(t)] \times \frac{\Delta t}{\Delta x} \tag{12}$$

Since the flow to the downstream cell is limited by the supply and demand of each cell from the basic CTM, the resulting outcoming flow can be either equal to or lower than them, depending on the parameters of the Drake speed-density relationship.

As an example, given the next set of parameters, the following fundamental diagrams (see Figures 2, 3 and 4) are obtained:

$\Delta t = 1\ s$
Δx = 15 m
Q_i = 1800 veh/h
k_j = 200 veh/km
k_m = 55 veh/km
V_f = 15 m/s
ω = 5 m/s

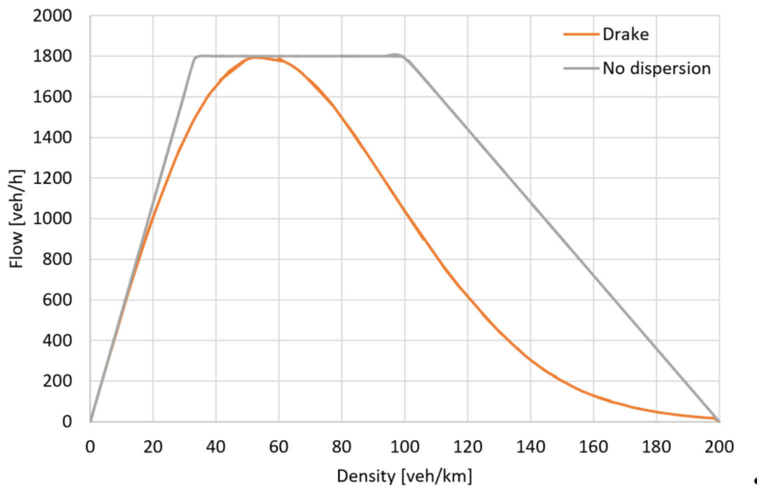

Figure 2: fundamental diagram: flow–density relationship

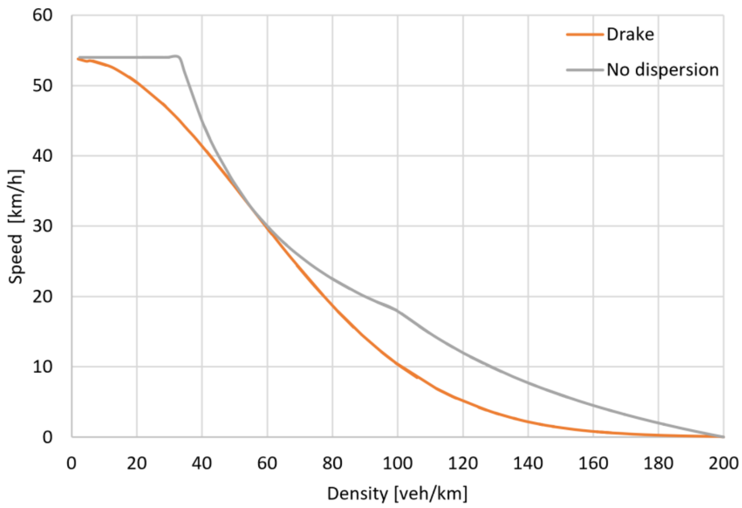

Figure 3: fundamental diagram: speed–density relationship

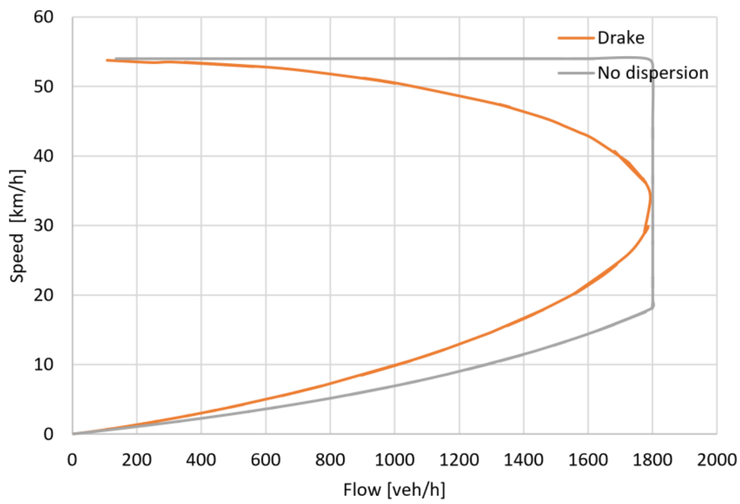

Figure 4: fundamental diagram: speed – flow relationship

2.2 Microscopic Models

2.2.1 KRAUSS'S MODEL

Several classes of models may be identified at the microscopic level, amongst which are safety distance models. The definition of this distance is crucial in order to avoid collisions between vehicles, and these models are based on the idea that following vehicles try to respect the safety distance from the leading vehicles. The main contributions in the literature concern works by Kometani & Sasaki (1959), Gipps (1981) and Krauss (1997). The model proposed by Gipps is a multiregime model able to reproduce the free flow driving condition and the car following regime. The two main limitations of the Gipps model concern its unsuitability in the case of unstable traffic flow conditions and the possibility that the model has no solutions due to its analytical formulation. Therefore the Krauss model, which can overcome such limitations, may be considered an alternative approach to that of Gipps. In accordance with the Krauss model, the safe speed is given by the following expression:

$$v_{safe} = v_l(t) + \frac{g(t) - v_l(t)t_r}{\frac{v_l(t) + v_f(t)}{2b} + t_r} \tag{13}$$

where

$v_l(t)$ is the speed of the leading vehicle at time t
$g(t)$ is the gap between leader and follower at time t
t_r is the drivers' reaction time and
b is the max value of deceleration.

Finally, the desired speed is given as the minimum between the maximum speed, the speed that can be achieved by the vehicle according to its acceleration, and the safe speed as defined above. That is:

$$v_{des} = \min\left[v_{max}, v + at, v_{safe}\right] \tag{14}$$

2.2.2 INTELLIGENT DRIVER MODEL

Next are the continuous time models, based on first-order differential equations. The two main contributions in the literature concern the optimal velocity model (OVM) (Bando et al., 1995) and the intelligent driver model (IDM) (Treiber et al., 2000).

In the above class of models, it is supposed that each vehicle has a desired speed depending on the distance between vehicles or the difference between the speed of a pair of vehicles, namely the leader and follower. The OVM refers to the former case, whereas the IDM to the latter.

With regard to the OVM, it must be highlighted that the acceleration of the vehicle depends on the desired speed and can be formulated as

$$a_n(t) = \frac{V\left[\Delta x_n(t)\right] - v_n(t)}{\tau} \tag{15}$$

where

n is the following vehicle;
Δxn(t) is the spacing between the leading and the following vehicle;
vn is the speed of the vehicle;
τ is driver sensitivity.

However, one of the main limitations of the model concerns the unrealistic (high) values of maximum acceleration when the drivers' sensitivity is of the same order as the drivers' reaction time, which depends on the difference between the vehicles' speeds (Treiber et al., 2000) that is not considered. In general, in the IDM formulation, acceleration is a continuous function of speed, distance and speed difference.

In particular, let

a0 be the maximum acceleration;
v0, the drivers' desired speed;
δ, a parameter to be calibrated and
Δx0, the desired distance, a function of the follower's speed and the speed difference.

The final formulation of acceleration is composed by two terms, the free flow term and the interaction term as detailed in the following:

$$a_n(t) = a_0 \cdot \left\{ 1 - \left[\frac{v_n(t)}{v_0}\right]^{\delta} - \left[\frac{\Delta x_0\left(v_n(t), \Delta v_n(t)\right)}{\Delta x_n(t)}\right]^2 \right\} \tag{16}$$

2.2.3. CA - Nagel-Schreckenberg Model

The approach adopted was proposed by Nagel and Schreckenberg (1992) who developed a model which was discrete in time and space, considering a single lane road and dividing it into cells that can have two states (occupied or empty), and a length equal to the length of a vehicle. Every vehicle occupies a cell, which has an "occupied" state. At the next time step, if a vehicle moves to another downstream cell, its speed has integer value (ranging from zero to a maximum value) which represents the number of cells that the vehicle moves downstream, from position $x_i(t)$ to $x_i(t+1)$. Because of this, the behaviour of an upstream vehicle i is influenced by a downstream one $i+1$, if the gap g_i between them is smaller than the speed v_i of the upstream vehicle. The speed can be converted to a dimensional value through multiplying it by both the ratio of the cell length and the time step. The acceleration is equal to 1 or 0, thus increasing, or otherwise, the integer value of the speed at each time step.

The model also contains a stochastic component[4] called the *dawdling probability,* in which, with probability p, a vehicle can remain at the same speed (if it was accelerating) or decelerate. This allows us to model stop-and-go waves in congested traffic, varying the flow-density relation as well.

The model is applied by following four rules. At each time step, and for each vehicle i on the road, their speed $v_i(t)$ and position $x_i(t)$ are updated as:

Slowing down Obtain the *gap* at time t. If **speed** > *gap*, then slow down.

Acceleration If **speed** < *gap* and **speed** < **max speed**, then accelerate by one.

$$v_i^*(t+1) = \min\,(v_i(t)+1, v_0, g_i) \tag{17}$$

Randomization (Dawdling rule) If **speed** > 0, then with probability p (dawdling probability, that is the random term) reduce it by one.

$$v_i(t+1) = \begin{cases} max\,(v_i^*(t+1)-1) & with\,probability\,p \\ v_i^*(t+1) & otherwise \end{cases} \tag{18}$$

Car motion Update the position

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{19}$$

The Nagel-Schreckenberg Model is not the only type of cellular automata. There are also other types, such as the Barlovic model (Barlovic et al., 1998) which adds a “slow to start” rule, the Kerner Klenov and Wolf model (Kerner et al., 2002) which considers the cell length equal to 0.50 m (thus considering an acceleration of 0.5 m/s2) and adds other parameters to model synchronized traffic in accordance with the three-phase traffic theory proposed by Kerner, and the same model but changing the safe speed rule by using a discretized version of the safe speed of the Gipps model (considering a braking deceleration parameter). In this study, the basic model remains that of Nagel-Schreckenberg, but given that each cell has a length of 2.50 m, the randomization rule is applied only if the speed exceeds a minimum value greater than 0.

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[4] Further details are provided in Appendix A.

2.3. Hybrid Traffic Flow Models

2.3.1. CA – CTM HYBRID

The general architecture of the proposed hybrid model consists of the combination of a macroscopic CTM with a meso-microscopic CA for each link (see Figure 5). The CA is used to model the traffic flow at disaggregate level at the junction, whereas the CTM models the traffic flow at aggregate level along the link. The transitions from CA to CTM and vice versa are based on the introduction of a transition zone. Both models have the same simulation time step of 1 s to obtain a consistent queuing formation and backend propagation of the congestion.

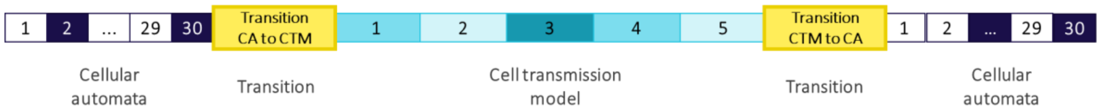

Figure 5: Example of the hybrid link representation

3. NUMERICAL RESULTS

In this section the proposed hybrid traffic flow model and the benchmark macroscopic and microscopic models are compared. To this end, three main layouts were considered with reference to an urban context:

- a link with a traffic signal (see section 3.1);
- an arterial consisting of three signalised junctions (see section 3.2);
- a nine-node grid layout with signalised junctions (see section 3.4).

All results were analysed in terms of travel time spent, max and mean queues.

The proposed traffic flow model was implemented in a code provided by the authors and developed in MATLAB (the Release 2020 was adopted) whereas the microscopic and macroscopic traffic flow analyses were run respectively in SUMO and TRANSYT16®TRL; all simulations were run on machine which has an Intel(R) Core(TM) i7-4510U CPU with a base speed of 2.6GHz, and 8GB of RAM

3.1. Link

This numerical application was run considering a link 300 metres long with a signalised junction at the end. In terms of demand, to test the impact of the undersaturation and oversaturation conditions, three different entry flows were tested: the first was 400 veh/h, the second, 800 veh/h, and the third, 1200 veh/h. In Figure 6 the layout in terms of the hybrid model is displayed, and the details of the cellular automata model and cell transmission model are shown.

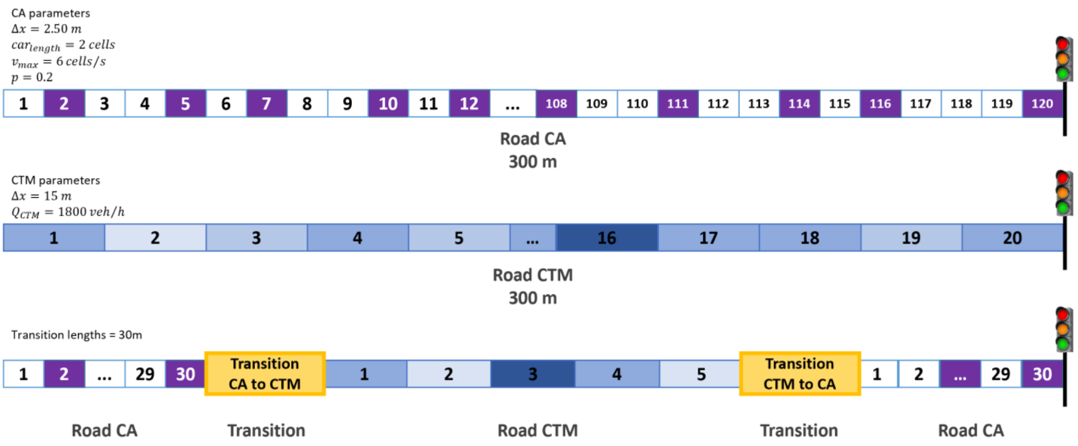

Figure 6: Urban link layout with signalised junction

Comparison among models highlights that in the case of low demand (undersaturation) all models provide very similar results. In particular, the proposed hybrid model CA&CTM is very similar to the other benchmark models with respect to both indicators of travel times and queues. However, in the case of higher demand (oversaturation), microscopic models underestimate travel times whereas they overestimate queues with respect to the other models. In particular, the proposed hybrid model behaves very similarly to the CTM and CA models. Further details regarding the numerical results are shown in Table 1 below.

Table 1: Numerical results of the link application

	Travel time [veh s]	Max queue [veh]	Mean queue [veh]
Scenario Flow 1 [400 veh/h]			
KRAUSS$_{SUMO}$	493.08	6.10	1.69
IDM$_{SUMO}$	480.55	5.90	1.51
CA	453.25	5.90	1.683
CTM	449.37	5.98	1.651
PD&CTM	456.05	5.11	1.466
CA&CTM	***450.10***	***5.98***	***1.748***
Scenario Flow 1 [800 veh/h]			
KRAUSS$_{SUMO}$	1104.40	14.48	4.91
IDM$_{SUMO}$	1072.48	14.34	4.30
CA	1023.45	11.90	4.083
CTM	1013.69	11.98	3.408
PD&CTM	1064.12	10.95	3.388
CA&CTM	***1022.38***	***11.98***	***4.254***
Scenario Flow 1 [1200 veh/h]			
KRAUSS$_{SUMO}$	4490.43	75.88	58.34
IDM$_{SUMO}$	5076.93	75.20	61.31
CA	15585.65	44.50	38.278
CTM	15032.90	32.18	13.067
PD&CTM	17907.33	6.15	2.412
CA&CTM	***16357.43***	***34.50***	***26.130***

3.2. Artery

In this section the results concerning the artery with three successive signalised junctions (see Figure 7) are considered. The entry flows in each node are displayed in the figure below. In particular, the distance between successive junctions is equal to 810 meters, while the sources and sink arcs have 90 meters. The parameters of the models are: free flow speed = 15 m/s, wave speed = 5 m/s, outflow capacity = 2000 veh/h, jam density = 200 veh/km, CTM cell length = 15m, CA cell length = 2.50 m, dawdling probability = 0.266, min CA speed to apply dawdling = 2 cells/s = 5 m/s.

