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Understanding urban mobility and the impact of public policies: The role of the agent-based models

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ABSTRACT

This paper provides a critical review of research on Agent-Based Models (ABMs) focusing on urban mobility, dealing either with passengers or with freight transport. The work concentrates on urban areas where public policies aiming at improving the sustainability of city systems necessarily affect both passengers and freight dimensions. Traffic in towns is responsible for a high share of congestion and pollution and consequently, it contributes to the climate change problems. The following conclusions can be derived. ABMs present important advantages for analysing urban transport and its sustainability but more efforts are needed in order to test and improve their use. In the literature, there is still a gap in urban transport AB modelling. The number of developed models is limited and they are often applied in broader geographical areas than urban ones. Only some of the works includes the estimation of environmental impacts as a result of certain types of agents' behaviour. Despite their potential effectiveness to represent the impacts of different public policies on agent behaviour and on the environment, none of the ABMs have been implemented in the real word by the researchers and there is no evidence of application of any model by policy-makers.

1. Introduction

Recently the role of Agent-Based models (ABM) for studying city logistics and passenger mobility in urban areas is highly debated in academic literature. However, the emphasis given at a theoretical level to the potential advantages of these types of models has not yet been translated in an intensive production of agent-based models addressing urban mobility (Tamagawa, Taniguchi, & Yamada, 2010). The aim of this paper is to provide a review of the existing works which utilize this tool for analysing either freight transport, or passengers mobility, or both at the same time, in cities and for predicting the impact of the different urban public policies on the agents' behaviour. By simulating the effects of the policies on stakeholders' transport choices, it could be also possible to estimate the potential environmental improvements and the ability of the regulation to meet sustainability and climate change goals.

The paper focuses on the urban environment because, in practice, freight and passenger flows co-exist and share the same physical scarce spaces. Public policies have an impact at the same time on the whole urban dimension, affecting the entire transport system. Moreover, the majority of world population lives in urban areas and continues to increase, supporting the negative externalities (pollution, noise, vibration, energy consumption, congestion, etc.) coming from transport and other social and economic activities.

In the European Union, over 60% of the population lives in urban areas and a car runs 75% of its mileage in and around cities. According to a recent opinion poll, 90% of Europeans think that the traffic situation in their area should be improved (European Commission, 2007). In Europe increasing traffic in the city centres is leading to permanent congestion. The delays and other damages caused by traffic jams cost the European Union 1% of its Gross Domestic Product. Many European citizens are exposed to high levels of air pollution, especially from the concentration of PM10, NOx and SOx (European Commission, 2009). The combustion of gasoline and diesel from people and goods transport accounts for 31% of total U.S. CO_2 emissions and 26% of total U.S. greenhouse gas

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emissions in 2013 (United States Environmental Protection Agency 2015). In particular, the domination of oil as a transport fuel generates CO_2 and air pollutant emissions in towns. In fact, urban mobility accounts for 40% of all CO_2 emissions of road transport and up to 70% of other pollutants from road transport (European Commission, 2007). This kind of phenomena contributes to the wider and highly debated process of climate change. However, in turn, climate change has consequences on the transport sector itself. For example, global warming producing a rise in sea level may amplify the vulnerability of coastal infrastructures. Extreme weather occurrences may affect the safety of all modes (European Commission, 2009). There is urgency for the transport sector to mitigate its negative impact on the environment both at local and global level. The EU adopted a package that sets a target of reducing greenhouse gas emissions within its area by 20% with respect to 1990 (European Commission, 2009). Within this framework it is clear that urban sustainability is one of the most important challenges of the present and future societies.

According to the analysis of this paper, agent-based modelling can be an effective instrument able to describe in a dynamic way the behaviour of each stakeholder or group of homogenous stakeholders and their relations. Nevertheless, the use of ABMs for the analysis of urban mobility issues is at relatively initial stages. The literature on city logistics and urban passenger transport has concentrated its attention on other models and tools different from ABM, as briefly explained at the end of Section 2.2, but their analysis is beyond the scope of this paper.

The contribution of the paper to the transport economics literature is to develop a critical review and a classification, according to specific features, of the works focused on the use of ABMs for the analysis of urban systems, considering one or both the dimensions of passengers and freight flows. Therefore, the intention of the work is to identify a space in the academic literature to provide the basis for agent-based modelling, having the aim of simulating the whole system of mobility in cities and evaluating the effectiveness of public policies in terms of sustainability and climate change goals.

The paper is structured as follows. In the next section an overview on the complexity of the urban mobility system and on the potential role of ABMs in analysing this complexity is provided. Moreover, the possibility to integrate ABMs with Geographical Information Systems (GIS) in order to better describe the actors' spatial interactions is underlined. In Section 3 a framework for the creation of a taxonomy of existing research about ABMs and urban systems is presented. Section 4 is dedicated to the analysis of the surveyed literature according to this taxonomy, while in the last section some conclusions are drawn and further research needs are suggested.

2. The urban system and the agent-based models

2.1. The complexity of the urban mobility system

Urban mobility presents all the characteristics of a very complex system: a high number of stakeholders, very heterogeneous and with different roles, needs and aims; strong interactions between these numerous agents and between them and the environment in which they act; very complex transportation networks used for mobility often at the same time. Moreover, the system and the environment are evolving over time; agents evolve continuously, changing their specific behavioural patterns, according to their interactions and time-based feedback and following the dynamics of the urban context and structure.

