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A meso-simulation approach for the estimation of traffic flows in presence of automated vehicles

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Abstract

This paper presents an assignment model able to reproduce mixed traffic flows made of automated vehicles (AVs) and conventional ones (CVs). In order to apply to large urban networks, such a model is specified in the framework of the meso-simulation approach. This approach is suitable for the assessment of feasibility studies involving AVs in transport policy decisions, which can be employed as input for a successive validation on single or limited number of links by using the more complex and time-consuming microsimulation.
First results of a test case application to a network of realistic dimensions are reported to show the capability of the proposed assignment model to support the assessment of future mobility scenarios characterized by the presence of both AVs and CVs.

Keywords: automated vehicles; multiclass assignment; mesosimulation

1. Introduction

Future mobility scenarios in our cities are expected to be deeply and quickly revolutionized by the presence of Automated Vehicles (AVs). If combined with eco-friendly technologies, as electric engine, automated electric vehicles (AEVs) could also represent a clear opportunity to reduce air pollution and health risks, as well as to increase road safety.

In response to the increasing reality of AV future, the definition of future mobility scenarios and the related modeling of transportation systems involving automated vehicles (AVs) and conventional ones (CVs) are becoming a trend topic in the transportation research.

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Among the open issues are the traffic regulations in presence of AVs, the effects on capacity of a mixed flow of AVs and CVs, the possibility to apply reserved-lane policies to shared automated (electric) vehicles, the definition of parking rules and, in general, the search of the optimal management of demand and supply to foster the introduction of AEVs in our cities.

For this reason, the development of models is crucial to support the solution of some technical, economic and social problems connected to the planning, the implementation as well as the assessment of these transport systems.

Such models have to support policy assessment by estimating specific Network Performance Indicators (NPIs) in the view of both users (e.g. travel time and cost) and system (e.g. road safety, pollutant emissions, energy consumption).

In the literature, the studies involving AVs are focused on motorways and in general on extra-urban networks, which are usually modelled by a single or a limited sequence of links by using a micro-simulation approach. Few studies investigate the urban case, which is characterized by larger and more complex networks and is very challenging by using a microsimulation approach.

For this reason, this paper presents an assignment model able to reproduce mixed traffic flows made of automated vehicles (AVs) and conventional ones (CVs). The use of a meso-simulation assignment model, instead of a micro-simulation one, allows to speed up the problem solution as well as to apply to large and complex networks. This is suitable to be used in the view of the assessment of a feasibility scenario as it allows a better estimation of link flows and performances used for the calculation of the NPIs on which the assessment is based.

The paper is structured as follows. Section 2 reports the state-of-the-art of modelling in presence of AVs. Section 3 presents the proposed modelling framework, while Section 4 describes the results of an application to a test case of real-size dimensions. Finally, Section 5 summarizes conclusions and further developments of this study.

2. State-of-the-art

The technological change due to the rise of automated vehicles (AVs) produce a change in the transportation system modeling, considering also (at least for some years) the need to simulate mixed traffic conditions (traditional and AVs). The topics treated in literature range from technological aspects (e.g. vehicle tracking, Zein et al., 2018) to planning or simulation (You et al., 2019). One of the main points is the feasibility of the introduction of automated vehicles in a city (or in a nation) and their interaction with the other traffic components. Fagnant and Kockelman (2014) explore the feasible aspects of AVs considering the transportation system as a whole deepening the benefits of AVs, the obstacles for their introduction and the possible policies to adopt. Another important research topic regards the capacity analysis: Van der Berg et al. (2016) study the effects of AVs by means of a dynamic model to evaluate the increase in road capacity and the variation (decrease) in the value of time; Meyer et al. (2017) simulate the impact of AVs on accessibility, by demonstrating that autonomous vehicles could produce an increase in accessibility as the result of the increase in road capacity; Ghiasi et al. (2017) propose a capacity model for mixed traffic based on a Markov chain to quantify the impact in the capacity of automated vehicles; Chen et al. (2017) provide a formulation of capacity in mixed conditions, considering AV penetration rate, characteristics of traditional and automated vehicles and different policies for lane accommodation. Similarly, Kloostra and Roorda (2019) analyze the performances of a transportation network when AVs are introduced by considering different scenarios, aiming at evaluating the impacts in case of different AVs penetration rates.