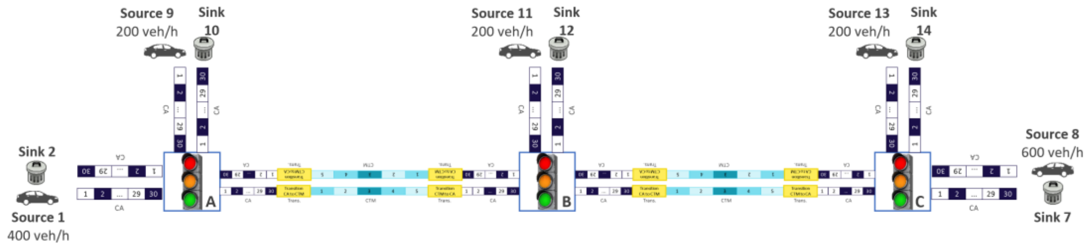

Figure 7: Artery with three successive signalised junctions

The results are summarised in Table 2. It may be observed that, unlike the previous case, the travel times of microscopic models are higher than those of other models, and the hybrid model provides very similar results to those of microscopic models, especially to the CA model in which travel times fall between those of the Krauß (travel time is 213984.21 veh h) and IDM (travel time is 154512.18 veh h).

Table 2: Numerical results of the artery application

Time	Travel time [veh s]	Max queue [veh]	Mean queue [veh]
$KRAUSS_{SUMO}$	213984.21	84.80	63.88
IDM_{SUMO}	154512.18	113.81	89.23
CA	199872.31	10.60	1.70
CTM	154980.45	7.01	0.89
PD&CTM	155520.15	9.41	1.98
CA&CTM	***197136.17***	***9.35***	***1.16***

However, as in the previous case, queues are overestimated by microscopic models, especially by the KRAUSS model and the IDM, whereas very similar values are shown by the other models (including the microscopic CA model).

3.3. Network

The third application concerns a network layout in which all links have one lane in each direction and the saturation flow of each lane is assumed equal to 2000 PCU/h. Regarding link length, links connecting node 5 with other nodes (2-5, 4-5, 5-6, 5-8) are 405 metres long (equal to 27 cells, each 15 m long in the CTM), the other links on the network are 810 metres long (equal to 54 cells, each 15 m long in the CTM), and finally the links connecting the entry/exit nodes with the network (the connectors) are 90 metres long. A scheme of the network layout is shown in Figure 8 and the details of the entry-exit matrix are displayed in Table 3.

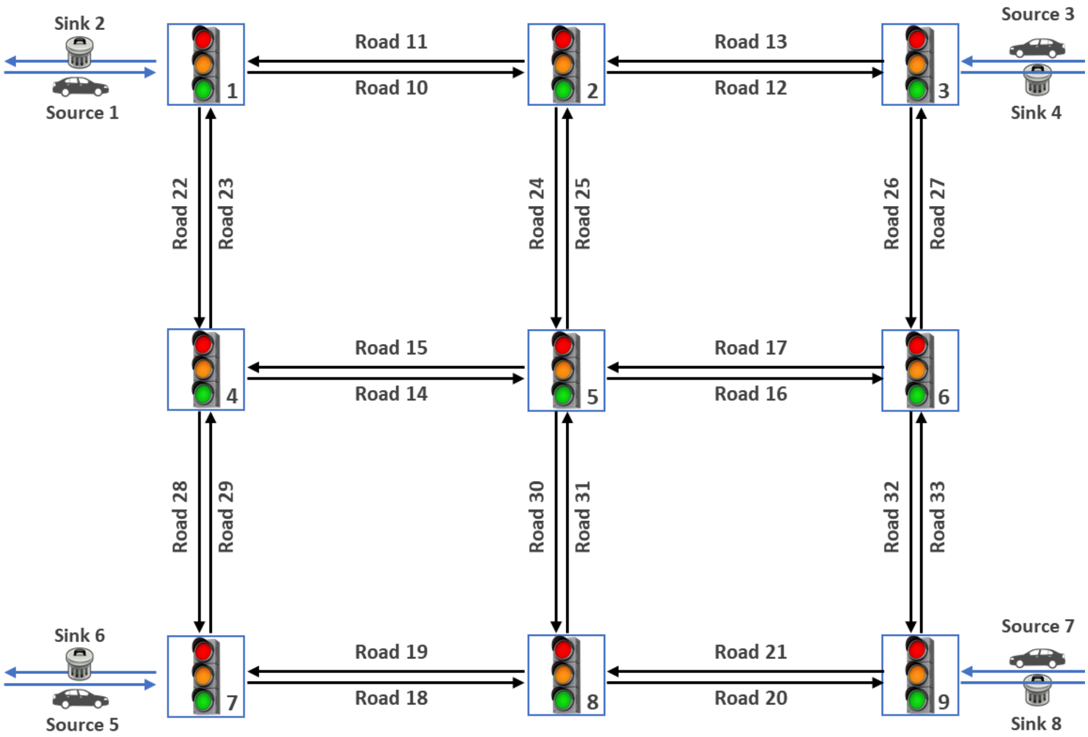

Figure 8: representation of the nine-node grid network layout modelled with the CA & CTM model

The network has signalised junctions at each node, while the solution for the optimisation control problem is based on the criterion of minimising total delay, considering green times and offsets as network decision variables. For this application, path choice modelling has an explicit (enumeration) approach (see Cascetta, 2009).

Table 3: Entry-exit matrix of the OD pairs for the network layout

		Exit [PCU/h]				TOTAL
		2	**4**	**6**	**8**	
Entry [PCU/h]	**1**	-	480	382	336	1198
	3	433	-	288	382	1103
	5	480	624	-	422	1526
	7	336	575	433	-	1344
TOTAL		1249	1679	1103	1140	**5171**

Results are displayed in Table 4 below. It may be observed that, as in the previous case of the artery, the travel times are very similar to the case of microscopic models and generally to the CA model.

Table 4: Numerical results of the nine-node application

Time	Travel time [veh s]	Max queue [veh]	Mean queue [veh]
$KRAUSS_{SUMO}$	213984.02	174.79	125.06
IDM_{SUMO}	154512.15	115.40	77.11
CA	199872.37	48.00	5.88
CTM	154980.12	28.33	3.08
PD&CTM	155520.24	25.93	2.92
CA&CTM	**197136.42**	**33.13**	**4.62**

With regard to the number of vehicles in the queue, this value is still overestimated in the case of microscopic models. However, the hybrid model provides very similar results to the case of the CA model (slightly lower due to the smoothing effect of the CTM).

4. CONCLUSIONS AND FUTURE PERSPECTIVES

This paper compared a proposed hybrid traffic flow model with the three main approaches generally used to describe traffic flow, namely macroscopic, microscopic and mesoscopic models. Macroscopic models are usually adopted for wide-area analysis whereas microscopic models are adopted for sub-area analysis, especially in the case of critical junctions; mesoscopic models may be indifferently adopted for both wide-area and sub-network analysis.

However, hybrid models based on combining two models at different scales are being increasingly used. For instance, wide areas may be directly analysed by combining macroscopic models with microscopic models or mesoscopic models with microscopic models. Furthermore, hybrid traffic flow modelling may also be suitable when the researcher is interested in representing links and nodes at different scales; in other words, microscopic link representation allows for consideration of driver behaviour, and macroscopic node representation avoids single manoeuvre analysis at junctions. Alternatively, specific analyses may require macroscopic link representation, in the case in which driver behaviour may be neglected, but microscopically represented nodes, when information about vehicles approaching signalised junctions is required. This may well be the case of mixed traffic flow analysis in which flow composition is based on human-driven vehicles and connected and autonomous vehicles, and the latter need to be sketched[5] in order to collect all information required for traffic signal decision variables optimisation.

The main focus of the paper was on comparing the proposed hybrid traffic flow model (CA&CTM), based on combining a macroscopic cell transmission model (CTM; Daganzo, 1994) for link representation and a microscopic cellular automaton (CA; Nagel and Schreckenberg, 1992) node representation and some benchmark macroscopic and microscopic models. While the reliability of the CTM is amply studied in the literature mainly with reference to queue propagation, CA reliability requires further investigation.

In terms of the macroscopic approach, the model was compared with both the CTM and the CTM with dispersion (Cantarella et al., 2015). Indeed, dispersion may not be directly observed in macroscopic modelling and a specific analytical representation must be included in the CTM. However, as dispersion is endogenously present in microscopic models, consistent traffic flow representation is expected with respect to the CA and especially the CTM & CA. With regard to the microscopic approach, the proposed model was compared with both the Krauss model (Krauß, 1998) which is considered the stochastic enhancement of the Gipps model (Gipps, 1981), the reference model in the context of the collision avoidance class of approaches, and with the intelligent driver model (IDM; Treiber, M., Helbing, 2002) which is based on the idea of combining the ability to reach the desired speed limit in a traffic-free situation with the ability to identify how much braking is necessary to steer clear of any collision situations.

To this end three main applications were considered: i) a link with a signalised junction required to introduce capacity constraints to traffic signal stages and suitable for the preliminary interpretation of queuing phenomena; ii) an artery comprising three successive signalised junctions suitable for queuing and dispersion analysis; iii) a more complex grid network with signalised junctions required to capture queue spillbacks in a more complex layout of urban interacting junctions. All signalised junctions were optimised with a pre-timed approach and according to the total delay minimisation criterion. All results were analysed in terms of travel time, max and mean queue.

In the first application, numerical results were analysed with reference to three different entry flow values in order to observe the different model behaviour in

[5] Connected and autonomous vehicles (CAV) may be used in two ways: first, as probe vehicles providing information about traffic flow conditions, and secondly to make information available about themselves.

undersaturation and oversaturation conditions. Comparison shows that in the case of low demand all models provide very similar results. However, in the case of higher demand, microscopic models underestimate travel times whereas they overestimate queues with respect to the other models. In general, the hybrid CA&CTM behaves very similarly to the CTM and CA models, with higher values of travel times and lower values of queues.

In the signalised artery, our results show that, unlike the link layout case, the travel times of the CA model lie between the values provided by the KRAUSS model and the IDM, while the KRAUSS model clearly overestimates travel times. Queues, as in the previous case, are overestimated by microscopic models, whereas very similar values are shown by the other models (including the microscopic CA model).

Finally, the results of the network layout were analysed. In terms of travel times, the proposed CA&CTM model provided very similar results to those of microscopic models, especially to the CA which has an intermediate value between the KRAUSS model and the IDM. By contrast, in terms of queue modelling, it was again observed that microscopic models clearly overestimate queues, while the proposed model behaved very similarly to the CA model.

Two main research fields are considered worthy of further exploration: the first task would be to investigate application of the proposed model to the context of connected and autonomous vehicles, also in the presence of human-driven vehicles; secondly, the proposed model could be profitably applied to a real case study.

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6 CONCLUSIONS AND FUTURE WORKS

On the traffic control problem, the implementation of two simultaneous traffic control strategies: the link metering with a scheduled synchronisation approach (e.g. network decision variables, green timings, offsets, stage sequences, which are all optimised together), applied to the considered test network proved the effectiveness of the proposed framework using the queue lengths and the travel times as indicators for each path. However, such strategy becomes increasingly complex as the network is larger, making it less convenient for an online application.

When considering the presence of Electric Vehicles on the network, a methodological framework was obtained to support the design of a control strategy at signalised junctions. A link-based macroscopic energy consumption function was estimated based on a microscopic energy consumption model, which was calibrated with real-world vehicle trajectory and power data collected nearby two signalised junctions. To this aim, a dedicated tool (TET-TCSA) has been developed to extract from a large dataset the individual trajectory of the vehicles which cross the considered area. The tool was integrated with a microscopic energy consumption model, VT-CPEM, and the extracted data was applied to calibrate VP-CPEM model parameters. The results of such calibration show an error lower than 2% between the simulated and observed energy consumed and recovered. The calibrated model was run in a quasi-Monte Carlo framework to simulate the microscopic energy consumption of individual vehicles, which allowed for the estimation of a link-based macroscopic energy consumption function. This function was used to solve a multi-objective traffic control problem, being the Total Time Spent the second objective. A Cell Transmission Model was used as the model to define the optimisation problem. This analysis was performed considering real data trajectories collected on the Salaria road in the city of Rome (Italy), while the traffic data was derived through the application of the queuing theory at signalised junctions.

The numerical applications considered a penetration rate of 100% of electric vehicles. In general results encourage the multi-objective optimisation even if the considered context of congestion based on undersaturation conditions slightly highlights the effectiveness of the proposed approach.

When considering Connected Autonomous Vehicles (CAV), a traffic control strategy composed by two sub models was developed: one referred to the centralised traffic management the other one is characterised by the link metering strategy; while for the vehicle control, a speed optimisation procedure based on Green Light Optimal Speed Advisory (GLOSA) has been applied, referred 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), testing three scenarios: 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 TCMULTI and S-GLOSA therefore it is verified that S-GLOSA provides worse performances than the TCMULTI method; finally, the combination between TCMULTI and S-GLOSA provide, as expected, the best results.

The developed hybrid traffic flow model (H – CTMCA) was obtained by combining a macroscopic approach to model links with a microscopic approach to model nodes. To this end, two traffic flow models were adopted: a simplified microscopic Cellular Automata model (CA; Nagel and Schreckenberg, 1992), and a macroscopic Cell Transmission Model (CTM; Daganzo, 1994). To our knowledge, the combination has not yet been investigated. Within the model, an alternative approach to the representation of the transition region is described.

The proposed hybrid model proved suitable for analysing traffic flow phenomena, and can also be adopted for traffic control in both cases: in the context of multi objective optimisation (for instance based on surrogate indicators) and with the presence of connected vehicles.

This model was applied to test it, considering three main applications:

1. a ring layout, to test and verify the local consistency of the model, describing the conservation of the vehicles through local interfaces;
2. an arterial with two traffic control strategies: a simple fixed optimisation procedure and a model predictive control strategy. The latter was used to test the impact of a different and more complex procedure using traffic light timings and offsets as optimisation variables;
3. a nine-node signalised network, to test the impact of a different and more complex network layout.

When the model was coupled with a traffic control strategy, two main results were achieved: first the model demonstrated suitable with a simple fixed-time strategy and a more complex MPC for traffic signal design; second, the two traffic flow models, the CTM and the proposed H – CTMCA model were compared, and both models have a similar execution times during the optimization process.

With the nine-node grid network, the hybrid model was tested on a more complex layout. In this layout, the model's effectiveness regarding the network throughput is confirmed, as it was in the arterial application.

This hybrid traffic flow model (H – CTMCA) was compared with some benchmark macroscopic and microscopic models. While the reliability of the CTM is amply studied in the literature mainly with reference to queue propagation, CA reliability requires further investigation.

In terms of the macroscopic approach, the model was compared with both the CTM and the CTM with dispersion (Cantarella et al., 2015). Indeed, dispersion may not be directly observed in macroscopic modelling and a specific analytical representation must be included in the CTM. However, as dispersion is endogenously present in microscopic models, consistent traffic flow representation is expected with respect to the CA and especially the CTM & CA. With regard to the microscopic approach, the proposed model was compared with both the Krauss model (Krauß, 1998) which is considered the stochastic enhancement of the Gipps model (Gipps, 1981), the reference model in the context of the collision avoidance class of approaches, and with the intelligent driver model (IDM; Treiber, M., Helbing, 2002) which is based on the idea of combining the ability to reach the desired speed limit in a traffic-free situation with the ability to identify how much braking is necessary to steer clear of any collision situations.

To this end three main applications were considered:

i) a link with a signalised junction required to introduce capacity constraints to traffic signal stages and suitable for the preliminary interpretation of queuing phenomena;

ii) an artery comprising three successive signalised junctions suitable for queuing and dispersion analysis;

iii) a more complex grid network with signalised junctions required to capture queue spillbacks in a more complex layout of urban interacting junctions. All signalised junctions were optimised with a pre-timed approach and according to the total delay minimisation criterion. All results were analysed in terms of travel time, max and mean queue.

In the first application, numerical results were analysed with reference to three different entry flow values in order to observe the different model behaviour in undersaturation and oversaturation conditions. Comparison shows that in the case of low demand all models provide very similar results. However, in the case of higher demand, microscopic models underestimate travel times whereas they overestimate queues with respect to the other models. In general, the hybrid CA&CTM behaves very similarly to the CTM and CA models, with higher values of travel times and lower values of queues.

In the signalised artery, our results show that, unlike the link layout case, the travel times of the CA model lie between the values provided by the KRAUSS model and the IDM, while the KRAUSS model clearly overestimates travel times. Queues, as in the previous case, are overestimated by microscopic models, whereas very similar values are shown by the other models (including the microscopic CA model).

Finally, the results of the network layout were analysed. In terms of travel times, the proposed CA&CTM model provided very similar results to those of microscopic models, especially to the CA which has an intermediate value between the KRAUSS model and the IDM. By contrast, in terms of queue modelling, it was again observed that microscopic models clearly overestimate queues, while the proposed model behaved very similarly to the CA model.