In this system the performance of each network is influenced by individuals choice and behaviours and vice versa. Moreover, each stakeholder group has particular decision-making processes (Anand, Duin, Quak, & Tavasszy, 2011; Anand, Yang, Van Duin & Tavasszy, 2012; Buliung & Kanaroglou, 2007). Particularly, as regards passenger transport, commuters aiming to reach the work place quickly, on time and comfortably interact with tourists, shoppers and other city users with specific and different transport choices. The single transport mode and infrastructure used by the passengers are components of complex chains and networks.

Referring to freight transport, the economic services offered are fragmented in a high number of small activities and the decision-making process is highly distributed. In cities different Urban Supply Chains (UBCs), i.e. the last mile of the supply chain in charge of delivering goods to urban areas, interact (Danielis, Maggi, Rotaris, & Valeri, 2013). They have a very complex nature and can assume different profiles, according to the characteristics of the urban area and of the other economic activities and to the product and the structure and organisation of the whole distribution system. Also from the demand side of urban logistics services, there is high fragmentation, since citizens often derive high benefits by buying items in small local shops or ordering the goods online. The level of demand fragmentation is higher in some countries, such as in Italy, where the large-scale retail trade in the cities is less widespread while the urban sprawl is great (Maggi, 2007).

As summarized in Table 1, the different categories of actors involved in freight urban mobility domain have different roles that generate different kinds of needs and interests, often conflicting. As a consequence, these actors follow their own goals without any centralized control, creating both economic and environmental inefficiency: a higher number of vehicles and trips per day than the optimal one, very low average load factor per vehicle and higher levels of pollution and congestion. For example, shopkeepers order small but frequent deliveries, because they have very small space for warehousing in order to contain the total logistics costs. In this way they reduce the inventory cost, but at the same time they limit the capacity of operators delivering the goods to maximize the vehicle loading factor. On the other hand, local administrators impose rules such as weight restrictions to mitigate the disturbance from commercial vehicles, but these limits may damage the efficiency and the quality of services supplied by the transport carriers.

For these reasons, in the last two decades a specific transport economic domain has been developed, called city logistics, that can be defined as “the process for totally optimizing the logistics and transport activities by private companies in urban areas while considering the traffic conditions, congestion issues and combustible consumption, with a view to reduce the number of vehicles on the cities, through the rationalization of its operations” (Institute for City Logistics, www.citylogistics.org).

City logistics and urban passenger mobility analyses need to be supported by economic models and tools, helpful in creating a knowledge base about freight and people flows and behavioural issues of the different stakeholders (Taniguchi, Thompson, &

Table 1
Interests of stakeholders involved (Macário, Galelo, & Martins, 2008).

Stakeholders	Interests
Residents	Products and services Negative environmental impact
Retailers	Competitiveness and profitability
Authorities and public service	Accessibility Governance and legislation Negative environmental impact
Suppliers	Market growth Profitability
Carriers	Congestion Cost effectiveness

Yamada, 2013), simulating the current and the future scenarios about freight and passenger vehicles, commodity flows, infrastructure and actors' needs. An analytical approach should be followed to investigate the different decision-making processes among different stakeholders in order to address systematically the organization of urban mobility (Anand et al., 2011; 2012).

These models and tools should be the basis on which the right mix of policy measures could be identified to facilitate an efficient urban mobility system and to boost solutions that sustain economic growth. These policies in fact should be designed, considering the efficiency of the whole system, not of its single components. The total performance of the system should be optimized, accepting a sub-optimization of one component if it permits to improve the efficiency of the whole.

2.2. The simulation of the urban mobility complexity using agent-based models

Within the above described framework, agent-based models can be considered as a useful and effective tool to model the complexity of urban mobility systems and to capture the dynamic behaviour of individual autonomous stakeholders and their interconnections (Gilbert, 2008; Gilbert & Troitzsch, 2005; Shafiei, Stefansson, Asgeirsson, Davidsdottir, & Raberto, 2013). In fact, an ABM has been defined as “a computational method that enables a researcher to create, analyse, and experiment with models composed of agents that interact within an environment” (Gilbert, 2008, p. 98).

These types of models are characterized by four elements that are absolutely essential to describe urban mobility: (1) an environment, i.e., a set of objects the agents can interact with; (2) a set of interactive agents; (3) a set of relationships linking objects and/or agents; and (4) a set of operators that allow the interaction between the agents and the objects. In particular, ABMs assume each stakeholder is an autonomous agent with certain attributes and states. In the simulated environment, agents interact with other agents and the environment to make autonomous rational decisions, proact or react, given previous experiences and communications with other agents (Gilbert & Troitzsch, 2005; Wooldridge & Jennings, 1995).

ABMs implement a generative approach, which allows the investigation of social patterns using a bottom-up technique (Natalini & Bravo, 2014; Shafiei et al., 2013). The use of bottom-up approaches instead of top-down approaches, like for example System Dynamics, gives different advantages. One of the most important is the consideration of emerging properties. The researcher shapes the agents with heterogeneous behavioural rules, goals that must be reached and criteria for satisfaction levels. Agents will be embedded in networks, which will influence their actions. By modelling components rather than the entire system, the structure of the system is not pre-defined and one may observe the emergent properties. Moreover, by modifying the variables of interest, the modeller may explore different kinds of scenarios.