The optimal plan location and scheduling of a vehicle sharing system for AVs is investigated in Ma et al. (2017). Among recent studies on the impacts of lane reservation for AVs, Nickkar and Lee (2019) and Nuzzolo et al. (2019) can be cited.

In order to simulate the interaction between automated and traditional vehicles, assignment models need to be reformulated. Among proposals in this research field, Levin and Boyles (2015) propose a multiclass traffic assignment formulation to take into account AVs and traditional vehicles. A four-step model is formulated to consider how AV ownership can affect transit demand during the (congested) rush hours. The mode choice is analyzed specifying a generalized cost function including the travel time, the monetary fees, and fuel consumption. Cantarella and Di Febbraro (2017) propose algorithms for stochastic assignment to extent the traditional multi-vehicle assignment. Melson et al. (2018) present a dynamic traffic assignment by developing a method to model the cooperative adaptive cruise control typical of AVs. Aiming at validating their model, the authors also propose a flow-density fundamental diagram for the AVs. Levin et al. (2017) present an event-based framework for implementing shared AVs in existing traffic models (macro, meso or micro) and test it proposing some scenarios.

Other studies focus on specific aspects of the traffic flow in presence of AVs. Among these studies, Ye and Yamamoto (2018) develop a flow model to study the impact of AVs on the traffic flow by considering the own characteristics of AVs technology (e.g. adaptive cruise control); Wen-Xing and Li-Dong (2018) propose a car-following model in which the stability analysis and the fundamental diagram are used to check the parameters introduced in the model; Gong and Du (2018) develop a cooperative platoon control for a platoon of mixed vehicles (AVs and traditional) by taking into account the car following behavior and develop a procedure to optimize it. Auld et al. (2017) use an activity-based travel demand simulation model to simulate the travelers moving in a transportation network. The simulator consists of a demand model, a dynamic traffic simulator and a model for route choice. Levin (2018) extents the route choice to shared AVs, by considering a dynamic approach and simulating the traffic flow by means of a link transmission model.

Most literature mentioned above does not investigate urban problems and it usually applies to a very limited sub-network (even simplified to a few links) due to the complexity of the microsimulation implementation for real (large and complex) road networks. For this reason, the following section presents a modelling proposal to estimate mixed traffic flows in presence of AVs based on the use a meso-simulation approach, which is suitable for the assessment of transport policies involving AVs in urban areas.

3. Modelling

This section describes an assignment model able to reproduce separately route choices of different vehicle types (AVs and CVs) as well as the explicit use of dedicated supply facilities (AV dedicated lanes), if any exists.

The main features of the assignment model are: (i) multiclass compliant, as it explicitly considers the demand and supply components related to AVs and CVs; (ii) easy-to-use, as it is designed for large scale applications and solution robustness; (iii) computationally fast, because it could be potentially usable within a network design procedure.

In the following, the main features of the assignment model to adhere the above points are described in terms of demand, supply and demand-supply interaction modelling.

On the demand side, O/D matrices per different vehicle types are considered. In particular, at least, O/D matrices for both AVs and CVs vehicle types are taken into account. Such O/D matrices are here an input for the assignment model but they can be easily obtained by using demand models whose specification is out of the scope of this paper.

On the supply side, the network model is able to explicitly consider the supply facilities for different vehicle types (AVs and CVs), as well as those shared by them. For this reason, the graph representation is compliant with a possible layout of future roadside comprising AV dedicated lanes, for which Figure 1 shows an example for a street with two lanes per direction.

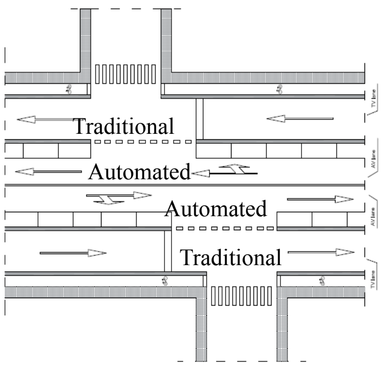

Fig. 1. Example of road section with dedicated AV lanes.

Aiming at modelling the above road section, the road graph (see Figure 2) is made of links characterizing the supply facilities of Figure 1. It includes links that explicitly represent AVs dedicated lanes (i.e. links used only by AVs) and links that represent conventional lanes (i.e. links shared by AVs and CVs). Of course, links connecting the above two types are also considered to model merging zones at intersections.