FUTURE WORKS

The proposed hybrid traffic flow model (H – CTMCA) will be validated against real data or data gathered from microsimulation. Furthermore, it will be tested on an application of traffic modelling which considers the presence of connected and autonomous vehicles, taking advantage of the information they provide for the optimisation procedure of the network. Such application would consider different penetration rates of such connected vehicles. To this end, a choice behaviour model would be appropriate to define the effective penetration rates for these applications. In this case, a real case study could be used to survey the potential users of connected vehicles, and thus obtain the utility function for this vehicle type. This function can be applied to an origin-destination matrix (de Luca, S., Di Pace, R., 2018) and obtain a more realistic penetration rate. This methodology of data acquisition and analysis to specify, calibrate, and validate a choice behaviour model was applied to analyse the user willingness to buy an electric vehicle, as can be seen in Appendix A. However, if the aim is to test the willingness to buy a connected autonomous vehicle, a potential problem that may arise could be the lack of information or experience of the respondents with such vehicles. This could result in incorrect or casual responses on the surveys; therefore, the subsequent choice model would not be appropriate.

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About the author

Facundo Storani is an Argentinean researcher who achieved a double M.Sc degree in Civil Engineer on 2017 at the University of Salerno, Italy, and at the University of Cordoba, Argentina. His final thesis focused on users' perception and willingness to buy electric vehicles. On the same year, he won a Ph.D. scholarship, and became a student in Transportation Engineering at the Department of Civil Engineering of the University of Salerno. There, he was mentored by Professors Roberta Di Pace and Stefano de Luca, under the supervision of Professors Giulio Erberto Cantarella and Fernando Fraternali. During his Ph.D., he was a vising student at the Delft University of Technology, under the supervision of Professor Bart De Schutter. At Salerno he contributes on the courses of "Transportation System Theory", "Transportation System Design", "Transportation Planning" and "Transportation Techniques and Economics" while also a co-supervisor of transportation Bachelor theses. He participated in several seminars, conferences and summer schools related to Transport Engineering to learn, improve, and extend his knowledge on smart and sustainable mobility. He is also co-author on some publications in scientific journals, book chapters and international conference proceedings.

His research field involves discrete choice models, travel behaviour, and transportation systems simulation and analysis, specifically traffic flow modelling and traffic control. Recently he is participating on several research projects on Cooperative Intelligent Transportation Systems while cooperating with ITS LAERTE Laboratory of the University of Naples.

Facundo's main skills are: the identification of the Key concepts and the subjects in research questions formulation; the work scheduling; the ability in data collection, organisation and interpretation; the ability in model development and results presentation

APPENDIX

The impact of attitudes and perceptions in modelling users' willingness to purchase electric vehicles in immature markets

ABSTRACT

The paper aims to investigate the different attributes that may influence the choosing decision on the purchase of an electric vehicle. In particular, the research focuses on the analysis and comparison of two "immature" markets: the Argentinean and the Italian context. From the methodological point of view, the main purpose relies on the survey data collection and data analysis and modelling. Furthermore, the results achieved from a specific Stated Preferences survey carried out on a sample of Argentinian and Italian university students are shown. Therefore, the research aims to quantify and discuss the main determinants of the choice phenomenon through the specification and calibration of three different choice model based on the Random Utility Theory:

- A Mixed Multinomial Logit Model (MMNL0) with random parameters distribution.
- A Mixed Multinomial Logit Model (MMNL).
- A Hybrid Choice Model (HCM) in which users' attitudes and perceptions are properly modelled with latent variables estimations.

1. INTRODUCTION AND RESEARCH GOALS

Over the past years, there has been a constant growth of the market share of EVs and are expected to progressively reduce technology costs in the forthcoming years, making EVs an increasingly attractive option. They offer a clean alternative to internal combustion engines by having zero tailpipe emissions (reducing the air pollution from fuel combustion) and limiting noise, both key issues in heavily dense urban areas. The relevance of EVs regarding these concerns are demonstrated by the role that cities assume on stimulating the deployment of EVs; as in 2015 nearly a third of global EV sales took place in 14 cities worldwide (Hall, Moultak and Lutsey, 2017). The market penetration of EVs tends to be higher in major global urban centres compared to their country averages.

In accordance with the automakers, many governments have initiated policies for reducing CO2 emissions by stimulating the production, introduction and adoption of EVs (Brady and O'Mahony, 2011). Currently, the global electric car stock surpassed 2 million of vehicles in 2016 after crossing the 1 million thresholds in 2015. Norway, with the 29% market share shows the most successful deployment of electric cars, followed by the Netherlands, with a 6.4% market share, and Sweden with 3.4%. China, France and the United Kingdom all have electric car market shares close to 1.5% and the United States about the 1%. In 2016, China was the largest electric car market, accounting for more than 40% of the electric cars sold in the world and more than double the amount sold in the United States (International Energy Agency, 2017).

However, it should be argued that markets may be classified in different ways in terms of maturity, and customers may exhibit different behaviours depending on the context. In particular, two types of markets could be distinguished: "mature" and "immature".

The former market is characterized by a clear perception of the advantages and disadvantages of the EVs, and is characterized by an increasing EVs offer and market share, and by systematic investments in charging infrastructures. By contrast, the "immature" markets may be further differentiated in markets "aware" and "not aware". In the former, it can be assumed that the potential users have a clear perception of EVs, but the electric mobility has negligible market shares and is not supported by adequate technological infrastructures. In the "not aware" market, the potential users have knowledge of the technology, but EVs are not even commercialized and no charging infrastructures exist. The markets differ for the different perception of EVs as a potential automotive solution.

Within the above-mentioned context, it is of great interest to comprehend the main determinants of these "immature" markets and also to understand the differences between two "immature" markets. The interpretation of the users' behaviour towards these innovative technologies is a fundamental support for industrial and marketing strategies.

The paper aims to investigate the attributes/determinants that may influence the decision on choosing an electric vehicle in two different "immature" markets such as Argentina and Italy. The main purposes of the paper rely on (i) the survey data collection, (ii) data analysis, (iii) purchase behaviour modelling.

The importance of the case study builds in the fact that in both countries the EVs' market is in its early beginnings; in Italy are being offered by most of the automakers but its market share is still insignificant, whereas in Argentina there are no battery electric vehicles currently offered and only one hybrid electric vehicle (the Toyota Prius) is available to purchase, moreover no charging stations exist. Nevertheless, on 2017 the Argentinean national government reduced the import tariffs from 35% to 2% for hybrid cars and to 0% to electric ones with the aim to stimulate the creation of a framework that allows the diffusion of these innovative technologies and in this way to encourage the development of a local industry of these characteristics (Nomenclatura Común Del Mercosur. Decreto 331/2017).

Moreover, the paper investigates the behaviour of young potential users (university students). If on the one hand they could not be car buyers in the immediate future and could not have not ever had experience in buying a car, on the other hand they represent the real future market, the future market of which industry and decision makers should be aware.

Different questioning approaches were investigated and a specific questionnaire based on statements related to the psychometric indicators was designed. Thus, users' attitudes and perceptions that may affect their willingness in purchasing an EV were collected. From the methodological point of view, the role of attitudes and of the perception towards EVs advantages/barriers were finally analysed through the specification of two Mixed Multinomial Logit Models (MMNL) and a Hybrid Choice Model (HCM). In particular regarding the two MMNLs, the main difference between them was in the attitudes and perceptions representation, which were not included in the first model (MMNL0) and considered as dummy variables in the second model; finally users' attitudes and perceptions were explicitly modelled within the HCM framework as latent variables.

The remainder of the paper is organised as follows: literature review is discussed in section 2; a detailed description of the case study, the experiment set-up including the methodology, the questionnaire description and the preliminary analyses of the sample and collected outcomes are discussed in section 3; the modelling approach is presented in section 4; the estimation results including the sensitivity analyses are displayed in section 5. Finally, conclusions and future perspectives are drawn in section 6.

2. LITERATURE REVIEW

In general, decision makers in the automotive and energy industry as well as in politics are particularly interested in market forecast. According to most relevant studies three main classes of approaches for market penetration may be identified (Jochem et al., 2018): the bottom up methods which are based on disaggregated data; the top down models which are based on macroeconomic theory and relies on historical data of attributes affecting users' preferences (such as prices, consumption, etc.); and mixed models combining both approaches. In fact, the latter is more recommended to consider individual preferences and overall information about trends in society and vehicle supply. However, it must be also specified that these methods require some specific data on market share; an example is provided by Jensen et al. (2017) that propose the combination between discrete choice models and diffusion model aiming to reproduce the trend of diffusion of new technologies. Regarding diffusion model, in order to properly apply the approach, it is required that some assumptions must be satisfied; particularly that the penetration of the new technology has been recently observed. It may be argued that the suitability of forecasting models in the case of "immature" market is still an open issue and not reliable when there is a lack of data.

Main studies on the potential demand for EVs have been conducted worldwide, but in particular in the United States (Bunch et al., 1993; Segal, 1995; Brownstone and Train, 1998; Brownstone, Bunch and Train, 2000; Hidrue et al., 2011; Hess et al., 2012; Cirillo, Liu and Maness, 2017); Canada (Ewing and Sarigöllü, 2000; Potoglou and Kanaroglou, 2007; Mau et al., 2008; Mohamed et al., 2016), China (Qian and Soopramanien, 2011), Denmark (Jensen, Cherchi and Mabit, 2013), Germany (Achtnicht, Bühler and

Hermeling, 2012; Ziegler, 2012; Hackbarth and Madlener, 2013; Degirmenci and Breitner, 2017; Schmalfuß, Mühl and Krems, 2017), Italy (Valeri and Danielis, 2015), Japan (Ito, Takeuchi and Managi, 2013), Netherlands (Kim, Rasouli and Timmermans, 2014), Norway (Dagsvik et al., 2002), Spain (Junquera, Moreno and Álvarez, 2016), South Korea (Ahn, Jeong and Kim, 2008), Switzerland (Glerum et al., 2014), UK (Brand, Cluzel and Anable, 2017), just to cite a few. Over the last few years, some studies performed a comparative analysis between the choices made by the respondents in different countries: US / JAPAN (Tanaka et al., 2014); US / CANADA (Axsen, Mountain and Jaccard, 2009); US / CHINA (Helveston et al., 2015).

Most studies focused on the estimation of basic MultiNomial Logit (MNL) model (McFadden, 1974) to examine automobile demand. Lave and Train were the first to apply a MultiNomial Logit model to survey data of new car buyers to examine how vehicle attributes and consumer covariates influence choice (Lave and Train, 1979). Other studies use the same model to examine the propensity to buy an EV (Junquera, Moreno and Álvarez, 2016; Krause et al., 2016; Brand, Cluzel and Anable, 2017; Cirillo, Liu and Maness, 2017); moreover, some studies used Nested Logit Model to relax the restriction of independence of irrelevant alternatives (Train, 2003). Several researches used Mixed Logit (MXL) models accounting for preference heterogeneity to study the choice of EV's (Tanaka et al., 2014; Helveston et al., 2015; Valeri and Danielis, 2015; Rudolph, 2016; Cirillo, Liu and Maness, 2017).

Particularly socio-psychological approaches highlight that several factors may affect the users' outcomes, which are crucial to know in order choice and design proper interventions. For instance, one contribution was from Stern (2000) which identified four categories of determinants: contextual based, attitudinal factors, personal capabilities (such as knowledge and skills), and habits and routine; the integrated approach postulates that the individual behaviour is affected by all these factors. Other conceptual frameworks proposed in the literature also include the effect of environmental attitudes and environmental knowledge on users' outcomes (Flamm, 2009). Moreover, the consumer purchase intentions are investigated and the theory of reasoned action (Hill, Fishbein and Ajzen, 1977) and the theory of planned behaviour (Ajzen, 1991) are the most adopted approaches. Regarding the influence of environmental attitudes, as well as price and range are broadly demonstrated in the literature in the field of EV consumer purchase intentions. Other approaches framed within Random Utility Theory (Ben-Akiva et al., 2002) highlight that the cognitive processes affecting users' behaviour may be represented through attitudes and perceptions (Raveau, Yáñez and Ortúzar, 2012; Vij and Walker, 2016). Indeed some of the attributes that play a significant role in the choice phenomena can be unobservable factors for the researcher, such as subjective beliefs and personal tastes of the respondents. In order to recognize and incorporate them into the discrete choice analyses, Hybrid Choice Models (HCM) have been developed. They include latent variables and choice models with flexible error structures in an integrated approach to evaluate the impact of attitudes on choice (Walker, 2001; Ben-Akiva et al., 2002; Walker and Ben-Akiva, 2002). Latent attitudes are treated as latent variables based on indicators collected from attitudinal surveys. Several studies have employed these models on studies of travel choice behaviour to research the effects of attitudes and perceptions (Walker and Ben-Akiva, 2002; Temme, Paulssen and Dannewald, 2008; Daly et al., 2012; Kim, Bae and Chung, 2012; Prato, Bekhor and Pronello, 2012). These models have also been used on the choice of alternative fuel vehicles analysing the influence of diverse attitudes, related to the environment (Daziano and Bolduc, 2013; Hess, Shires and Jopson, 2013; Jensen, Cherchi and Mabit, 2013; Soto, 2014); attitudes towards vehicle features (e.g., design, spaciousness, technology, etc.) and leasing a vehicle (Glerum et al., 2014; Mabit et al., 2015); social influences and latent attitudes (Kim, Rasouli and Timmermans, 2014). The analysis is summarised in two overviews of the references: the first one, see Table 1 is about AVF categories and significant attributes whilst the second one, see Table 2, is about the investigated attitudes and perceptions.

In these papers, two instrumental attributes of EV's are always present: the purchase price and the running cost (mainly of electricity typically against fuel cost, and few times of maintenance). These studies also consider basic information about the socioeconomic characteristics of the respondent itself (gender, age, level of instruction); and the more recent gather socioeconomic characteristics of the household (number of members and of vehicles, level of income). Half of these studies considered the driving range and performance (as top speed and acceleration) of EV's, not only by assigning one or several values for them; but also in direct or indirect questions, alongside to the lack of emissions, to assess their importance. The recharging time, aesthetics of electric vehicles and governmental incentives (such as no parking or metered fees, no purchase taxes, access to HOV lanes, etc.) are present in only a quarter of these studies. Lastly, very few of these studies considered the reliability and comfort of EV's.

Table 1: Overview of main references of AVF categories and significant attributes

Reference	AFV category				Attribute(s)
	ICV	BEV	HEV	PHEV	
Beggs et al., 1981	•	•			Instrumental and functional attributes such as: purchase price, running costs, annual taxes, reliability, performance, driving range and recharging time, performance, convenience, comfort and aesthetics
Bunch et al., 1993	•	•	•		
Chéron and Zins, 1997	•	•			
Batley, Toner and Knight, 2004	•	•	•		
Horne, Jaccard and Tiedemann, 2005	•		•		
Ong and Hasselhoff, 2005			•		
Potoglou and Kanaroglou, 2007	•		•		
Bolduc, Boucher and Daziano, 2008	•		•		
Skippon and Garwood, 2011	•	•			
Mabit and Fosgerau, 2011	•	•	•		
Musti and Kockelman, 2011	•		•	•	
Graham-Rowe et al., 2012		•		•	
Achtnicht, 2012	•	•	•		
Bockarjova, Rietveld and Knockaert, 2013	•	•	•		
Hackbarth and Madlener, 2013	•	•	•	•	
Hsu, Li and Lu, 2013			•		
Ito, Takeuchi and Managi, 2013	•	•	•		
Jensen et al., 2013	•	•			
Schuitema et al., 2013		•		•	
Petsching et al., 2014	•	•	•		
Kim et al., 2014	•	•			
de Luca et al., 2015	•		•		
Valeri and Cherchi, 2016	•	•	•		
Choo and Mokhtarian, 2004	•				non-instrumental attributes, as household socioeconomic characteristics
Potoglou and Kanaroglou, 2007	•		•		
Bolduc, Boucher and Daziano, 2008	•		•		
Mabit and Fosgerau, 2011	•	•	•		
Glerum et al., 2014	•	•			
Valeri and Cherchi, 2016	•	•	•		
Moons and De Pelsmacker, 2012		•			Consumer emotions and feelings
Schuitema et al., 2013		•		•	
Graham-Rowe et al., 2012		•		•	
Potoglou and Kanaroglou, 2007	•		•		Governmental incentive
Bolduc, Boucher and Daziano, 2008	•		•		
Mabit and Fosgerau, 2011	•	•	•		
Hackbarth and Madlener, 2013	•	•	•	•	
Glerum et al., 2014	•	•			
Rudolph, 2016	•	•		•	
Schuitema et al., 2013		•		•	Social influence, Hedonic (Pleasure of driving) and symbolic attribute - Using EV
Kim et al., 2014	•	•			
Petsching et al., 2014	•	•	•		
Choo and Mokhtarian, 2004	•				Attitudes and perceptions
Kishi and Satoh, 2005	•		•		
Bolduc, Boucher and Daziano, 2008	•		•		
Jensen et al., 2013	•	•			
Schuitema et al., 2013		•		•	
Glerum et al., 2014	•	•			
Kim et al., 2014; 2016	•	•			
Petsching et al., 2014	•	•	•		
Valeri and Cherchi, 2016	•	•	•		

Table 2: Overview of main references about investigated attitudes and perceptions

ATTITUDES AND PERCEPTIONS			
Choo and Mokhtarian, 2004	Travel dislike	Pro-high density urban area	
Kishi and Satoh, 2005	Environmental awareness		
Bolduc, Boucher and Daziano, 2008	Environmental concern	Appreciation of new car features	
Jensen et al., 2013	Environmental concern		
Schuitema et al., 2013	Pro-environmental identity	Car-authority identity	
Glerum et al., 2014	Pro-leasing attitude	Pro-convenience attitude	
Kim et al., 2014; 2016	Environmental	Battery	Innovation Value
Petsching et al., 2014	Perception of AFV innovation characteristics		
Valeri and Cherchi, 2016	Habitual car use behaviour		

On the base of all previous considerations, the main focus of the paper is on the identification of determinants affecting the willingness to purchase an EV in the context of immature markets, as a preliminary analysis to be pursued for further development of forecasting models of EV market penetration.