The behaviour of any system is the result of the interactions amongst its components. Indeed, ABMs are useful to analyse the non-linearity of aggregated behaviours with respect to individual ones. A macro-behaviour may be something different then the simple aggregation of several micro-behaviours. The value of this kind of models lies in the prediction of emergent system behaviour that would be difficult (if not impossible) to elicit with analytical methods (Gilbert & Troitzsch, 2005).

Different options for a transport system can be tested in a simulated environment (Sirikijpanichkul, Van Dam, Ferreira, & Lukszo, 2007). ABMs can be calibrated with real data (Squazzoni, 2012). This allows both to test ex ante the effect of potential policies, and to evaluate ex post the effects of actual policies that have been implemented in reality. For example, one may consider the impact of the actual transport mobility of a specific area on the total greenhouse gas emissions of that zone, and, in turn, the potential contribution to these emissions to climate change. One may also observe the impact of policy changes on these aspects, considering their capabilities to meet climate change goals.

Beside agent-based models, among the tools that have been utilized by the literature to study travel behaviour, we mention also activity-based models. This kind of modelling is extremely interesting while, according to the derivate nature of the transport demand, it represents travelling activities as direct consequences of the need of heterogeneous personal activities. Therefore, travel decisions build a scheduling process containing time and space constraints. This framework allows a good understanding of travel behaviour, of reactions to policies and, consequently, of the effect on pollutant emissions. It contains the added value of the translation of economic and social dimensions of a society into actual travel behaviours. Researchers have used these kinds of models since the 1990s, also with some large-scale applications (Shiftan, Kheifits, & Sorani, 2015; Shiftan & Shurbier, 2002; Shiftan, 2000; Yagi & Mohammadian, 2010). One interesting example is the Tel-Aviv Model (Shiftan et al., 2015). It aims to evaluate the response to different transport policies, such as parking pricing and restrictions, and improvements in infrastructures and services. Lower level choices are conditioned on decisions at a higher level, while the latter are informed from the lower level interactions. A mechanism called the “activity generator” applies the model to each person in the synthetic population sample. As a result, each individual's daily travel is fully represented: types and number of daily travels, number of intermediate stops, destinations of each activity and intermediate stops, modes of transport used and time of day. Agent-based models and activity-based models can be used in an integrated way (see Salvini & Miller, 2005).

Other methods, which are used to analyse travel behaviour, are discrete choice models (Koppelman & Wen, 1998; McFadden, 1973). They include the probit model (Gaudry, 1980), multinomial logit (MNL) model (McFadden, 1973) and nested logit model (Daly & Zachary, 1979). These approaches have some limitations, such as: i) the strict model structure needs to be specified in advance; ii) they are unable to model non-linear systems; and iii) they consider only conditions that hold across an entire population of observations (Shukla, Munoz, Ma & Huynh, 2013). These limitations can be overcome by using machine learning based methods such as Decision Trees (DT) and Artificial Neural Networks (ANN) (Cantarella & De Luca, 2003; Reggiani & Tritapepe, 1998; Shmueli, Salomon, & Shefer, 1996; Xie, Lu, & Parkany, 2003). In any case it must be noticed that agent-based models in many occasions use the decision rules of the agents based on such methods, therefore often it is possible to see the different methods as integrated (Shiftan et al., 2015). However, crucial issues remain unexplored, such as: (i) decision whether to implement a centralized or non-centralized learning approach, and (ii) choosing a learning algorithm (Shukla et al., 2013). For instance, even if ANN is useful at classifying large amounts of data, it is difficult to determine how classification decisions are made. This happens because they are black box type of models, without the possibility of tracing the mechanisms leading to the outputs. DT models provide structure to how decisions are made but are not good at classifying continuous data.

2.3. ABM and geographical information systems

Cities are complex systems, with many dynamically changing parameters and large numbers of actors. The heterogeneous nature of cities makes it difficult to distinguish between localized problems and city-wide problems. Najlis and North (2004) argue that there is a growing interest in the integration of GIS and agent-based modelling systems (Brown, Riolo, Robinson, North, & Rand, 2005; Parker, 2004; Torrens & Benenson, 2005). Examples of interesting applications include pedestrian dynamics, urban growth models and land use models (Crooks, 2006). This integration provides the ability to have agents that are related to real geographic locations. In ABMs, agents often have some spatial relationships to each other and are situated in an environment. The use of GIS allows a useful representation of this kind of relationship since it can contain multiple layers, such as for example a housing layer, a road network layer, or a population layer. The combination of layers allows one to model different kinds of agents situated at the same time in a geographical environment. The use of GIS in ABM, specifically its use of polygons for representation of space, represents a step forward from the regular lattice structures used in previous urban models (Wu, 1998). Since cities do not have regular spatial patterns, the use of GIS allows one to model cities using a variety of different land parcel shapes and sizes. One can deal with objects, such as people or houses, either as fixed or non-fixed objects. Fixed objects are things which have transition rules and cannot move, for example a park, while non-fixed objects have transition rules and can move, like individuals or firms. Area changes are normally associated with interactions taking place between agents and their environment (O'Sullivan & Torrens, 2000). Fixed and non-fixed objects have close relationships and dependences. Therefore a change in variables of either type will have immediate changes on the other variables. This change can be detected by geo-referencing the objects and agents simply using x and y coordinates (Crooks, 2006).