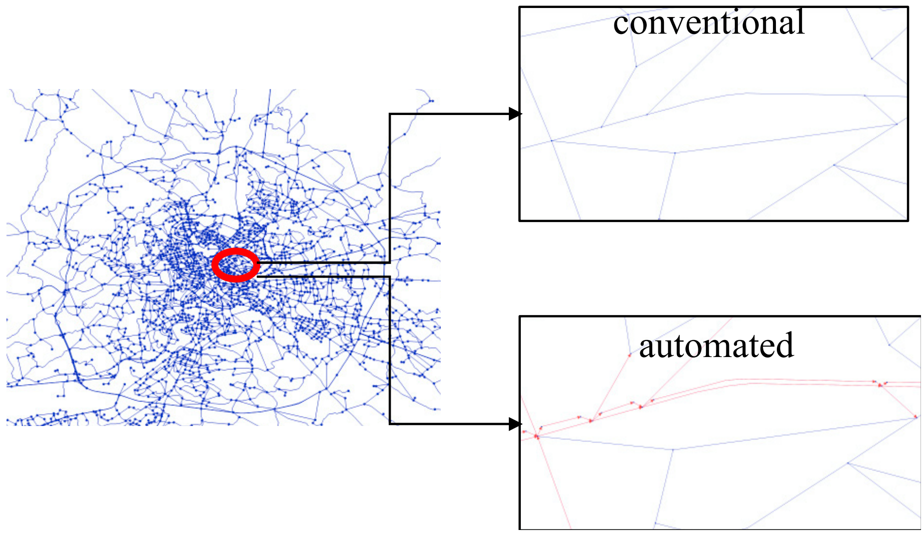

Fig. 2. Example of road graph.

In order to speed up the calculation time to obtain link flows and performances for large and complex (real) urban networks, an adjusted-BPR cost function for the generic link i is formalized. It allows taking into account both run time for link traversing and delay time at intersection as follows:

$$t_i(f_i) = \frac{L_i}{V_{0i}} + \frac{R_i^2}{2C_{Ni}}\left[1+\gamma\left(\frac{f_i}{S_{Ni}}\right)^{\delta}\right] \tag{1}$$

where L_i is the length of link i, V_{0i} is the "free-flow" speed on link i, f_i is the flow of link i, (obtained by summing up flows for each vehicle type) and, considering the final node N of link i, R_i is the red time, C_{Ni} is the cycle time, S_{Ni} is the saturation flow (function of green factor G_i/C_{Ni} and capacity $S_{sat,i}$) and γ and δ are function parameters. The values of V_{0i}, R_i, C_{Ni}, S_{Ni} and of the parameters γ and δ are differently specified according to link types and allowed vehicles (AVs or CVs).

Parameters of such functions, as well as saturation flows can be defined for different road and intersection layouts. Such layouts can be characterized by several factors such as the vehicle type allowed (AVs and/or CVs), the link priority (main or side street) and link position within the urban area (city center, inner ring, outer ring).

In order to propose an easy-to-use and computationally fast assignment model, the demand-supply interaction is formalized in the framework of the user equilibrium approach as follows:

$$\underline{f}^* = f\left[\underline{c}^*(\underline{f}^*, \underline{u}) \cdot \underline{d}\right] \tag{2}$$

where $\underline{f}^*$ is the vector of equilibrium link flows, obtained summing up the flow on each link for each vehicle type (AVs and CVs), $\underline{c}^*$ is the vector of equilibrium link costs, calculated by using (1) with function parameters $\underline{u}$, and $\underline{d}$ is the demand vector representing the O/D matrices per demand segment.

The use of the adjusted-BPR link cost function (1) and the use of random utility based route choice models assure the existence and uniqueness of the assignment solution because, if the network is connected, such functions are continuous (assuring the existence) and the cost function (1) is monotone increasing (assuring the uniqueness).

Moreover, as the Jacobian of the link cost function (1) is symmetric, the convergence of the MSA solution algorithm towards the equilibrium link flow represented by f^* is also demonstrated.

Further details on equilibrium assignment models and algorithms for transport systems with AVs can be found in Cantarella and Di Febbraro (2017).

4. Application

This section presents the first promising results obtained by the application of the assignment models to a test network of realistic dimensions, which shows the ability of the proposed model to reproduce effects of AV in a mixed traffic flows of AVs and CVs, as well as effects of introduction of dedicated AV lanes in the actual road network serving a city center.