3. CASE STUDIES AND EXPERIMENTAL DESIGN

3.1 Samples description

Nowadays, the market of electric vehicles in Argentina is in its early beginnings as currently only one hybrid-electric vehicle (HEV) cars is offered by automakers. The information regarding features, prices, benefits and any other characteristic of battery-electric vehicles (BEV's) can be made only through internet and is performed primarily by people interested in this type of technology. Given this current situation, revealed preference data from the purchase of alternative fuel vehicles cannot be obtained. To overcome this obstacle, a choice-based stated preference (SP) survey method was adopted. The data was obtained from choice experiments in which respondents made their choice from a given set of alternatives. Attribute values vary between alternatives and can be hypothetical (as BEV are not currently sold). This approach is widely used to study the propensity or potential demand on electric vehicles even in countries where they are being sold since several years ago, but the development is still limited and the data is scarce. Individuals may have diverse responses in hypothetical choice situations than to real-world contexts, but SP surveys allows to investigate the impact of car characteristics which are absent from the market on the purchase choice (Mannering and Train, 1985).

The paper presents the results from two different socio-geographical contexts: Argentina & Italy. The first comparison between them may be carried out in terms of economic performance and living standards, by considering the nominal GDP (Gross Domestic Product) and the GDP per capita at purchasing power parity (GDPPPP) which are summarised in table below. In particular it may be observed that the relative difference between two indicators is lower in case of Italian case study.

Table 3: Measures of economic performance and living standards of two case studies

Measures of national development and progress	Argentina	Italy
Gross domestic product GDP per capita in 2017	14,402.0	31,953.0
Gross domestic product at purchasing power parity GDP (PPP) per capita in 2017	20,786.7	39,426.9
Relative difference: [GDP_{PPP} – GDP]/GDP	44%	23%

Córdoba (see Figure 1.a) is a city located in the geographic centre of Argentina, about 700 km (435 mi) northwest of Buenos Aires. It is the capital of Córdoba Province, and with its near 1,300,000 inhabitants is the second most populous city in Argentina after Buenos Aires. It is an important industrial centre but retains many of its historic buildings dating back to the colonial era. Salerno Córdoba (see Figure 1.b) is a city located in south-western Italy, in the Campania region, about 60 km (37 mi) from Naples. It has a

Location of the province of Cordoba in Argentina *Location of the province of Salerno in Italy*

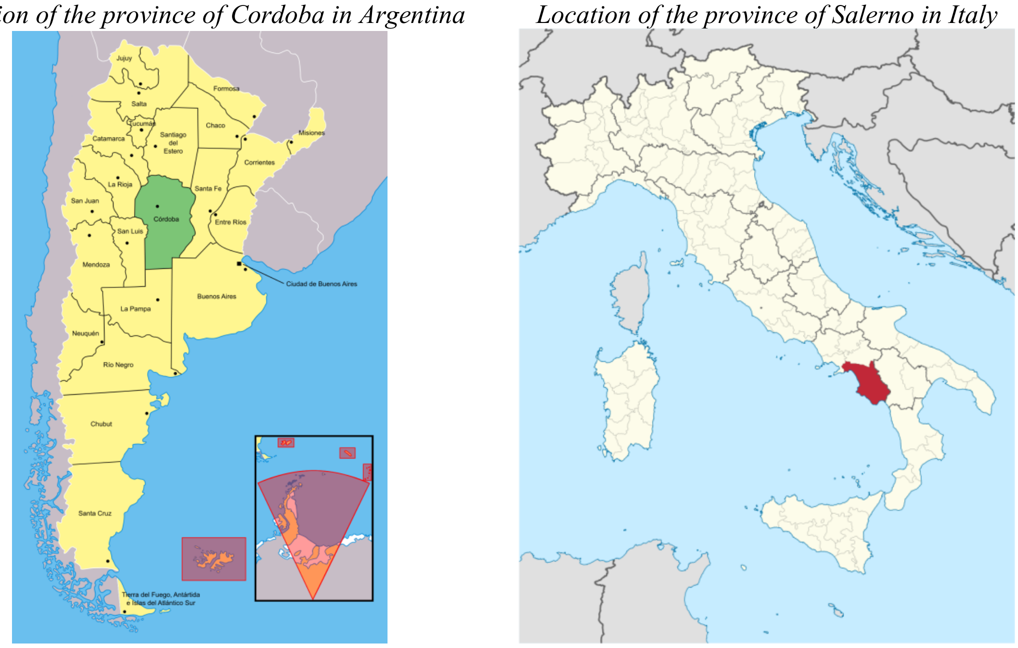

Figure 1: Case studies a) Argentina b) Italy

population of 130,000 inhabitants, becoming the second largest municipality in the region by population. The city is divided into three distinct zones: the medieval sector, the 19th century sector and the more densely populated post-war area, with its several apartment blocks. The economy of Salerno is mainly based on services and tourism. The remaining ones are connected to pottery and food production and treatment.

The dataset was collected from two surveys to university students: The University of Salerno (UNISA - Università degli Studi di Salerno) in Italy; and the University of Cordoba (UNC - Universidad Nacional de Córdoba) in Argentina. As already highlighted in the introduction, the case studies represent, first of all, two pilot studies, but they are worth of interest since they involve two countries in which the EVs' market are in its early beginnings and involve young potential users. The data was obtained through a stated preference (SP) approach and the questionnaire was provided with an on-line web-based questionnaire. In general, the questionnaire completion took less than 30 minutes. It must be observed that the academic fields covered by the two universities are very similar and regarding a wide range; from humanities, social sciences, natural and formal sciences to professional and applied sciences (particularly about education, engineering, communication, law etc.).

The University of Salerno is the second (out of four) largest university in the Campania region (Southern Italy) Italy. Its main characteristic is the external location from urban areas, and barycentric compared to the municipalities of Avellino and Salerno. The individual faculties are divided between the complex located in the municipality of Fisciano (SA) and the complex located near the village of Lancusi in the municipality of Baronissi (SA).

The Fisciano campus of the University of Salerno, with its 33.481 students, host all the main faculties except science and medicine. Most of the members belong to the Province of Salerno (64%) and the Province of Avellino (15%), interesting is the 8% of members of the Province of Naples as well as the influence on the neighbouring regions of Calabria and Basilicata (9%). The provinces of Caserta (0.7%) and Benevento (2%) do not seem to fall into the area of influence. The data on the geographical distribution of people who attend the university confirm what was said previously, highlighting once again that the Province of Salerno (80%) is the most important catchment area. Most of the university students live in an urban context of a small/medium size (40.000 - 145.000 habitants).

The National University of Córdoba (Spanish: Universidad Nacional de Córdoba, UNC), founded in 1613, is the oldest university in Argentina, the fourth oldest in South America and the sixth oldest in Latin America; located in Córdoba, the capital of Córdoba Province. Since the early 20th century it has been the second largest university in the country (after the University of Buenos Aires) in terms of the number of students, faculty, and academic programs. Córdoba has earned the nickname “La Docta” (roughly translated, "The Wise") because for more than two centuries was the only University in the country.

The university has a student population of approximately 132.000 members. It is composed by fifteen faculties (that offer more than 250 graduate, postgraduate and doctoral degrees); two secondary schools; 145 research centres and institutes; twenty-five libraries; seventeen museums; and several other facilities. The faculties of the UNC are located in the University City of Córdoba, a property of 1,115 hectares located in the centre-south sector of the city

The catchment area of the university has a national range. It is to notice that the 41% of the students of the UNC are from the city of Cordoba; and there is a 33% of students that either live or come from smaller cities in the province of Cordoba. Lastly, a 25% of students come from other regions; mainly from North-West (7,7%) and Patagonia (6,6%).

Regarding the questionnaire, the two case studies were investigated through a stated preference (SP) experiment specifically designed and carried out in the two universities. Respondents involved in the experiment were university students mainly between 18 and 24 years, and belonging to two type of cultural areas: scientific and “umanistica”. The Argentinean survey resulted in over 420 responses while the Italian one gathered 318 responses. Each respondent was faced with five scenarios therefore in all the number of collected observations was 1933 in the Argentina survey and 1462 in the Italian survey (see Vij and Walker (2012). Even though the minimum size requited for the survey was estimated around 510[6] all collected (and reliable) observations were still considered in

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6 The minimum sample size was preliminarily defined as in accordance with the literature (e.g. Louviere[6], et al., 2000; Hensher[6], et al., 2005) by using following analytical expression:

$$n \geq \frac{q}{pa^2}\left[\Phi^{-1}\left(\frac{1+\alpha}{2}\right)\right]^2$$

where p is the true proportion, q = 1 - p; α, is the level of confidence (0.95); a, is the accuracy (10%); $\Phi^{-1}(.)$ is the inverse cumulative normal distribution function.

the estimation procedure. Each respondent faced a questionnaire composed by five sections.

The first section focuses on the users' socioeconomic characteristics collection, therefore the people interviewed were characterised by asking different personal data, such as gender, age, province of residence, employment status, number of people in the household, quantity of cars/pick-ups in possess.

The second section aimed to collect the characteristics of the household vehicle, therefore the survey inquired about the characteristics of the car in possess, such as the type of fuel, brand, year, annual kilometres driven (optional answer) and the main use of the vehicle (urban, extra-urban, cargo).

The third section aimed to investigate the users 'attitudes that may affect their willingness to purchase an EV (see Figure 2a). In more detail, three main attitudes were identifies as significant in the users choice process (from literature): about the environment, the vehicle's technical features, the vehicle design. In particular, direct/indirect questions were specifically designed (see de Luca and Di Pace, 2019) adopting a five points likert scale (ranging from strongly disagree to strongly agree) and some specific psychological statements are identified.

The fourth section (see Figure 2b) was about the users' choice in buying a new car when the electric vehicle (EV) is compared with a conventional one (CV). Since EVs are not sold yet in the Argentinean market and they are not very widespread in Italy, also following the recommendations of Anable et al. (Anable et al., 2011), the survey included an educational section that explains the basis of electric vehicle technology, among other items, to ground the adoption intentions on accurate information.

The main features exposed are: No tailpipes: electric motors don't pollute; Quiet operation; Domestic energy: batteries can be charged at home or in public charging stations; Charging time: from 30 minutes to 8 hours; Motor: same power as combustion engines, but lighter; Fewer moving parts: reduced maintenance costs; Range 200 km or more: enough for a week of urban displacements.. After the description of an electric vehicle, a comparison is made between two alternatives; a conventional fuelled vehicle as alternative A; and a battery electric vehicle (BEV) as alternative B.

Future of Electric Cars in Argentina

III. Attitudes about environment and technical features

1. The vehicle fuel consumption significantly influences my choice in purchasing a new car. *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

2. I care about the amount of pollution generated by a car when it's being used. *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

3. The vehicle technical features significantly influence my choice in purchasing a new car. *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

4. I prefer driving a car with a powerful engine. *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

5. When I am choosing a car, I find myself spending a lot of time checking out differences in terms of top speed (km/h). *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

6. The immediate acceleration increases my driving pleasure. *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

7. The vehicle range is very significant with respect to my mobility needs in everyday life. *

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

	Vehicle A - GASOLINE Renault Clio Mío Dynamique 5p 	**Vehicle B - ELECTRIC** Renault ZOE Life R90 
Power	75 CV	92 CV
Top Speed	161 km/h	135 km/h
Acceleration 0-100	12,9 seconds	13,4 seconds
Consumption	13,3 km/l	10,9 km/kWh
	7,5 l/100 km	9,2 kWh/100 km
Fuel capacity / Batteries	50 litres	22 kWh
Range	660 km	240 km

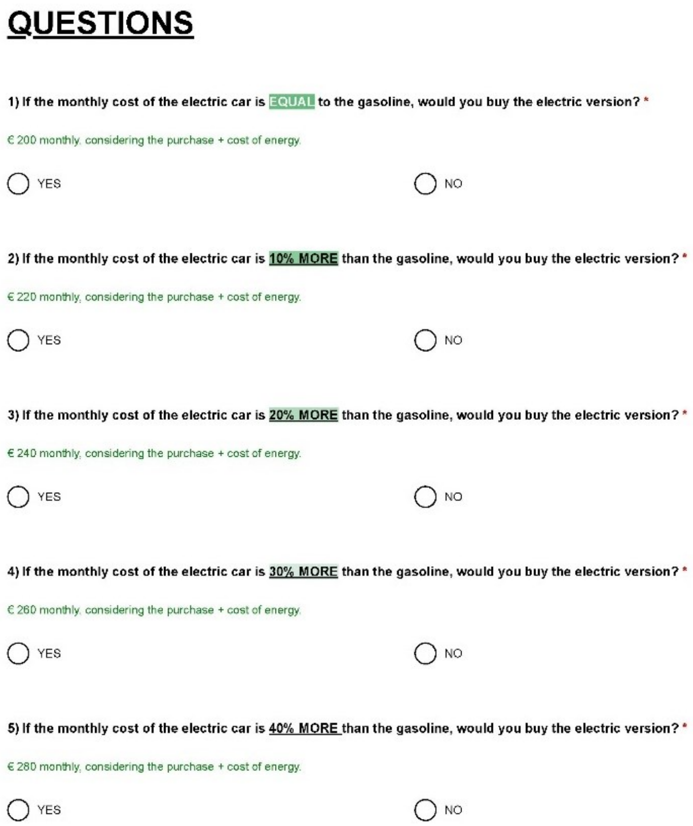
Monthly cost for the conventional vehicle	
Vehicle A - GASOLINE Renault Clio Mío Dynamique 5p	
Purchase price: **€13.000** Montly price in 8 years: **€135**	Fuel price: **€1 per litre** Consumption: **7.5 l/100km** Monthly mileage: **850 km** Montly cost of fuel: **€65**
Monthly cost (purchase + fuel) **€200**	

Figure 2: Snapshot of the third questionnaire section about attitudes towards environment and technical features

Furthermore, in order to minimize the influence of brand, size, and even colour of the vehicle on the choosing and purchasing decision, the comparison was made between both cars from the same car maker: Renault. This brand was selected because it's in the top 5 in sales and offers and affordable electric vehicle, the Zoe, the currently best-selling electric vehicle in Europe. The alternative A is represented by a Renault Clio since it is a very successful model of Renault in Argentina and Italy, and it's being compared with the Renault Zoe in terms of power, top speed, acceleration, consumption, size of the fuel deposit/batteries, and range. After comparing the two alternatives, is hypothesized that the interviewee has a budget enough to buy a new car to be used in urban areas. Therefore, each respondent was faced with different scenarios set-up starting from the monthly [7]cost of a conventional vehicle. For each scenario different monthly cost of an electric vehicle with respect to the conventional one was considered. Thus, five scenarios are obtained in all (i.e. equal monthly cost, +10%, +20%, +30% and +40%). Finally, by a stated preference method, it is asked if at an equal monthly cost, the person would be willing to choose the electric version over the conventional one. Then, the same question is asked if the electric car would cost 10% more (€220 monthly), 20% more (€240 monthly), 30% more (€260 monthly) and 40% more (€280 monthly), highlighting the absolute difference of the monthly cost and the total amount that would be spent at the end of the 8 years. Moreover, the results of the observed choices will be discussed in more detail in the sections about the outcomes discussion and the sensitivity analyses.