3. Framework for evaluating the literature on agent-based models on urban transport

In order to provide a critical classification of the literature containing ABMs on urban mobility, the analysis has been largely inspired to the taxonomy developed by Davidsson, Henesey, Ramstedt, Toernquist, and Wernstedt (2005). These authors in their useful literature review apply the taxonomy to the works dealing with transport logistics in general. They consider every transport domain: air, rail, road, sea and intermodal situations. The present paper however focuses on urban mobility only.

As indicated in Tables 2 and 3 (Appendix A), the reviewed works on ABMs in urban mobility have been classified according to different features. The following dimensions are explained below: the *time horizon*, the *structure*, the *agents' attitude*, the *maturity level* and the *usage* (derived from Davidsson et al., 2005). The dimensions that have been added for their importance are: *intention of the model*, kind of *variables or agents* utilized, *geographical dimension* and *calibration on actual data*. Moreover, in the passengers' domain the dimension *category of people* has been added, since often the ABMs used in this domain address specific subgroups of city inhabitants, while in the freight domain the whole system of city logistic is usually considered.

3.1. Time horizon

The dimension time horizon refers to what stage, in the decision-making process, the application is used or is intended to be used. The stage could be strategic, tactical or operational. Strategic decision-making concerns long-term decisions, determining the action line. The tactical level involves medium-term issues, while the operational level is about short-term issues. Of course the time horizon for these levels is dependent on the domain of research. For example, a simulation regarding the location of a distribution centre would be classified as strategic in its time horizon. A tactical approach would concern the planning of the vehicle fleet to satisfy the customer demand, while an operational issue would be the scheduling of every delivery with the controlling function.

3.2. Structure

The structure of the model may be either static or dynamic. Static means that the whole structure is predetermined and the set of agents, their roles, or their decision-making processes do not change during the execution of the simulation. Dynamic structure means that such mechanisms may change during the simulation according to specific criteria or to random elements.

3.3. Attitude

In many cases agents of these models interact among themselves in order to accomplish their tasks. They can do it either through a cooperative or competitive attitude. In the first case, as an example, they may be supposed to comply with social laws or collective aims. Therefore they may act following criteria which are more heterogeneous than only pure individual profit maximization, like for example, adapting the own behaviour to the majority of behaviours of the neighbourhood agents or seeking the social welfare maximisation. In the second case, actors only follow the principle of maximizing their own profit or utility.

3.4. Maturity

The degree of maturity of a model indicates how complete and validated an application is. The lowest degree of maturity in this taxonomy is the conceptual proposal. In this case the idea of the proposed application is described with its general characteristics. The second maturity degree concerns simulation experiments: the model runs in a simulated environment. The data used in simulation can either be real, that is to say they are taken from existing systems in the real world, or not real, which means that they may be artificial, synthetic or generated. The further maturity stage is the field experiment, which means that the model has been experimented in the environment where the application is supposed to be applied. In the final most mature stage, called deployed system, the system is implemented in the real world and used by the policy-makers to identify the most effective measures.

3.5. Usage of the agent system

ABMs can be classified as either serving as an automation system, or as a decision-support system. An automation system should have a mechanism that self-acts a required performance at a certain time or in case of occurrence of defined conditions. In this context the system influences directly the controlled environment and no human is involved. On the contrary, a decision-support system (DSS) may provide important elements that help the policy-makers take decisions. Indeed, in this last case the final decision is taken by a person and not by the application itself. As all the revised papers are developed as DSS, even if they have not been applied in the reality by decision-makers, this dimension has been excluded from Tables 2 and 3.

4. Application of ABM to urban mobility analysis

4.1. ABM and city logistics

The literature review on specific applications of agent-based models to transport issues has highlighted that few of them focus on freight transport in urban areas. Most of the works aim to develop models that represent the whole city logistic systems, considering the different stakeholders involved in the decision-making processes and their respective priorities and needs. Therefore, the authors of most of the reviewed papers declare that the main advantages of adopting an agent-based approach are the ones explained in Section 2: the possibility of representing heterogeneous types of agents that form various and coexisting decisions centres and the ability to deal with partial data and possibility to model complex problems (Roorda, Cavalcante, McCabe, & Kwan, 2010; Tamagawa et al., 2010). The researchers utilise this tool in order to go beyond the simple modelling of transport scheduling. In the reviewed papers, negotiations among actors normally take place through contracts and market-based operations (Taniguchi & Tamagawa, 2005; Van Duin, van Kolck, Anand, Tavasszy, & Taniguchi, 2012).