The meso-simulation assignment model proposed in section 3 has been implemented in the VISUM^{TM} transport modelling software (PTV-AG, 2017), which allows to easily adapt its multiclass assignment to the proposed modelling changes.

Figure 3 illustrates the simulated road network, in which one dedicated AV route (see red links) is introduced. The dedicated AV route is defined through a sequence of links made of 2-lane road sections per direction, in which one lane is reserved to AVs driving exclusively in automated mode and one lane is used by all vehicle types (AVs and CVs) driving in manual mode.

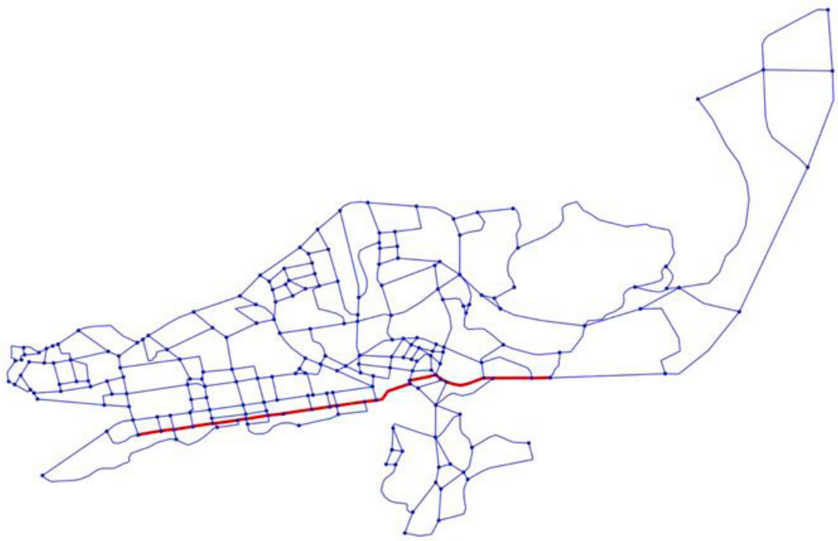

Fig. 3. Test network scheme and AV reserved lanes.

On the demand side, the simulation scenarios take into account a transport demand of about 19,000 vehicles in the morning peak hour. The different scenarios artificially simulate the presence of all-CV vehicles (0% AVs) and all-AV ones (100% AVs), passing through the mixed cases of 30% and 70% of AVs in presence of AV dedicated lanes.

On the supply side, the network model consists of 25 traffic zones, 309 nodes and 918 links. The implementation of the dedicated AV route requires the introduction of further 44 nodes and 132 links, respectively.

An adjusted-BPR cost function (see eqn. 1) is associated to each link. As an example, Table 1 reports parameters of the cost function used for links representing mixed lanes and dedicated AVs ones. Such parameters are proposed as the result of a preliminary microsimulation study similar to that used by Stanek et al. (2016) and Sagir and Ukkusuri (2018).

Table 1. Adjusted-BPR cost function parameters

link type	$V_{0,i}$	$S_{sat,i}$	γ	δ
mixed lanes	25	750	0.8	3.0
dedicated AV lanes	30	1000	0.5	2.0

By using a desktop computer based on an Intel Core I7-7700 CPU, 16 Gb RAM, O.S. Windows10 and VISUM V.17-01-08 Educational, it takes about 20 seconds to simulate each scenario.

An example of assignment results is shown in Figure 4, which reports the link flows for different vehicle types (AVs in green and CVs in red), while Table 2 reports detailed results for all simulated scenarios. In particular, Table 2 shows the ability of the proposed model to capture the different effects of the different mixed traffic flows (AVs and CVs) and the presence of dedicated AV lanes, which are summarized in terms of the following NPIs: the average travel time (min/veh), the average travel distance (km/veh) and the average (network) saturation rate.

Fig. 4. Application results – link flows per vehicle type: AVs (green) and CVs (red).