The fifth and last section of the survey aims to collect the users' perceptions referred to the advantages and disadvantages of electric vehicles that may affect their willingness to purchase them (see Figure 3.b). As in the third case, the evaluation is based on ordinal scale (ranging from strongly disagree to strongly agree) and some specific psychological statements are identified.

[7] the monthly cost of the conventional car is calculated considering the price of the car in 8 years and the fuel cost performing urban displacements for a daily travelled distance around 40 km; therefore, the estimated monthly cost is of €200.


QUESTIONS

1) If the monthly cost of the electric car is EQUAL to the gasoline, would you buy the electric version? *

€ 200 monthly, considering the purchase + cost of energy.

YES NO

2) If the monthly cost of the electric car is 10% MORE than the gasoline, would you buy the electric version? *

€ 220 monthly, considering the purchase + cost of energy.

YES NO

3) If the monthly cost of the electric car is 20% MORE than the gasoline, would you buy the electric version? *

€ 240 monthly, considering the purchase + cost of energy.

YES NO

4) If the monthly cost of the electric car is 30% MORE than the gasoline, would you buy the electric version? *

€ 260 monthly, considering the purchase + cost of energy.

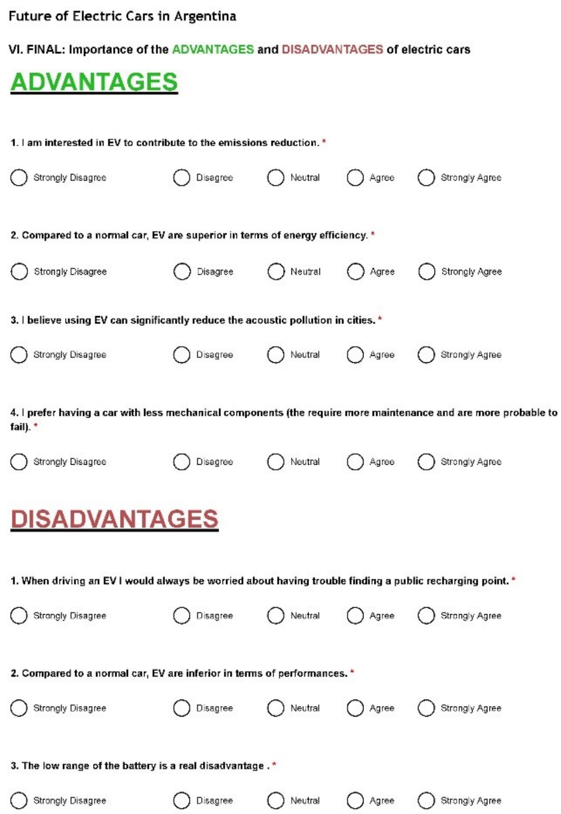
YES NO

5) If the monthly cost of the electric car is 40% MORE than the gasoline, would you buy the electric version? *

€ 280 monthly, considering the purchase + cost of energy.

YES NO

Figure 3: a) Snapshot of the fourth questionnaire section about vehicle choice (EV vs CV);


Future of Electric Cars in Argentina

VI. FINAL: Importance of the ADVANTAGES and DISADVANTAGES of electric cars

ADVANTAGES

1. I am interested in EV to contribute to the emissions reduction. *

Strongly Disagree Disagree Neutral Agree Strongly Agree

2. Compared to a normal car, EV are superior in terms of energy efficiency. *

Strongly Disagree Disagree Neutral Agree Strongly Agree

3. I believe using EV can significantly reduce the acoustic pollution in cities. *

Strongly Disagree Disagree Neutral Agree Strongly Agree

4. I prefer having a car with less mechanical components (the require more maintenance and are more probable to fail). *

Strongly Disagree Disagree Neutral Agree Strongly Agree

DISADVANTAGES

1. When driving an EV I would always be worried about having trouble finding a public recharging point. *

Strongly Disagree Disagree Neutral Agree Strongly Agree

2. Compared to a normal car, EV are inferior in terms of performances. *

Strongly Disagree Disagree Neutral Agree Strongly Agree

3. The low range of the battery is a real disadvantage . *

Strongly Disagree Disagree Neutral Agree Strongly Agree

Figure 3: b) Snapshot of the fifth questionnaire section about users' perceptions of EV advantages and disadvantages

3.2 Survey results

In table 4 the main characteristics of both samples are reported (see Table 4). With reference to the gender considered distributions are very similar in the surveys indeed male are the 65.2% in Argentina and 62.3% are in Italy. Moreover, in the Argentinean case the numbers are very similar with the percentages of driver's licenses emitted by the City of Buenos Aires on the last 5 years: 67,4% men and 32,6% women. (Ministerio de Hacienda GCBA, 2016). The Italian percentages are also similar to the number of active driver's licenses in 2017: 40.8% women and 59.2 % men (Ministero delle Infrastrutture e dei Trasporti). Further information is shown in following tables.

The age of the people surveyed can be characterised as a young adult, since it is mainly composed of university students who were the target of this analysis.

When analysing the composition of the family results that in both countries most of the respondents have 4 to 5 members. In Argentina this group is composed by the 60.71% while in Italy is around 76.7%. The number of vehicles in possess shows that in the Argentinean survey the 61,67% of the students have 2 or more of them in possess in their family. As a 9,05% does not own a car, the following part will have reduced the quantity of the sample due to it analyses the characteristics of the car (or the main one if possess two or more). In the Italian study, the largest part has 2 vehicles in the household.

Table 4: Sample socio-economic characteristics distributions

Socio-Economic Characteristics	Categories	Percentage [%]	
		ARG	*ITA*
Age	<18	3.1	0.0
	18-24	76.0	96.9
	25-29	19.5	31
	30-34	1.2	0.0
	35-39	0.2	0.0
n° of family members	1	2.9	0.3
	2	6.0	1.9
	3	13.3	13.5
	4	32.4	54.4
	5	28.3	22.3
	6	11.0	5.7
	7	4.5	1.6
	8	1.7	0.3
n° of vehicles in posses	0	9,0	0,0
	1	29,3	17,6
	2	38,6	57,9
	3	17,4	20,1
	4	4,0	3,5
	5	1,7	0,9

Regarding the vehicles fleet, in Argentina, the survey results shows that 68% of the vehicles in possess by the interviewed are fuelled by gasoline, almost three times more the quantity of diesel-fuelled vehicles. When comparing to the Italian results, there is a remarkable difference where the diesel cars are the first response and the gasoline comes in second place. As for the type of displacement, in Argentina the principal is urban type. When analysing the category "Extra urban" should be considered that in Argentina the distances among two cities in general are remarkably longer than Italy, so an "extra urban" displacement could be considered of 100 km or more while in Italy a journey of 10 km can already be treated as an extra urban type. Moreover, in the Argentinean study, a third category was added, called "Cargo". This should be interpreted mainly as a heavy-use of the vehicle due to the distance travelled and/or the load shifted.

In order to understand which attributes of EV are most likely to influence peoples' attitudes and perceptions, in this paper we focus on how attitudes towards environment and technical features may affect users' willingness to purchase an EV as well as perceptions of EV advantages and disadvantages. This section was designed and tested by submitting the questionnaire to a pilot survey therefore through the Cronbach 'Alpha[8] computation the internal reliability is ensured (results are displayed below). Furthermore, the results of some preliminary statistics (mean and standard deviations) are shown in Table 5 and Table 7.

Table 5: Descriptive statistics on psychometric statements about attitudes

Indicators		*ARG*		*ITA*	
Attitudes about environment	*Cronbach's alpha*	*mean*	*sd*	*mean*	*sd*
		0.575		*0.551*	
F_cons	The vehicle fuel consumption significantly influences my choice in purchasing a new car	3.88	0.83	4.32	0.71
F_poll	I care about the amount of pollution generated by a car when it's being used	2.94	1.17	3.13	0.98
Attitudes about technical features	*Cronbach's alpha*	*mean*	*sd*	*mean*	*sd*
		0.716		*0.656*	
F_tech_fea	The vehicle technical features significantly influence my choice in purchasing a new car	3.69	0.78	3.68	0.85
TF_power	I prefer driving a car with a powerful engine	3.48	0.77	3.51	0.84
TF_top_speed	When I am choosing a car, I find myself spending a lot of time checking out differences in terms of top speed (km/h)	2.94	0.86	2.98	0.85
TF_accel	The immediate acceleration increases my driving pleasure	3.02	0.93	3.14	1.00
TF_range	The vehicle range is very significant with respect to my mobility needs in everyday life	4.09	0.76	4.53	0.73

[8] Cronbach's alpha, assesses how well a set of items measures a single unidimensional latent construct

In the specific statement considered for each attitude is described. In particular, it must be observed that the results of two countries are slightly different. Regarding the Technical Features valuation, the trend and the values are similar, with a 3% of variation between both countries and over the 83% of responses were between "agree" and "neutral" responses, with the exact same value between "strongly agree" and "disagree". As for the top speed, the trend is equal in both surveys and it can be noticeable a reduction of the importance assigned compared with the power. The acceleration shows a similar trend in both countries, with the main result being "neutral" and then decreases for both sides. Finally, analysing the range valuation, over the 80% of responses of the Argentinean survey were "strongly agree" or "agree", while in the Italian survey this quantity goes up to 91% and then decreases, with zero responses to "strongly disagree". Summing up comparing the valuation of the different technical features, shows that the Range is valued as the most important one, while Power comes in second place. The Top Speed and Acceleration have a similar trend and are considered as less important.

On the following table, the results of the choices made are shown. As the differences in cost increases, the percentage of people willing to buy an electric car decrease as expected. The largest difference between both surveys is found on the higher quantity of people who claims that would buy an EV in Italy if the monthly cost is Equal or 10% more.

Table 6: Collected preferences in each scenario

Outcome	Scenario	Percentage [%]	
		ARG	ITA
YES	Equal	92.10	93.40
	10%	77.60	83.30
	20%	32.80	33.70
	30%	7.10	1.30
	40%	3.80	1.30
NO	Equal	7.90	6.60
	10%	22.40	16.70
	20%	67.20	66.30
	30%	92.90	98.70
	40%	96.20	98.70

As worth noting, also in case of users' perceptions analysis some specific statements, which are explained in more detail in following table, are needed. Each feature is evaluated by its importance, varying from I strongly disagree to I strongly agree.

In terms of attitude towards environment the trend of the valuation of importance of the pollution is similar in both countries, but the values are more distributed in the Argentinean survey, while the Italian the responses have less dispersion. It's interesting to notice that in the Argentinean case, over 37% of respondents assign "strongly disagree" or "disagree" to pollution and over 30% as "strongly agree" or "agree". Moreover, in the case of consumption, the Italian survey shows that the 89% of the people interviewed assigned an "strongly agree" or "agree" to it. In Argentina, the valuation "strongly agree" is over the half of the Italian, but the 94% of answers are spread between "strongly agree", "agree" and "neutral". Preliminary statistics as in previous case (mean and standard deviation) are provided.

Table 7: Descriptive statistics on psychometric statements about perceptions

	Indicators	*ARG*		*ITA*	
	Advantages of EVs	*mean*	*sd*	*mean*	*sd*
	Cronbach's alpha	*0.756*		*0.549*	
AD_{Red_CO}	I am interested in EV to contribute to the emissions reduction (ADred_co2_x)	4.06	1.04	4.11	0.82
$AD_{Efficiency}$	Compared to a normal car, EV are superior (ADefficiency_x) in terms of energy efficiency	4.15	0.86	3.42	1.08
AD_{Red_poll}	I believe using EV can significantly reduce the acoustic pollution in cities (ADred_poll_x)	3.77	1.13	3.62	0.97
AD_{Less_parts}	I prefer having a car with less mechanical components	3.85	1.01	3.01	1.14
	Disadvantages of EVs	*mean*	*sd*	*mean*	*sd*
	Cronbach's alpha	*0.535*		*0.364*	
DIS_{infr}	When driving an EV I have trouble finding a public charging stations(DISinfr_x)	4.44	0.79	4.21	0.82
DIS_{red_fea}	Compared to a normal car, EV are inferior in terms of performances (DISred_fea_x)	3.01	1.02	3.25	0.94
DIS_{batt_range}	The low range of the battery is a real disadvantage (DISbatt_range_x)	4.19	0.83	4.05	0.87

The responses to the importance given to the benefit of the reduction of CO2 emissions shows a decreasing trend as expected, being "Strongly agree" the most chosen response. Over 73% of respondents in the Argentinean, and 81% in the Italian one answered the statement as "Strongly agree" or "Agree". The benefit of the reduction of acoustic pollution shows a trend where the importance given to this feature is higher in the Argentinean survey than in the Italian one. The 65% of Argentinean responses were “Strongly agree” or “Agree” while in the Italian survey was 57%. As in the preceding case, the Argentinean survey shows a higher importance to the greater energy efficiency than the Italian survey, with over 82% of people answering “Strongly agree” or “Agree” in the Argentinean, and over 51% in the Italian. The benefit of having fewer moving parts in the electric vehicle has a similar trend to the reduction of acoustic pollution. The Argentinean survey shows a higher importance of this feature than the Italian, but less when compared with other benefits.

The lack of infrastructure has a differ trend when comparing both surveys. In the Argentinean one, the importance decreases from strongly agree to strongly disagree, with over 87% of interviewed assigning “Strongly agree” or “Agree”, being “Strongly agree” the most chosen category. In the Italian survey, there is a similar percentage of responses to “Strongly agree” and “Agree”, with a total of 83% when added. The trend of importance of the reduced features differs from the precedent disadvantages. It has a higher number of responses to “Neutral” and “Disagree” producing almost a symmetric chart centered in “Neutral”, as it is the most chosen category with a 38,33% in the Argentinean, and 40,6% in the Italian. The disadvantage of having a limited battery range has almost an equal quantity of responses in “Strongly agree” and “Agree”, with a total of 81% between them in the Argentinean, and over 74% in the Italian. Then, the percentage strongly decreases, arriving to less than 3% in “disagree” and less than 1% choose “strongly disagree”. In both surveys the trend for this weakness of EV’s is similar.

4. MODELLING APPROACH

As introduced in the previous sections, the paper aims to model the propensity to buy an EV and to investigate the role of attitudinal factors in the choice process. Therefore the attitudes were investigated through the specification of an Hybrid choice model founded on the random utility theory and incorporating attitudes/perceptions through latent variables (Ben-Akiva et al., 1999, 2002; McFadden, 2001; Walker, 2001; Walker and Ben-Akiva, 2002; Bolduc and Alvarez-Daziano, 2010; Raveau et al., 2010; de Almeida Correia et al., 2013). In particular, the proposed approach allows to quantify both the instrumental and the attitudinal determinants of the choice behaviour, allows to understand the reciprocal weights and, moreover, allows to carry out sensitivity analyses. In following, a detailed description of the model specification (mathematical formalization) is provided, as well as the whole set of the considered/investigated attributes.

Regarding the utility in the hybrid choice model which may be represented as in following displayed

$$U^i = \boldsymbol{\beta}_{\mathbf{X}} \cdot \mathbf{X}^i + \boldsymbol{\beta}_{\mathbf{SE}} \cdot \mathbf{X}^i_{SE} + \boldsymbol{\beta}_{\mathbf{LV}} \cdot \mathbf{LV}^i + \varepsilon^i$$

based on the assumption that each individual faced with a set of alternatives i, it may be specified that each alternative may be expressed as a function of a vector of (observable) instrumental attributes, $\mathbf{X}_i$, and users' attributes, $\mathbf{X}_{i,SE}$, and a vector of (non - observable) latent variables, $\mathbf{LV}_i$, and the error term ε_i, independent and identically distributed (IID).

With reference to the $\mathbf{LV}_i$ vector, two equations have to be specified: the structural and the measurement equations. The structural equations are introduced in order to specify the latent variables, whilst the measurement equations are introduced in order to specify the perception indicators.

In particular, if p is the generic latent variable, the structural equation for each latent variable may be expressed as follows

$$LV_p{}^i = \gamma_p + \Sigma_j \beta_{SE,pj} \cdot X^i{}_{SE,pj} + \omega_p{}^i$$

where: γ_p, is the intersect, $\mathbf{X}^i{}_{SE,pj}$ is the vector of the users' characteristics attributes, $\boldsymbol{\beta}_{SE,pj}$ is the vector of the coefficients associated with the users' characteristics (to be estimated), $\omega_p{}^i$ be the error term which is normally distributed with zero mean and $\sigma_{\omega p}$ standard deviation.

Furthermore, let $\mathbf{I}^i{}_n$ be a vector of perceptions indicators associated to each latent variable therefore each perception indicator (i.e. vector component, k) may be specified as follows:

$$I^i{}_{p,k} = \alpha_{p,k} + \lambda_{p,k} \cdot LV_p{}^i + \nu_{p,k}{}^i$$

where $\alpha_{p,k}$ is the intersect, $\lambda_{p,k}$ is the coefficient associated with the latent variable (to be estimated), $\nu_{p,k}{}^i$ is the error terms usually assumed normally distributed with zero mean and $\sigma_{\nu pk}$ standard deviation.