ABMs have different specific aims. In the paper by Donnelly (2007) a microsimulation approach was developed in order to estimate the urban freight demand in Oregon and the related supply organisation. The overall simulation environment provides information on global exchange, travel times, vehicle availability, the regional economy, and the characteristics of transportation networks. In the work of Tamagawa et al. (2010) a model for vehicle routing and scheduling, in case of time-windows policy application, has been developed. The authors apply the model to test the implementation of several city logistics measures to a road network, evaluating their effects on the environment in terms of NOx emissions. The results indicate that implementing a truck ban directly to environmentally damaged areas and together discounting motorway tolls entirely in the urban motorway network has large positive environmental effects. A similar model has been previously developed by Taniguchi and Tamagawa (2005) in order to perform a simulation of the impacts on the stakeholders' behaviours of implemented truck ban and tolling of urban expressway, as city logistics measures, on a test road network. They use a model which determines the optimal solution by minimizing total transportation costs and they also consider the impact on NOx emissions.

Roorda et al. (2010) develop an agent-based microsimulation framework that represents the different roles and functions of actors in the freight system and their interactions in markets through contracts. They indicate that one of the possible applications of the conceptual framework could be to study the impact of the public investment in infrastructure at intermodal terminals on the actors' behaviours. The environmental implications of the potential simulation are not considered.

The work of Anand et al. (2012) elaborate an ontology of city logistics ABMs, that is a formal specification of the concepts and relationships that can exist for an agent or a community of agents. This work is useful since it focuses on the need of a shared ontology serving as the basis for research and policy-making in the field of city logistics. From the point of view of semantics, a common language is needed in order to have coordination among users and sub-systems, and between researchers and policy-makers. Anand et al. (2012) insist on the fact that today ABMs knowledge bases are still built with little sharing or reuse. The introduction of a city logistics ontology may improve this situation.

The research of Van Duin et al. (2012) aims at providing insight into the urban distribution centre (UDC) success, by investigating dynamic price settings and cost-valued choices by individual agents. The simulation run by the ABM, comparing the impact of the UDC with the effects of other policies (e.g. different delivery schemes or toll rates), demonstrates that an increasing UDC usage will lead to a decrease of both NOx emissions and kilometres in the inner city. Indeed, the other measures do not have a significant impact on NOx emissions or trip length.

Finally, Teo, Taniguchi, and Qureshi (2014) describe the use of the multi-agent systems (MAS) modelling approach to solve the vehicle routing problem of carriers' delivery and to evaluate the short-term impact of distance-based road pricing and a simultaneous load factor control scheme on the major stakeholders (carriers, shippers, administrators and customers). The results from the experiment show that the city logistics joint scheme has the potential of improving average daily load factors and reduce emissions in comparison with no schemes implemented.

Coming to the features presented in Section 3, in the revised models the type of actors and the variables or components vary according to the specific objective of the simulation (for details see Table 2). Concerning the geographical dimension and the calibration of the model, only the work of Donnelly (2007) is calibrated on actual data and the conceptual proposal of Roorda et al. (2010) also plan to do that on real data on Toronto. Teo et al. (2014) experiment the model on a part of Osaka road network (Japan). Indeed the other models of this review do not utilize real data.

Regarding the time horizon, the considered models address mainly strategic decision-making, which involves long-term decisions about the whole city logistics system of an urban area. They try to go beyond the scheduling of single deliveries. Only the work of Donnelly (2007) has also an operational component, by modelling discrete daily shipments carried by specific vehicles, with specific departure and dwell times.

Referring to the structure of the models, most of them are dynamic. Agents change their behavioural rules according to their reactions to policies. Negotiations take place and new rules are established. When city logistics measures are implemented and their living environments are changed, the behaviour of the agents change to adapt to the new environment. Regarding the attitude of the agents, most of the time they have both cooperative and competitive behavioural rules.

As far as the maturity level of the model is concerned, two of the works are at the stage of a conceptual proposal (Anand et al., 2012; Roorda et al., 2010). This kind of work is extremely useful since it tries to highlight trends and critical issues that are common in different situations. Therefore, one researcher who is willing to develop an ABM on urban logistics may utilise these frameworks, their ontology and taxonomy. These works summarize the main types of actors involved in urban freight transport, the kinds of interactions and contracts they have, the kinds of output variables which are relevant for the urban system and the kinds of policies which are likely to influence the variables of interest. The other papers describe complete models, which run either on simulated experiment only, or use some partial real data. In this last case they may be labelled as field experiment (Donnelly, 2007). None can be labelled as deployed system: the models test simulated, not really applied policies. Despite that, all the ABMs have been conceived as decision support tools, since they provide useful insights for decision-makers into the evaluation process ex-ante, in itinere or ex-post.

Finally, concerning the software used by the works reviewed in this paper, Van Duin et al. (2012) utilizes Netlogo, while in the others this is not specified. Tamagawa et al. (2010) use also the method of Q-learning, a technique of reinforcement learning, in constructing a learning model for stakeholders, which evaluates their behaviour, learns their values and selects the behaviour considering such values.

4.2. ABM and urban passengers mobility

The tool of agent-based modelling is utilized for the investigation of passenger behaviour in urban areas more often than for the analysis of freight transport. Most of the works that are considered in this paper deal with a sub-category of citizens, such as, for example, university commuters, work commuters or pedestrians.

Only a minority of models address the whole array of inhabitants in an urban area.

At first glance, it is possible to divide the models into two groups. First, the ABMs that aim to test the effectiveness of policies which improve some specific services in the observed domain, such as for example the location of schools or parking areas (Benenson, Martens, & Birfir, 2008). Second, other models test policies that provide incentives for the agents to modify their behaviour in a desired way (e.g. Natalini & Bravo, 2014). Specifically, the intentions of the models are mixed and the categories of people and of variables used vary as a consequence.