Table 2. Application results – simulated scenarios NPIs

performance parameters comparison- average values								
Scenario	**Actual**	**1**			**2**			**3**
AV %	0	30			70			100
Vehicles	Total CV	Total	AV	CV	Total	AV	CV	Total AV
% Vehicles	100	100	30	70	100	70	30	100
Average time (min/veh)	11.63	19.70	16.53	21.06	18.65	19.59	16.46	9.23
Average distance (km/veh)	2.55	2.29	2.26	2.30	2.27	2.26	2.30	2.55
Average saturation rate	0.98	1.34	0.54	1.48	1.32	1.27	1.34	0.82

Focusing on results of Table 2, Figure 5 illustrates the comparison of results for all simulated scenarios in terms of average travel time calculated for all lanes together (total) as well as for AV lanes and CV ones, separately.

Obtained results highlights the best scenario as that featured by all-AVs (scenario 3). It confirms the benefits of automated systems in the case of a homogeneous AVs traffic flow, which is characterized by greater saturation flows w.r.t. CVs. As an example of model capability to quantify this effect, all-AVs (scenario 3) NPIs show a reduction of the 21% in terms of average journey time per vehicle (9.23 w.r.t. 11.63) and of the 17% in terms of average saturation rate (0.82 w.r.t. 0.98) comparing with NPIs calculated for the actual scenario (all-CVs).

Transition scenario 1 (30% AVs), characterized by a route with reserved AV lanes that drops capacity to conventional lanes (that can be used by both AVs and CVs), produces worse conditions for all NPIs w.r.t. the actual scenario, except of course for the average saturation rate calculated on dedicated AV lanes. Overall, the reduction of average saturation rate on AV lanes is not able to compensate the worsening conditions on the rest of the network, which causes the increasing of the (total) average travel time (about 8 minutes more), mainly due to the reduced capacity given to the CVs.

Such negative effects are confirmed and amplified in the transition scenario 2 (70% AVs) In fact, whatever the percentage of AV, transition scenarios clearly show a worsening of the congestion due to the introduction of dedicated lanes and the capacity drop on the mixed ones, suggesting to foster as fast as possible the transition towards an “all-AVs” mobility as the unique way to obtain external cost benefits by the introduction of AVs in our cities, especially when severe congestion in the morning peak hours occur.

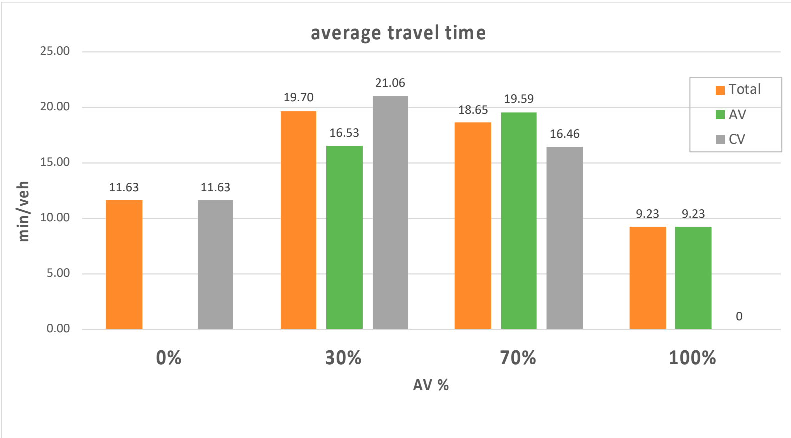

Fig. 5. Application results - average travel times.

5. Conclusions

This paper proposed a meso-simulation assignment model approach able to reproduce route choices for different vehicle types (AVs and CVs) and to explicitly consider effects of the introduction of dedicated AV lanes in the road network of our cities.

Aiming at considering the complexity of the whole urban road network, it has been defined in the framework of the multi-class equilibrium assignment. As it is based on a robust theoretical paradigm that assures existence, uniqueness and convergence of assignment problem towards a solution, the proposed model is easy-to-use, computationally fast and it can be easily implemented in commercial transportation software to obtain results suitable to be used both for analysis and design.

Results of the model application to a test case demonstrated the ability of the proposed model to capture effects of a traffic flow including AVs and of the presence of dedicated AV lanes, which should drive the future of our cities towards a fully AV mobility.

Further developments of this research mainly regard its use for the assessment of AV lane accommodation scenarios as well as the possible integration in a procedure of optimal network design. In the sphere of the scenario assessment applications, this model is going to be applied to a feasibility study on a sharing mobility scenario based on a quite large use of EAVs, AV dedicated lanes and restrictions of private CVs use in the central area of Rome at the 2035 time horizon.

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