Regarding the psychometric indicators, they were coded through the Likert scale (Likert, 1932). For the sake of simplicity and practical issues, indicators are usually considered a linear continuous expression of LV; however, this assumption may neglects the nature of indicators which have to be treated as ordinal (Daly et al., 2012) and introduce some biases. Thus in this paper the indicators are treated in an ordered fashion. The psychometric indicators revealing latent variables associated with attitudes and perceptions are most of the time coded using a Likert scale (Likert, 1932) which has different levels; if the measurement is represented by an ordered discrete variable I taking the values $j_1, j_2, \dots, j_M$, we have:

$$I = \begin{cases} j_1 & \text{if } z < \tau_1 \\ j_2 & \text{if } \tau_1 \leq z < \tau_2 \\ & \vdots \\ j_i & \text{if } \tau_{i-1} \leq z < \tau_i \\ & \vdots \\ j_M & \text{if } \tau_{M-1} \leq z \end{cases}$$

where z is defined by the measurement equation, and $\tau_1, \dots, \tau_{M-1}$ are parameters to be estimated, such that $\tau_1 \leq \tau_2 \leq \cdots \leq \tau_i \leq \cdots \leq \tau_{M-1}$. As the measurements are using a Likert scale with M = 5 levels, we define 4 parameters τ_i. In order to account for the symmetry of the indicators, we actually define two positive parameters δ_1 and δ_2, and define

$$\tau_1 = -\delta_1 - \delta_2; \tau_2 = -\delta_1; \tau_3 = \delta_1; \tau_4 = \delta_1 + \delta_2$$

Finally, the probability of a given response is $\Pr(I_i = j_i) = \Pr(\tau_{i-1} \leq z \leq \tau_i)$ The choice utility and the structural and measurement functions were specified starting from a set of attributes. These attributes can be subdivided in two different categories: if they are related to the users' characteristics, or related to the vehicles. In the former group the investigated attributes were the sociodemographic characteristics, the displacement types, the engine characteristics of the owned car and the Price compared to user's conventional car Attitudes towards Instrumental attributes. Meanwhile, in the second category five sub-groups of attributes have been identified that include different statements aiming to collect the users' concerns, attitudes and perceptions. In particular, they refer to the attitudes towards the instrumental attributes, the perceptions of EVs' advantages and disadvantages, the attitudes towards the environment, and the users' concern about EV's price. A more detailed description of the attributes is provided in following section focusing on the estimation results.

5. RESULTS AND DISCUSSION

In this section the estimation results are provided and discussed. Models calibration is based not only on sociodemographic attributes, but specially on users' perceptions of technical features and environment and on their perceptions of some investigated advantages and disadvantages. They are also suitable in order to draw some important operative remarks for government policies and car manufactures strategies in order to increase EV market penetration.

Three different models were estimated:

1) A Mixed Multinomial Logit Model (MMNL0) with random parameters distribution in which attitudes and perceptions are not included in the specification model and then it is considered a benchmark model;
2) A Mixed Multinomial Logit Model (MMNL) in which the role of attitudes and perceptions is preliminary investigated through dummy variables;
3) A HCM in which users' attitudes and perceptions are properly modelled trough hybrid choice models based on latent variables estimations.

Investigated attributes may be grouped in nine subcategories as in following summarized:

[1] Socio economic attributes (*gender; age; number of family members in household; number of vehicles in household; number of vehicles divided by the number of members*);

[2] Displacement type (*type of main displacement performed by the vehicle in possession*);

[3] Owned car engine (*type of fuel of the main vehicle owned*);

[4] Price compared to user's conventional car Attitudes towards Instrumental attributes (*variation of the monthly cost between EV and CV*);

[5] Attitudes towards instrumental attributes (*Importance of technical features; importance of power; importance of top speed; importance of acceleration; importance of range*);

[6] Attitudes towards environment (*Importance of consumption/of pollution*);

[7] Perceptions of the advantages of EV (*Importance of having a simpler vehicle by having fewer moving parts; importance of greater energy efficiency; importance of CO2 reduction; importance of acoustic pollution reduction*);

[8] Perceptions of the disadvantages of EV (*Importance of lack of infrastructure; importance of reduced features of an EV; Importance of limited battery range*);

[9] Users' concerns about EV's price (*Importance of price; importance of higher price of an EV*).

In all cases models were significant and the signs of the parameters were consistent with the expectations. An overview of models' statistics is displayed in following Table 8.

Table 8: Models statistics

Survey	Models	*Init log-likelihood*	*Final log-likelihood*	*rho-square*	*adjusted rho-square:*
ARG	HCM	*-1339.85*	*-583.47*	*0.565*	*0.543*
	$MMNL_0$		*-667.60*	*0.502*	*0.497*
	MMNL		*-560.92*	*0.581*	*0.568*
ITA	HCM	*-1013.38*	*-385.55*	*0.620*	*0.596*
	$MMNL_0$		*-391.60*	*0.614*	*0.607*
	MMNL		*-365.37*	*0.639*	*0.625*

First of all it may be observed that models' rho-squares related to the Italian survey are slightly higher than them related to the Argentinean survey. Furthermore within each survey results highlight that the models are in general very similar in terms of goodness-of-fit.

Table 9: Estimation results – Mixed Logit without dummies

Attribute	ARG		ITA	
	BUY	NOT BUY	BUY	NOT BUY
ASC	**+4.120** *(+8.98)*		**+5.41** *(+9.02)*	
SE_age_less25		**+0.245** *(+1.04)**		
SE_delta_age				**+0.192** *(+1.77)*
SE_male		**+0.684** *(+3.06)*		**+0.806** *(+2.71)*
SE_n_car		**+0.146** *(+1.37)**		
SE_n_ family		**+0.089** *(+1.12)**		
SE_alim_diesel				**+0.619** *(+2.26)*
VAR_monthly_cost		**+0.0875** *(+15.53)*		**+0.133** *(+14.51)*
S_VAR_monthly_cost		**+0.011** *(+1.52)**		**+0.025** *(+3.93)*

Estimation results for $MMNL_0$ (Table 9) show that age, gender and monthly cost were all statistically significant in both case studies. In particular, being male and younger increase the probability of not buying an EV. Indeed, male students are more attracted by a traditional and more performing vehicle, whereas younger students do not perceive (or are less conscious) of the overall benefits of more a sustainable vehicle. The monthly cost is the only randomly distributed [9]attribute (in accordance with the random parameters specification) and, as expected, decreases the probability to buy an EV. However, it is interesting to note how the standard deviation for both case studies are similar (13% of the estimated coefficient for the Argentina case study and 19% for Italian case study). For completeness it must be highlighted that have been also tested the error components but the monthly cost randomly distributed attribute was the only significant one. Furthermore regarding the random parameters distribution two functional forms have been tested the normal distribution and the lognormal distribution and the most significant was the normal distribution. In both case studies, it should also be noted how the alternative specific constants (positive in Buying alternative) show high values, indicating a not negligible propensity to buy an EV independently from measurable and/or observable attributes. This result is worth of note, since highlights how the main determinants of the choice process might not be easily observed/measured.

The two models differ for two attributes: the proxy attribute of income and the fuel type of the main vehicle owned by the interviewee.

Regarding the income some proxy attributes have been tested in both models: firstly the ratio between number of vehicles and the number of family components which was not significant in both surveys and then the number of vehicles and the number of family components (number of vehicles may be considered a proxy of the income are significant only in the Argentinean survey, and increase the probability of not- buying an EV. Regarding the number of owned internal combustion engine vehicles (ICEV) it must be highlighted that the greater is, the smaller the probability of buying an EV is. This result indicates that Argentinean users will prefer to continue to buy an ICEV if they already own an ICEV, and as the number of the owned vehicles increases the probability of buying an EV rapidly decreases. A different interpretation holds for the number of households. Large families show smaller propensity to buy a EV, indeed they continue to

[9] The monthly cost attribute was the only continuous attributes differently from the others.

prefer an ICEV, preferring a riskless behaviour. The two attributes are not statistically significant for the Italian case study for two main reasons. Though the market is immature, the EV users' perception is not such immature as in the Argentinean market, and the users perceive EVs in the same way as they perceive ICEVs.

By contrast, type of fuel of the main vehicle owned by the interviewee [*SE_alim_diesel*] attribute representing that the main vehicle owned by the interviewee is diesel fuel type, plays a role in the Italian case study only. In this case, Italian users which already own a diesel ICEV are more inclined in continuing to buy an ICEV diesel solution.

The previous model was further improved including dummy variables (see Table 11). First of all it is important to highlight how all the previously introduced attributes continue to be statistically significant.

With regards to dummy variables, it is interesting to distinguish those dummy variables significant in both case studies from the all the others ones.

In particular, attributes statistically significant in both case studies are listed in the following:

- The importance of technical features (F_tech_fea)
- The importance of pollution (F_poll)
- The importance of consumption (F_cons)
- The Importance of reduction of CO2 (AD_red_co2)
- The importance of greater energy efficiency (AD_efficiency)
- Importance of the lack of infrastructure (DIS_infr)
- The importance of the reduced features of an EV (DIS_red_fea)

The interpretation is straightforward.

Users that show more attention to the technical features of a car are less inclined to buy an EV; whereas, users sensitive to car pollution, consumption, and energy efficiency show an higher propensity to buy an EV. Estimation results show the not negligible weight of the afore-mentioned attributes, and show how only highly concerned users are attracted by an EV (level of concerns greater than 4). These results allow to conclude that the typical features of an EV are clearly perceived by both Italian and Argentinian users and that the level of users' involvement is a crucial point for EV market penetration.

Analysing the coefficient values in both case studies (ratio between dummy variable coefficient and monthly cost attribute) , it is interesting to note the technical features as well as the reduced features of an EV are equally important for both type of users, whilst consumption and lack of infrastructure are more important for Italian users and pollution, reduction of CO2 and efficiency concerns are much more important for Argentinean users. Power is also significant in the Argentinean sample whereas acceleration is significant in Italian survey. Furthermore, air pollution as well as the pollution reduction and the battery range play a role only in the Argentinean model; in particular the first two attributes positively affect the probability of buying an EV whilst the third one has negative sign highlighting the impacts of EV disadvantages. Also, the acceleration negatively affect the probability of buying an EV. These results indicates the differences existing between the two potential contexts, partially dependent from the type and maturity of markets.

Preliminary results highlight that the two surveys have comparable attitudes whilst different perceptions are present in users particularly related to the disadvantages which are further related to the battery range in case of Argentina depending on longer distances usually travelled by respondents. On the statistical point of view, it may be also discussed the difference in the magnitude of the alternative specific constant which is comparable in first model ($MMNL_0$ without dummies) and lower in the Argentina case study in the second one (MMNL with dummies) highlighting that dummy variables are more effective in the second case on explaining users' behaviour.

Indeed, in general benchmark models with respect to the basic attributes compared to the alternative specific constants provide similar results, on the other side results in MMNL with dummy variables are significantly different in accordance with following table showing the (mean) ratios of attitudes and perceptions attributes with respect to the alternative specific constant.

Table 10: Mean values of the ratios of latent variables with respect to the alternative specific constant.

Attitude/Perceptions	ARG	ITA
ATT - Technical Features	18.6%	2.6%
ATT - Environment	39.7%	10.4%
Perception Advantages	60.3%	6.3%
Perception Disadvantages	43.8%	9.1%

Table 11: Estimation results – Mixed Logit

Attribute	**ARG**		**IT**	
	BUY	**NOT BUY**	**BUY**	**NOT BUY**
ASC	**+1.41** *(+1.55)*		**+4.90** *(+3.06)*	
SE_male		**+0.39** *(+1.64)*		**+0.80** *(+2.79)*
SE_n_family		**+0.11** *(+1.42)**		
SE_alim_diesel				**+0.56** *(+2.08)*
SE_delta_age				**+0.23** *(+2.08)*
F_tech_fea_9		**+0.45** *(+1.27)**		**+0.39** *(+1.00)**
TF_power_9	**+1.15** *(+1.84)*			
TF_power_7_5	+0.50 *(+1.39)**			
TF_accel_9_7_5				**+0.62** *(+1.98)*
F_poll_9	**+1.27** *(+2.92)*		**+0.46** *(+0.69)**	
F_cons_9_7_5	**+0.97** *(+1.71)*		**+1.58** *(+1.86)*	
AD_red_co2_9	**+0.93** *(+3.83)*			
AD_red_co2_9_7			**+0.54** *(+1.51)*	
AD_red_poll_9_7	**+0.74** *(+2.96)*			
AD_efficiency_9_7_5	**+1.73** *(+2.78)*		**+0.69** *(+2.03)*	
DIS_infr_9		**+0.29** *(+1.19)*		
DIS_infr_9_7_5				**+1.23** *(+1.03)*
DIS_red_fea_9		**+1.07** *(+2.22)*		**+0.99** *(+1.88)*
DIS_batt_range_9		**+1.27** *(+3.72)*		
DIS_batt_range_7		**+0.46** *(+1.44)*		
VAR_monthly_cost		**+0.11** *(+17.07)*		**+0.14** *(+14.79)*
S_VAR_monthly_cost		**+0.02** *(+3.80)*		**+0.02** *(+3.51)*

Finally, the estimation results of HCM are discussed. Regarding the identification of latent variables and the specifications of the measurement equations, a preliminary principal factor analysis [10](PCA) on all perceptions indicators is required. Indeed in order to identify the attitudes affecting individuals' choices and characterize them by identifying the statements measuring these attitudes, the exploratory factor analysis was performed. The achieved results of the component matrix and the rotated component matrix (using Varimax with Kaiser Normalization) are shown for the Argentinean case study in Table 12 and Table 13, for Italian case study in Table 14 and Table 15. In both cases, based on the achieved results of a calculated PCA with varimax rotation, 2 scales remained and other items were excluded from further analysis.

Table 12: Component matrix – Argentina survey

Variables	***Component***	
	1	**2**
TF_power	0.814	-0.136
F_tech_fea	0.767	-0.191
TF_acceleration	0.737	-0.125
F_consumption	0.119	0.814
F_pollution	0.224	0.786

Table 13: Rotated component matrix (Varimax with Kaiser Normalization).– Argentina survey

Variables	***Component***	
	1	**2**
TF_power	0.826	0.013
F_tech_fea	0.771	0.048
TF_acceleration	0.748	0.010
F_consumption	-0.029	0.822
F_pollution	0.079	0.814

Table 14: Component matrix – Italy survey

Variables	***Component***	
	1	**2**
AD_red_CO2	0.721	-0.306
AD_red_poll	0.601	-0.018
AD_efficiency	0.553	-0.532
F_consumption	0.548	0.518
F_pollution	0.352	0.686

Table 15: Rotated component matrix (Varimax with Kaiser Normalization). – Italy survey

Variables	***Component***	
	1	**2**
AD_red_CO2	0.773	0.125
AD_red_poll	0.751	-0.156
AD_efficiency	0.519	0.305
F_consumption	-0.068	0.768
F_pollution	0.188	0.731

In general all tested and significant attributes in case of latent variables models are summarised in following tables 16 and 17.

[10] For sake of brevity the results are displayed in the Appendix only with reference to the significant perception indicators.