The TRansportation ANalysis and SIMulation System (TRANSIMS) project by Smith, Beckman, Anson, Nagel & Williams (1995) represents an area broader than the urban one, including the regional population of individual travellers and freight loads, their individual interactions and their environmental impacts. The model analyses if the agents change their planned route in response to changing road conditions, such as congestion or accidents.

Schelhorn, O'Sullivan, Haklay, and Thurstain-Goodwin (1999) develop the STREETS model for investigating, by a dynamic way, the pedestrian behaviour in urban centres. The ABM and GIS-based socio-economic data integrate in the model the configuration and the location of attractions, both of which influence the pedestrian movements.

The model ILUTE (Integrated Land Use, Transportation, Environment) developed by Salvini and Miller (2005) simulates the evolution of an integrated urban system over an extended period of time with the aim to support the analysis of transportation, housing and other urban policies. The modelled behaviour includes land use, location choice, car ownership, economic activity and daily travel. ILUTE provides useful information for decision-makers to explore the role of transportation in shaping urban systems, to experiment with many of the variables which affect it and understand the relationships between them, and to show that the consequences of a given change are not always easy to predict.

Harland and Stillwell (2007), analysing the daily pupil movements between schools and residences in Leeds, develop a framework for a planning support system and policy formulation, which is based on Spatial Interaction Models or ABMs. The estimation of environmental effects is not included in this version of the model. The paper of Lu, Kawamura, and Zellner (2008) uses an agent-based model to study the effects of six land use regulations on urban form and travel behaviour, focusing on transit use, in a hypothetical urban area loosely based on the Chicago metropolitan area. The estimation effect of congestion on traveller's mode choice behaviour was incorporated in the model. The results show that land use policies are not able to increase the transit mode share for the area in a significant manner and so they fail to encourage more sustainable transport choices.

Benenson et al. (2008) develop a very specific ABM to analyse only one component of the whole mobility problem: parking. In fact, this model, called PARKAGENT, simulates the behaviour of each driver, capturing the complex dynamics of the parking agents within a non-homogeneous road space. The model has been applied to Tel Aviv in order to study the impact of parking policy and management alternatives to improve the parking situation. It analyses also the effect of a shortage in parking supply on the distribution of search time and distance to destination. The effects on the environment made by the parking agents' behaviour are not estimated.

The paper of Shukla et al. (2013), focusing on a University campus, presents a methodology for developing a hybrid agent-based micro-simulation model to identify the impacts of commuter travel mode choices on the transport network. University land use, commuter demographics, and socioeconomic conditions are considered. In a next step of the work, the model also estimates overall carbon dioxide emission due to travel mode. Some other decisions are included, such as the dynamic agent decision strategies on mode choice, and alternative infrastructure configurations to enable higher public transport usage.

Natalini and Bravo (2014) develop an ABM called Mobility USA which reproduces the transport choices of a sample of citizens and the corresponding GHG emissions of their daily commutes in the USA. They aim at testing ex ante the impact of public policies willing to foster commuting choices with lower GHG emissions. The focus is on the effects of two sets of policies: market-based and preference-change ones; the first ones (an increase in the prices of motorised transport and an incentive for non-motorised transport use) prove to be effective in promoting green behaviour for short commutes, but not for long commutes. The second type of policies leads to the highest share of non-motorised transport and CO_2 emissions reduction for both short and long commutes. Moreover, the model results suggest that the combination of these policies can be remarkably effective on short commutes, but not on long ones.

With respect to the framework presented in Section 3 and summarized in Table 3, it can be noticed that the variables and the types of agents in the revised models vary according to the specific aim of the modelling. Usually, the variables included in the models reflect features of the agents (such as demographic characteristics, information on their activities and their choices on transportation patterns), monetary aspects (e.g. parking fees, ticket price for the public transport or fuel price) and information related to travel time. In the cases in which the model is geographically located, it includes information on the distribution of relevant points, accordingly to the scope of the model.

Referring to the time horizon indicator, all the works analysed can be considered strategic, in the sense that they address the question of interest from a broad point of view and consider each component as part of the whole urban area, without restricting the simulation to sub-dimensions of the problem. They build the complex interactions of a high number of variables belonging to different domains. The structure is usually dynamic, since the behavioural rules of the agents change according to various criteria during the simulation, like for example the feedback given in the previous time step. In the work of Salvini and Miller (2005) higher level decisions (e.g. residential mobility) influence lower-level decisions (daily travel behaviour). In Natalini and Bravo (2014), work agents adopt one out of four possible decision rules according to the level of social and material satisfaction of each commute. In Lu et al. (2008) mode choice and residential location choice are interdependent.

Regarding the attitude of the agents, in one of the works reviewed, agents have both cooperative and competitive behaviour depending on their tasks. In Lu et al. (2008) agents compete over the use of land, while in Benenson et al. (2008) they compete for parking areas. In Natalini and Bravo (2014) agents have a cooperative behaviour, in the sense that social influence and imitation mechanisms play an important role in the decision processes. In the other papers, the distinction between competitive or cooperative behaviour does not really apply, since each agent decides for itself and there is almost no interaction.

Concerning the maturity level of the models, two works are at the stage of a conceptual framework, although they plan to calibrate the future model with actual data from specific cities. The model of Schelhorn et al. (1999) uses agents whose behaviour and features are informed by GIS-based data. However, the model itself remains at the stage of a simulation experiment. The other papers concern models which are field experiments and have been conducted in an environment reproducing actual cities. None of the works concern a deployed system. All the works considered are calibrated on actual data or, in the case of conceptual frameworks, are planned to be calibrated on real data. The majority of them use GIS.

Finally, as regards the final indicator, all the models considered in this review are conceived to be decision support systems for policy-makers. To the best of our knowledge, the only model addressing both passengers and freight transport is the Transportation Analysis and Simulation System (TRANSIMS), which is an integrated set of tools developed to conduct regional transport system analyses (Smith et al., 1995). The work of Roorda et al. (2010) cited above only plans to do this integration. In TRANSIMS, the simulation environment includes a population of individuals with travel activities and plans and a transport freight system. The environmental impacts of these activities are as well determined by the model. TRANSIMS is based on a cellular automata microsimulator. The model has been applied to the Dallas and Portland case studies. In Dallas researchers developed a microsimulation in TRANSIMS that executed the travel itinerary of each individual in an urban region, limiting the focus on automobile trips. In the Portland case researchers explored a wider range of actors and their impact on the sensitivity of TRANSIMS. Large vehicles, transit vehicles and transit passengers were also included.

The reviewed models utilise different kind of software. Benenson et al. (2008) use ArcGIS whilst Shukla et al. (2013) design a customized software platform, which in turn uses different tools: Java, used to implement algorithms managing the synthetic population; PostgreSQL, an open source object-relational database system; TRANSIMS, that receives information from the Java and Postgres database to simulate agents' travel patterns and their multi-modal transport activities; and YellowFin, a data visualisation software used to represent congestion profile. Natalini and Bravo (2014) and Lu et al. (2008) use NetLogo, an open-source software for agent-based modelling and Schelhorn et al. (1999) use the SWARM simulation environment and GIS. Finally, Salvini and Miller (2005) use C++.

5. Conclusions

In the last years the efforts to develop ABMs for transport analysis have strongly increased. Although many methods are available in order to analyse transport issues, ABMs present some important advantages. Their success is due to the capability to represent complex interactions, the diversity and the inherent variability which characterise the transport systems (Donnelly, 2007). Without any doubt urban transport systems have all the characteristics of complex systems. They have a high number of heterogeneous stakeholders with different goals and needs, and a dense degree of interaction between the numerous agents and the environment. In ABMs, through the use of bottom-up approaches, it is possible to observe and analyse the emerging properties of the system. Agents may own heterogeneous behavioural rules; they may act or react given previous states and interactions among each other. Moreover they may be embedded in networks and therefore the researcher may observe the impact of the social influence on agents' choices. Another very useful instrument is activity based model, which offers the additional advantage of representing travel activities as a direct consequence of diverse personal activities, building a link between economic and social dimensions, and travel behaviour.

Nevertheless, in the literature there is still a gap in urban transport AB modelling. The present literature review has highlighted that few ABMs on freight transport are focused on urban areas only. Most of the existing works in this field consider rather broader regions. However, the specificities of freight transport in urban areas and its crucial role in terms of sustainable development require focusing the analysis on the flows in and to/from the cities, even if in connection with the mobility of other more extended areas. The ABMs dealing with passengers' mobility in urban areas are more numerous than those dealing with city logistics but their number is still limited. They are usually focused on sub-categories of city inhabitants, such as school pupils, students, pedestrians or car owners, without a systemic view.

Regarding environmental issues, around half of the models aim to estimate pollutant emissions or congestion as one of the outputs or plan to do that in the future versions of their works. Only one study determines the impact on climate change.

The maturity level which can be labelled as field experiment is reached more often in the passengers' domain than in the freight one. In general, it would be extremely interesting and useful to implement real surveys in order to calibrate the ABMs using first-hand data. This would be true particularly for data on the needs and problems of stakeholders involved in city logistics, even if it is clear that this kind of survey would be extremely complicated and expensive, given the heterogeneity of actors involved. Most of the models analyse their respective issue from a strategic point of view, in the sense that they consider it as a whole system and aim to provide policy recommendations that address the problem at its roots, and not only in some sub-parts of it.

Despite all the models being theoretically conceived as DSS, little work has already been implemented in the real world by policy-makers. As indicated in the last column of Tables 2 and 3 any model is located at the stage of a deployed system. Some of the work provides an ex-ante estimation of the impacts of policies. In this way they provide important information for potential decision-makers. However, we could not find any evidence about the actual use of these models. Indeed, in the opinion of the authors and according to this review, the main role for ABMs in this field should be that of external support for public decision-making.

The analysis suggests that the most useful frontier that needs scientific advances in the field of urban studies is the development of ABMs that integrate the passenger and freight dimensions. The reason for this recommendation is that any public policy, having the aim of improving one of the two dimensions, inevitably influences the other. ABM would provide the important possibility of integrating the two dimensions. Such research should exploit the existing expertise developed in the field of freight mobility in cities and broader areas, and in the few models dealing with passengers commuting behaviours in towns. The main challenge of such an integrated model would be the coordination among all the activities and the consistency between passenger behaviour and the requirements of freight mobility in the city.