Table 161: Overview of investigated attributes: description; correspondence with models in which they have been tested

Summary of the tested attributes × Argentina | • Italy																							
Subcategory	Attribute	Description	Min	Max	V^1 – EV		V^2 – CV		LV_1^1				LV_2^1			LV_3^1				LV_4^1			
					X^1	X^1_{SE}	X^2	X^2_{SE}	$X^1_{SE,1}$	$I^1_{1,1}$	$I^1_{1,2}$	$I^1_{1,3}$	$X^1_{SE,2}$	$I^1_{2,1}$	$I^1_{2,2}$	$X^1_{SE,3}$	$I^1_{3,1}$	$I^1_{3,2}$	$I^1_{3,3}$	$X^1_{SE,4}$	$I^1_{4,1}$	$I^1_{4,2}$	$I^1_{4,3}$
1	SE_{male}	Interviewee's Gender (0 = female; 1 = male)	0	1		×•			×•				×•			×•				×•			
	SE_{age_17}	Age class of individuals. (1 = if Age ≤ 17)	0	1		•																	
	$SE_{age\_18\_24}$	Age class of individuals. (1 = if 18 ≤ Age ≤ 24)	0	1		•																	
	$SE_{age\_25\_29}$	Age class of individuals. (1 = if 25 ≤ Age ≤ 29)	0	1		•																	
	$SE_{age\_30\_34}$	Age class of individuals. (1 = if 30 ≤ Age ≤ 34)	0	1		•																	
	SE_{age_less25}	Age class of individuals. (1 = if Age ≤ 25)	0	1		×							×							×			
	SE_{delta_age}	Age class of individuals (0 = 19 years; 1 = 20 years; 2 = 21 years; 3 = 22 years; 4 = 23 years; 5 = 24 years; 6 = 25 years; 7 = 26 years)	0	7		•			•				•			•				•			
	SE_{n_family}	Number of family members in household	0	1		×•							×										
	SE_{n_car}	Number of vehicles in household	0	1		×•							×										
	$SE_{n\_car\_family}$	Number of vehicles divided by the number of family members	0	1		×•			×•				×			×•				×			
2	SE_{use_urban}	Type of the main displacement performed by the vehicle in possession (1 = Urban displacements)	0	1		×																	
	SE_{use_extrau}	Type of the main displacement performed by the vehicle in possession (1 = Extra urban displacements)	0	1		×																	

	SE_{use_cargo}	Type of the main displacement performed by the vehicle in possession (1 = as a Cargo vehicle)	0	1						
3	$SE_{alim\_gasoline}$	Type of fuel of the main vehicle owned by the interviewee (1 = if fuelled by Gasoline)	0	1	×			×		×
	SE_{alim_diesel}	Type of fuel of the main vehicle owned by the interviewee (1 = if fuelled by Diesel)	0	1	×•					
	SE_{alim_gnc}	Type of fuel of the main vehicle owned by the interviewee (1 = if fuelled by compressed natural gas)	0	1						
	SE_{alim_no}	Possession of a vehicle by the interviewee (1 = if doesn't own a car)	0	1	•			×		×
4	$VAR_{monthly\_cost}$	Variation in monthly cost [EUR] between an Electric car and a conventional one	0	80		×•				
5	F_{tech_fea}	Importance of Technical Features (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•		×• ×• ×•			
	TF_{power}	Importance of Power (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•		× × ×			
	TF_{top_speed}	Importance of Top Speed (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					
	TF_{accel}	Importance of Acceleration (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•		×• ×• ×•			
	TF_{range}	Importance of Range (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					

6	F_{cons}	Importance of Consumption (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•			×• ×•		
	F_{poll}	Importance of Pollution (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•			×• ×•		
7	$AD_{simplicity}$	Importance of having a simpler vehicle by having fewer moving parts (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					
	$AD_{efficiency}$	Importance of Greater energy efficiency (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					×• ×• ×•
	AD_{red_co2}	Importance of Reduction of CO2 (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					×• ×• ×•
	AD_{red_poll}	Importance of Reduction of acoustic pollution (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					× × ×
8	DIS_{infr}	Importance of the Lack of infrastructure (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•				×• ×• ×•	
	DIS_{red_fea}	Importance of the Reduced Features of an EV (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•				×• ×• ×•	
	DIS_{batt_range}	Importance of the limited Battery range (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•				× × ×	
9	F_{price}	Importance of Price (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5						
	DIS_{price}	Importance of Higher Price of an EV (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5						

Table 17: Overview of significant attributes: description; correspondence with models in which they have been tested

Summary of the significant attributes × Argentina | • Italy																							
Sub$_{category}$	**Attribute**	**Description**	**Min**	**Max**	V^1 – EV		V^2 – CV		LV_1^1				LV_2^1			LV_3^1				LV_4^1			
					X^1	X^1_{SE}	X^2	X^2_{SE}	$X^1_{SE,1}$	$I^1_{1,1}$	$I^1_{1,2}$	$I^1_{1,3}$	$X^1_{SE,2}$	$I^1_{2,1}$	$I^1_{2,2}$	$X^1_{SE,3}$	$I^1_{3,1}$	$I^1_{3,2}$	$I^1_{3,3}$	$X^1_{SE,4}$	$I^1_{4,1}$	$I^1_{4,2}$	$I^1_{4,3}$
1	SE_{male}	Interviewee's Gender (0 = female; 1 = male)	0	1		×•			×				×•							•			
	SE_{age_17}	Age class of individuals. (1 = if Age ≤ 17)	0	1																			
	$SE_{age\_18\_24}$	Age class of individuals. (1 = if 18 ≤ Age ≤ 24)	0	1																			
	$SE_{age\_25\_29}$	Age class of individuals. (1 = if 25 ≤ Age ≤ 29)	0	1																			
	$SE_{age\_30\_34}$	Age class of individuals. (1 = if 30 ≤ Age ≤ 34)	0	1																			
	SE_{age_less25}	Age class of individuals. (1 = if Age ≤ 25)	0	1																			
	SE_{delta_age}	Age class of individuals (0 = 19 years; 1 = 20 years; 2 = 21 years; 3 = 22 years; 4 = 23 years; 5 = 24 years; 6 = 25 years; 7 = 26 years)	0	7		•														•			
	SE_{n_family}	Number of family members in household	0	1		×																	
	SE_{n_car}	Number of vehicles in household	0	1																			
	$SE_{n\_car\_family}$	Number of vehicles divided by the number of family members	0	1					×				×										
2	SE_{use_urban}	Type of the main displacement performed by the vehicle in possession (1 = Urban displacements)	0	1																			
	SE_{use_extrau}	Type of the main displacement performed by the vehicle in possession (1 = Extra urban displacements)	0	1																			

	SE_{use_cargo}	Type of the main displacement performed by the vehicle in possession (1 = as a Cargo vehicle)	0	1						
3	$SE_{alim\_gasoline}$	Type of fuel of the main vehicle owned by the interviewee (1 = if fuelled by Gasoline)	0	1				×		
	SE_{alim_diesel}	Type of fuel of the main vehicle owned by the interviewee (1 = if fuelled by Diesel)	0	1	•					
	SE_{alim_gnc}	Type of fuel of the main vehicle owned by the interviewee (1 = if fuelled by compressed natural gas)	0	1						
	SE_{alim_no}	Possession of a vehicle by the interviewee (1 = if doesn't own a car)	0	1				×		
4	$VAR_{monthly\_cost}$	Variation in monthly cost [EUR] between an Electric car and a conventional one	0	80		×•				
5	F_{tech_fea}	Importance of Technical Features (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•		× × ×			
	TF_{power}	Importance of Power (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×		× × ×			
	TF_{top_speed}	Importance of Top Speed (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5						
	TF_{accel}	Importance of Acceleration (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	•		× × ×			
	TF_{range}	Importance of Range (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5						

6	F_{cons}	Importance of Consumption (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•			×• ×•		
	F_{poll}	Importance of Pollution (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•			×• ×•		
7	$AD_{simplicity}$	Importance of having a simpler vehicle by having fewer moving parts (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	•					
	$AD_{efficiency}$	Importance of Greater energy efficiency (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					• • •
	AD_{red_co2}	Importance of Reduction of CO2 (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					• • •
	AD_{red_poll}	Importance of Reduction of acoustic pollution (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×					• • •
8	DIS_{infr}	Importance of the Lack of infrastructure (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					
	DIS_{red_fea}	Importance of the Reduced Features of an EV (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					
	DIS_{batt_range}	Importance of the limited Battery range (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5	×•					
9	F_{price}	Importance of Price (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5						
	DIS_{price}	Importance of Higher Price of an EV (5= Strongly agree; 4= Agree; 3= Neutral; 2= Disagree; 1= Strongly disagree)	1	5						

In particular in the Argentinian case study the attitudes about the technical features (LV1) and the environment (LV2) were considered whilst, in the Italian case study, the attitudes about the environment (LV2) and the EV advantages (LV4) were evaluated. To be more precise, these latent variables representing users' attitudes and perceptions were specified as in following detailed:

- $LV_1^1 = \gamma_1 + \Sigma_i \beta_{1,i} \cdot X_{1,i} + \omega_1$, be the attitude towards Technical Features;
- $LV_2^1 = \gamma_2 + \Sigma_i \beta_{2,i} \cdot X_{2,i} + \omega_2$, be the attitude towards Environment;
- $LV_4^1 = \gamma_4 + \Sigma_i \beta_{4,i} \cdot X_{4,i} + \omega_4$, be the perception of EV advantages.

Furthermore, in accordance with the provided statistical analyses, the significant statements for each one of three latent variables are summarised in table below.

Table 18: Overview of significant statements for both surveys

LV_1^I	LV_2^I	LV_4^I
F_tech_fea $[I^1_{1,1}]=\alpha_{11} + \lambda_{11} \cdot LV_1^I + \nu_{11}$ *[The vehicle technical features significantly influence my choice in purchasing a new car]*	*F_cons* $[I^1_{2,1}]=\alpha_{21}+ \lambda_{21} \cdot LV_2^I + \nu_{21}$ *[The vehicle fuel consumption significantly influences my choice in purchasing a new car]*	*AD_red_co2_x* $[I^1_{4,1}]=\alpha_{41} + \lambda_{41} \cdot LV_4^I + \nu_{41}$ *[I am interested in EV to contribute to the emissions reduction]*
TF_power $[I^1_{1,2}]=\alpha_{12} + \lambda_{12} \cdot LV_1^I + \nu_{12}$ *[I prefer driving a car with a powerful engine]*	*F_poll* $[I^1_{2,2}]=\alpha_{22} + \lambda_{22} \cdot LV_2^I + \nu_{22}$ *[I am willing to purchase a car that emit little carbon dioxide]*	*AD_efficiency_x* $[I^1_{4,2}]=\alpha_{42} + \lambda_{42} \cdot LV_4^I + \nu_{42}$ *[Compared to a normal car, EV are superior in terms of energy efficiency]*
TF_accel $[I^1_{1,3}]=\alpha_{13} + \lambda_{13} \cdot LV_1^I + \nu_{13}$ *[The immediate acceleration increases my driving pleasure]*	-	*AD_red_poll_x* $[I^1_{4,3}]=\alpha_{43} + \lambda_{43} \cdot LV_4^I + \nu_{43}$ *[I believe using EV can significantly reduce the acoustic pollution]*

Final estimation results are shown in following Table 19, Table 20 and Table 21.

First of all, it may be observed that all sociodemographic attributes are not still significant in the choice model but only in the structural one in the meantime some dummy variables which are not significant as perceptions indicators in attitudes/perceptions are introduced in the choice model. In particular the importance of technical features attribute [*F_tech_fea [9]*] is the only variable representing the attitude about technical features in Italian survey, whilst all the advantages and disadvantages are significant in Argentinean sample and finally reduced features are significant in Italian survey. It is most important to observe that the alternative specific constants are not still significant highlighting the explaining role of introduced latent variables.

Table 19: Estimation results – HCM/choice model

Attribute	ARGENTINA		ITALY	
	BUY	**NOT-BUY**	**BUY**	**NOT-BUY**
VAR_monthly_cost_abs		**+0.0963**		**+0.118**
		(+22.12)		*(+17.65)*
F_tech_fea [9]				**+0.451**
				(+1.67)
AD_red_co2 [9]	**+1.08**			
	(+6.45)			
AD_red_poll [9-7]	**+0.546**			
	(+3.18)			
AD_efficiency [9-7-5]	**+2.57**			
	(+8.10)			
DIS_red_fea [9]		**+0.764**		**+0.778**
		(+2.42)		*(+2.25)*
DIS_batt_range [9]		**+1.09**		
		(+5.16)		
DIS_batt_range [7]		**+0.341**		
		(+1.69)		
B_LV_1		**+0.665**		
		(+3.15)		
B_LV_2	**+0.296**		**+2.100**	
	(+4.10)		*(+11.86)*	
B_LV_4			**+0.435**	
			(+1.57)	
DELTA TAU_1	**0.785**		**+0.531**	
	(+40.27)		*(+30.25)*	
DELTA TAU_2	**1.48**		**+1.27**	
	(+43.93)		*(+38.94)*	

** in parenthesis the t-test values*

Furthermore, as already anticipated, two latent variables are introduced in each one of two models, the attitudes about technical features and environment in the Argentinean sample and the attitudes about the environment and the advantages perceptions in Italy. This result may be evaluated considering that due to higher level of diffusion of EV in Italy, users' perceptions of advantages are more evident than Argentinean respondents which are particularly adverse due to the preconception of limiting technical features (not affected by directly experiences). In general, for both surveys the attitudes towards the environment is significant. The signs of all estimates are in line with the identified nature of each latent – attitude variable. Results highlight that the environment has a positive effect on the willingness to purchase an EV as well as the perception of EV advantages; whereas the attitude towards the technical features negatively affects the willingness to purchase an EV meaning that concerns about technical features significantly reduce the willingness to purchase an EV.

Table 20: Estimation results – HCM/structural model

STRUCTURAL MODEL		
Attributes	**ARGENTINA**	**ITALY**
LV 1: Technical Features		
β_{MEAN1}	-1.83 *(-26.02)*	
ω_1	+0.217 *(+3.29)*	
SE_male	+0.28 *(+4.32)*	
SE_n_car_family	-0.39 *(-3.36)*	
LV 2: Environment		
β_{MEAN2}	-0.389 *(-3.02)*	+1.83 *(+33.70)*
ω_2	+1.82 *(+29.26)*	+0.119 *(+3.84)*
SE_male	-0.875 *(-7.97)*	-0.242 *(-5.41)*
SE_n_car_family	-1.61 *(-8.47)*	
LV 4: EV's advantages		
β_{MEAN4}		+0.857 (+11.57)
ω_4		+0.584 *(+9.86)*
SE_male		-0.0445 *(-1.01)*
Delta_age		-0.0246 *(-1.39)*

Regarding measurement model, as already anticipated in section 3.2, for each one of the significant latent variables some statements which link the latent variables to the psychometric indicators are identified; and for each latent variable one indicator has been normalized to 1. All signs are consistent with the interpretative expectations. In particular in the Argentinean survey it must be observed that car power is positively linked to the attitudes towards the technical features, whereas that technical features and car acceleration are negatively linked; regarding the environment both statements are positively related to the attitude towards the environment in both surveys in particular the difference is that in the Argentinean survey normalisation is with respect to the first indicator whilst in Italian survey it is with respect to the second one. Furthermore, in Italian sample, in terms of advantages perception, all significant statements playing a role in a model about emission, energy efficiency and acoustic pollution are positively linked to the latent variable. In this last case, normalization has been made with respect to the acoustic pollution statement.

Table 21: Estimation results – HCM/measurement model

MEASUREMENT MODEL							
ARGENTINA				*ITALY*			
LV 1: Technical Features		*LV 2: Environment*		*LV 2: Environment*		*LV 4: EV's advantages*	
F_tech_fea		*F_cons*		*F_cons*		*AD_{Red_CO2}*	
α_{10}	0	α_{20}	0	α_{20}	-4.62 *(-4.92)*	α_{40}	+0.391 *(+2.96)*
λ_{10}	-1	λ_{20}	1	λ_{20}	+2.85 *(+5.23)*	λ_{40}	+1.32 *(+8.40)*
ν_{10}	1	ν_{20}	1	ν_{20}	+1.03 *(+30.15)*	ν_{40}	+0.742 *(+11.55)*
TF_power		*F_poll*		*F_poll*		*$AD_{Efficiency}$*	
α_{11}	+0.515 *(+6.63)*	α_{21}	+1.55 *(+23.96)*	α_{21}	0	α_{41}	-0.143 *(-1.37)*
λ_{1}	-0.21 *(-3.02)*	λ_{21}	+0.362 *(+11.14)*	λ_{21}	1	λ_{41}	+0.881 *(+7.27)*
ν_{11}	+1.11 *(+42.19)*	ν_{21}	+1.25 *(+23.95)*	ν_{21}	1	ν_{41}	+1.22 *(+27.41)*
TF_accel						*AD_{Red_poll}*	
α_{12}	-0.205 *(-1.81)*					α_{42}	0
λ_{12}	-0.226 *(-2.26)*					λ_{42}	1
ν_{12}	1.38 *(+40.40)*					ν_{42}	1

Finally, in order to analyse the results, a proper comparison is provided in which the ratios between attributes of choice model and the level of service attribute are evaluated (Table 22).

Table 22: comparative analysis of the attitudes/perceptions ratios with respect to the level of service attribute

Attributes	**ARG**		**ITA**	
VAR_monthly_cost_abs		#		#
F_tech_fea [9]	0	0	0	3.82
AD_red_co2 [9]	11.22	0	0	0
AD_red_poll [9-7]	5.67	0	0	0
AD_efficiency [9-7-5]	26.69	0	0	0
DIS_red_fea [9]	**0**	**7.93**	**0**	**6.59**
DIS_batt_range [9]	0	11.32	0	0
DIS_batt_range [7]	0	3.54	0	0
B_LV_1	0	6.91	0	0
B_LV_2	**3.07**	**0**	**17.80**	0
B_LV_4	0	0	3.69	0

** common attributes are in bold*

Two main considerations may arise comparing the two models between them. The first one refers to importance of the reduced features attribute [*DIS_red_fea [9]*] which has a similar value in both models. The second one refers to the attitudes towards the environment which have higher value in terms of magnitude in the Italy case study. Moreover, within each model it may be concluded that in the Argentinean case study in terms of magnitude the technical features are higher than the environment, whereas in Italian survey, the environment magnitude is significantly higher than the advantages perception.

In general, results are consistent with the literature. The majority of these studies (Bunch et al., 1993; Batley, Toner and Knight, 2004; Horne, Jaccard and Tiedemann, 2005; Potoglou and Kanaroglou, 2007; Mabit and Fosgerau, 2011; Achtnicht, 2012; Daziano and Bolduc, 2013; Hackbarth and Madlener, 2013; Valeri and Cherchi, 2016) analysed the effect of car features (such as purchase price, driving range, fuel costs) and charging location (Batley, Toner and Knight, 2004; Bockarjova, Rietveld and Knockaert, 2013; Ito, Takeuchi and Managi, 2013; Jensen et al., 2017) on the AFV's demand. Some recent studies have also explored the role of individuals' attitudes, mainly toward environment sensitivity (Daziano and Chiew, 2012; Daziano and Bolduc, 2013; Jensen, Cherchi and Mabit, 2013; Glerum et al., 2014). Indeed, researchers highlighted that reasons of low penetration are related to the purchase price, some vehicle features which is further investigated in the paper with respect to the vehicle performances (power, acceleration) and perceived disadvantages such as the driving range and the charging infrastructures availability; on the other side, the attitude towards the environment significantly affects users' willingness to buy an EV.

6. SENSITIVITY ANALYSIS

In this section the results of a sensitivity analysis are displayed and discussed in order to further explore the explanatory power of HCM applied to the considered case studies.

Preliminary analyses are based on the choice probability shown in following table[11]. In general, consistently with models' statistics, overall results are very similar as previously anticipated on the base of models' statistics.

[11] In order to properly validate the model, we randomly split the sample in two parts: an 80% was considered in order to re-estimate the parameters, while this model was applied on the remaining 20%.

Table 232: Choice probabilities

	Observed choice		MML0		MML		HCM	
	ARG	ITA	ARG	ITA	ARG	ITA	ARG	ITA
0%	92,14%	93,40%	94,02%	97,79%	94,12%	97,60%	93,37%	97,20%
10%	77,62%	83,34%	73,60%	78,94%	73,90%	79,11%	74,66%	79,63%
20%	32,81%	33,69%	33,08%	25,53%	32,31%	27,78%	35,15%	31,05%
30%	7,14%	1,26%	8,43%	2,55%	8,25%	2,95%	9,94%	4,38%
40%	3,81%	1,26%	1,58%	0,18%	1,16%	0,20%	1,70%	0,43%

In the following further considerations are provided under specific scenarios (based on different ΔCost), varying choice attributes and measuring the effect in terms of direct and cross-elasticities. First evaluations are referred to the effect of VAR_monthly_cost_abs attribute, then other analyses are referred to the variations of latent attributes that may potentially highlight the opportunity of policy measures. All the above analyses are made for both models. First analysis discussed below refers to cross-elasticity with respect to the level of service attributes (VAR_monthly_cost_abs). Preliminary evaluation was referred to three reference values of the level of service attribute (ΔCost=10 €,20 € and 40 €); results are displayed in following diagram (see Figure 4), highlight that elasticities are more sensitive in case of higher differences (in case of higher values of VAR_monthly_cost_abs).

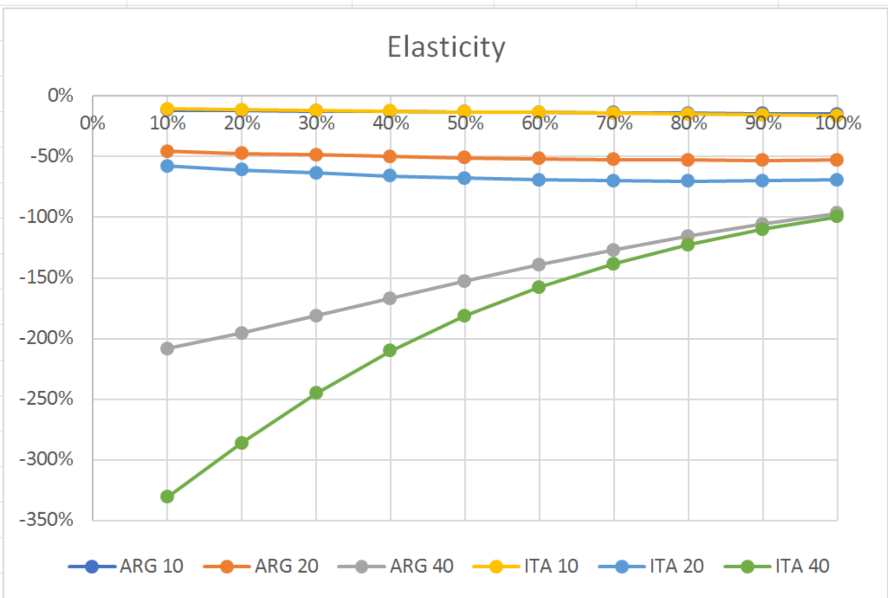


Figure 4: Cross –elasticities of HCM models for each sample

On the bases of previous considerations, a reference cost has been fixed equal to 40 euros therefore over different scenarios (still based on ΔCost variations) the cross elasticities and the absolute differences (ϕHCM- MML and ϕHCM- MML0) for each model are computed. First of all, it may be argued that within each sample, models provide similar results; moreover, calibrated models for the Italian survey is more elastic than model calibrated for the Argentinean survey, and, as already anticipated, results are more sensitive in case of values lower than the reference ΔCost than higher values (see Table 24).

A similar analysis was carried out in order to evaluate the sensitivity to the latent variables. In case of Argentina survey the effect of attitude about technical features (LV1) was analysed whereas in case of Italian sample the effect of the perception of advantages (LV4) was evaluated; the effect of attitude towards the environment (LV2) was finally considered on both samples.

Results are displayed in following Table 25. Regarding LV1 and LV2 lower values of elasticities are shown, particularly the lowest one is in Italian case study with respect to the perceived advantages, whilst slightly higher effects are observed in the Argentinean survey with respect to the technical features.

Table 25: Direct and cross elasticities with respect to the latent variables

Direct/Cross Elasticities				
ΔAttitude(s)	**ARGENTINA**	**ITALY**	**ARGENTINA**	**ITALY**
	(LV1: Att. Tech. Feat.)	(LV4: Per. advantages EV)	(LV2: Att. Environment)	
-100%	0.208	0.059	0.085	0.669
-90%	0.208	0.058	0.085	0.673
-80%	0.208	0.058	0.086	0.675
-70%	0.209	0.058	0.086	0.674
-60%	0.209	0.058	0.086	0.670
-50%	0.209	0.058	0.086	0.665
-40%	0.209	0.058	0.086	0.656
-30%	0.209	0.058	0.086	0.646
-20%	0.210	0.058	0.086	0.635
-10%	0.210	0.058	0.086	0.625
0%	-	-	-	-
10%	0.211	0.058	0.086	0.608
20%	0.211	0.058	0.086	0.602
30%	0.212	0.058	0.086	0.598
40%	0.212	0.058	0.086	0.596
50%	0.213	0.057	0.086	0.596
60%	0.213	0.057	0.086	0.599
70%	0.214	0.057	0.087	0.603
80%	0.214	0.057	0.087	0.609
90%	0.215	0.057	0.087	0.616
100%	0.215	0.057	0.087	0.622

On the other side it may be observed that, with respect to the environment, the Italian sample is more sensitive to the variable variation whilst it has a very slightly incidence in the Argentinean survey. Summing up Italian users are more sensitive to the environment whereas in Argentina are more sensitive to the technical features.

Table 24: Cross elasticities with respect to the VAR_monthly_cost_abs attribute

CROSS- ELASTICITIES											
ITALY						ARGENTINA					
Δ_{Cost}	MML	MML_0	HCM	$\phi_{HCM-MML}$	$\phi_{HCM-MML0}$	Δ_{Cost}	MML	MML_0	HCM	$\phi_{HCM-MML}$	$\phi_{HCM-MML0}$
-100%	-3.105	-3.608	-2.623	0.482	0.985	-100%	-1.706	-1.780	-1.479	0.227	0.301
-90%	-3.374	-3.931	-2.848	0.527	1.083	-90%	-1.823	-1.903	-1.578	0.245	0.325
-80%	-3.664	-4.282	-3.091	0.573	1.191	-80%	-1.941	-2.028	-1.680	0.261	0.348
-70%	-3.960	-4.642	-3.342	0.618	1.300	-70%	-2.057	-2.151	-1.782	0.274	0.368
-60%	-4.238	-4.975	-3.583	0.656	1.392	-60%	-2.162	-2.262	-1.879	0.283	0.383
-50%	-4.466	-5.229	-3.787	0.679	1.442	-50%	-2.250	-2.353	-1.965	0.285	0.388
-40%	-4.599	-5.341	-3.920	0.679	1.421	-40%	-2.310	-2.414	-2.032	0.278	0.382
-30%	-4.600	-5.261	-3.949	0.651	1.312	-30%	-2.336	-2.435	-2.075	0.261	0.361
-20%	-4.449	-4.979	-3.855	0.594	1.125	-20%	-2.324	-2.413	-2.088	0.237	0.326
-10%	-4.154	-4.533	-3.640	0.514	0.893	-10%	-2.275	-2.348	-2.068	0.206	0.279
0%	-	-	-	-	-	0%	-	-	-	-	-
10%	-3.304	-3.440	-2.981	0.323	0.458	10%	-2.081	-2.112	-1.939	0.143	0.173
20%	-2.857	-2.926	-2.622	0.235	0.304	20%	-1.952	-1.961	-1.838	0.114	0.124
30%	-2.450	-2.482	-2.288	0.162	0.194	30%	-1.811	-1.804	-1.722	0.090	0.083
40%	-2.101	-2.114	-1.993	0.108	0.121	40%	-1.667	-1.649	-1.598	0.070	0.051
50%	-1.810	-1.815	-1.741	0.070	0.075	50%	-1.526	-1.502	-1.472	0.053	0.029
60%	-1.574	-1.575	-1.530	0.044	0.045	60%	-1.391	-1.366	-1.351	0.040	0.015
70%	-1.382	-1.382	-1.355	0.027	0.028	70%	-1.267	-1.243	-1.237	0.030	0.006
80%	-1.226	-1.226	-1.209	0.017	0.017	80%	-1.155	-1.134	-1.133	0.022	0.002
90%	-1.099	-1.099	-1.089	0.010	0.010	90%	-1.055	-1.038	-1.039	0.016	-0.001
100%	-0.994	-0.993	-0.987	0.006	0.006	100%	-0.967	-0.953	-0.955	0.012	-0.002

7. CONCLUSIONS AND FUTURE PERSPECTIVES

Several studies have demonstrated that Electric vehicles (EV) are an effective option in order to mitigate the congestion impact in terms of fuel consumption. Therefore it is expected that the EV market penetration is supported by the potential advantages. However EVs market penetration faces two main kinds of barriers which are the technological feasibility and the social acceptance and perception. In general the technological barriers are mainly related to the immature batteries and inadequate refueling infrastructures while social barriers may be identified with the lack of knowledge and then the inertia in the acceptance of new technologies. This two kinds of barriers are strictly related between them specially in case of immature markets where a further classification in ‘aware’ and ‘not-aware’ may be introduced in order to highlight that users may have a different technology perception; the main difference between them is in the lack of information and experience that negatively affect users’ choice. In particular in the former case, it can be assumed that the potential users have a clear perception of EVs, but the electric mobility has negligible market shares and is not supported by adequate technological infrastructures; in the latter case, the potential users have knowledge of the technology, but EVs are not even commercialized and no charging infrastructures exist.

In general the main factors affecting the users’ behaviours may be grouped in technological, political and economic, however this is not enough in order to properly interpret the users’ behaviour and then exhaustively support industrial and marketing strategies. Within the aforementioned context, the aim of the paper was twofold: (i) to investigate the main behavioral determinants of the choice process; (ii) to set up an operational model suitable for real case studies applications and then able to support the government and marketing strategies. Then the paper focuses on the investigation of the main determinants influencing the willingness to purchase an EV in two different “immature” markets Italy, as aware market and Argentina as not aware market. The main purposes of the paper rely on (i) the survey data collection, (ii) data analysis, (iii) purchase behavior modelling.

Three models were calibrated: two Mixed Multinomial Logit Models and a latent variables Hybrid Choice Model; the main difference between the two proposed MMNL models was on the introduction of dummy variables aiming to capture the users' attitudes and perceptions.

Our results allow both operational and methodological conclusions to be drawn. In particular the results highlighted that the behavioral assumptions made were reasonable and the choice mechanism can be fruitfully interpreted and modelled within the random utility paradigm. Furthermore, modelling the willingness to purchase an electric vehicle may be interest of manufacturers and decision – makers since it provides information on how influence the choice to buy an EV.

In general estimation results highlight the main determinants within each context of choice and then the difference between them.

Three classes of attributes were tested in the first MMNL model: the socio economic characteristics, the displacement type, the owned car engine and the variation of monthly cost between the electric vehicle and the conventional car. In both surveys being male and younger increase the probability of not buying an EV as well as the monthly cost; two models differ only for the number of owned cars and the number of family members that are significant in the Argentinean survey as proxy of the income; whilst in the Italian survey the diesel fuel type of the main vehicle owned by the interviewee is significant and influences the probability of not buying an EV. Regarding the monthly cost it must be specified that it follows the random distribution empathizing that the explicit simulation of taste variation allows for a better goodness-of-fit.

The same attributes were significant in the second MMNL model which was based on the introduction of the dummy variables focusing on the representation of non-observable variables affecting users 'behaviour. In order to provide a general overview the significant attributes in both surveys were about technical features, air pollution, fuel consumption, energy efficiency, lack of infrastructures and reduced features.

The tested dummy variables aimed to describe

- the users' attitudes about EV technical features and towards the environment
- the users' perceptions of EV advantages/disadvantages
- the users 'concerns about EV price.

In order to stress the relevant differences between two surveys it must be specified that consumption and lack of infrastructure are more important in Italian survey whilst Argentinean survey is more sensitive to pollution, reduction of CO2 and efficiency.

Furthermore pollution, pollution reduction and the battery range are significant only the Argentinean survey. Regarding power and acceleration this are respectively significant in the Argentinean and Italy samples.

Finally it must be observed that the role of the dummy variables is highlighted trough the relevant reduction of the alternative specific constant magnitude reduction.

Starting from these MMNL models and after the preliminary statistical analyses, the Hybrid Choice Model based on latent variables for each one of two surveys was estimated.

The significant latent variables for each one of two models were: the attitudes towards the technical features and the environment for the Argentinean survey and the attitude towards the environment and the perception of EV advantages for the Italian sample. Each one of the latent variables was estimated trough perceptions indicators consistently with results of MMNL with dummy variables. Furthermore with regards to the attributes in the utility choice function, the alternative specific constant is not still significant as well as sociodemographic attributes since they participate in the structural model specification.

In order to provide a comparative analysis of the latent variables the ratio of attitudes/perceptions with respect to the level of service attribute is analysed. Results displayed that within Argentinean survey the importance of reduced features is more relevant than environment differently from Italian case study in which the magnitude of environment importance is higher than the EV advantages perception. By comparing two survey it may be observed that the Italian sample is more sensitive to the environment than Argentinean survey.

Final considerations may be collected from the sensitivity analysis; in particular both models are sensitive to the monthly cost variation but the elasticity is evident only in case of higher costs (more than 40euros is the reference cost to be considered). It must be also stressed that the trend of probability variation against cost follows a linear trend in case of Argentinean case study and a non-linear landscape in case of Italian case study. Finally with respect to the latent variables it may be observed that, consistently with previous analysis of the ratio of attitudes/perceptions with respect to the level of service attribute, Italian users are more sensitive to the environment whereas in Argentinean sample are more sensitive to the technical features.

Finally, the following operational considerations can be made:

1) market segments to be captured by EV technology mainly consist in male users in Argentina and male and younger users in Italy;
2) both surveys are sensitive to the monthly cost variation;
3) both surveys are sensitive to the environment concern;
4) Italian survey is more sensitive to the environment than the EV advantages perception;
5) Argentinean survey is more sensitive to the reduced features than environment
6) Italian survey is more sensitive to the environment than Argentinean survey

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