As far as the authors know, only one model tried to integrate freight and passenger issues in the same application: TRANSIMS (Smith et al., 1995), even though it mainly focused on passenger transport. The conceptual work of Roorda et al. (2010) also plans to try this integration, starting from a model on urban passengers' mobility and extending it to urban freight transport. They indicate, for example, that jobs modelled for the passengers system are coincident with the necessity of labour in the freight system or the travel times of commercial vehicles are consistent with the flows of passengers' means of transport.

The present literature review is the first step in widening the research, which has the final objective to develop a model able to consider GHG emissions of the whole urban mobility system and the capability of public policies to meet climate change goals. As a second step in this research, an agent-based model will be developed to consider firstly only the passenger mobility and secondly also the freight flows. The model will be calibrated on Varese area (North West of Italy). The total GHG emissions derived from commuting patterns and from city logistics decisions will be estimated with different transport modes and under the influence of different kinds of policies.

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Appendix A

Table 2
Literature containing agent-based models on freight transportation in urban areas

Author(s)	Intention of the model	Type of variables and/or agents	Geographic dimension	Calibrated on actual data	Time horizon	Structure	Attitude	Maturity level
Taniguchi & Tamagawa, 2005	Evaluation of city logistics measures impacts on the stakeholders behaviour	Administrators; Residents; Shippers; Freight carriers; Urban expressway operators	–	No	Strategic	Dynamic	Both	Simulation experiment
Donnelly, 2007	Urban freight demand estimation and supply design	Economic drivers; Modal alternatives; Trans-shipment; Exports & Imports, Shipment generation, Destination choice, Carrier and vehicle choice, Tour optimization	Oregon	Yes	Strategic & operational	Static	–	Field experiment
Tamagawa et al. 2010	Model for vehicle routing and scheduling problem with time window-forecasted	5 kinds of actors with different objectives on a test urban road network: Freight carriers; Shippers; Residents; Administrators; Motorway operators	–	No	Strategic	Dynamic	Both	Simulation experiment
Roorda et al. 2010	Development of a framework for a description of actor heterogeneity and interaction in freight system	Business establishments, firms and facilities; commodity production and business service facilities; logistics service facilities; End consumers Contracts; Commodity contracts; Business service contract; Logistics service contract; Shipments Time	Toronto Area	Yes, 2006	Strategic	Dynamic	Both	Conceptual proposal
Anand et al. 2012	Design of an ontology		–	–	Strategic	Dynamic	Both	Conceptual proposal
Van Duin et al. 2012	Investigation on the impact of policy measures for the success or urban distribution centres	Trucks and freight carriers; one type of goods; UDC operator; Retailers; Municipality; Road network	–	No	Strategic	Dynamic	Cooperative	Simulation experiment
Teo et al. 2014	Evaluation of the short-term impact of distance-based road pricing on the major urban stakeholders	Carriers' profit and cost, shippers' cost, distance travelled by trucks, n. of trucks, n. of customer complaints, nitrogen oxide, NOx, carbon dioxide, CO_2, suspended particulate matter	Osaka road network	No	Strategic	Dynamic	Both	Simulation experiment

Table 3
Literature containing agent-based models on passenger transportation in urban areas

Author(s)	Intention of the model	Variables	Categories of people	Geographical dimension	Calibrated on actual data	Time horizon	Structure	Attitude	Maturity level
Smith et al., 1995	TRansportation ANalysis SIMulation System (TRANSIMS) as integration of transport system with environmental analysis	Socio-economic characteristics; Economic activities	Commuting choices	Dallas, USA, 1,200,000 inhabitants Albuquerque, USA, 555,417 inhabitants	Yes From 1995	Strategic	Dynamic	Competitive	Field experiment
Schelhorn et al. 1999	Investigating pedestrian behaviour in urban centres. Pedestrian movement is influenced by attractions' configuration and location	Socio-economic characteristics: income, gender, Behavioural characteristics; speed; visual range; fixation on the schedule	Pedestrian behaviour in the city	None (simulated data)	YES GIS-based socio-economic data	Strategic	Dynamic	–	Simulation experiment
Salvini & Miller, 2005	Simulation of the evolution of an integrated urban system over an extended period of time	Demographic features; Transportation nodes and links; Travel times; Buildings; Location; Monetary values	City inhabitants, Households, Firms, Establishments, Property owners	Greater Toronto Area, 5,700,200 inhabitants	Yes-Year not specified	Strategic	Dynamic	Both	Field experiment
Harland & Stillwell, 2007	Simulation of daily pupil movements between schools and residences for planning support system	School rolls; commuting distances; pupil mobility; residential migration; pupil gender; pupil ethnicity	Commuting to school, residential migration and movement between schools	Leeds, England, 700,000 inhabitants	Yes 2002–2007	Strategic	–	–	Conceptual proposal
Benenson et al. 2008	Development of a model for parking space supply	Destination of the drivers; Search time; Walking distance; Parking costs	Inhabitants searching for parking	District of Tel Aviv, Israel	Yes 2005–2006 GIS	Strategic	Static	Competitive	Field experiment
Lu et al. 2008	Development of a simulation model to study the impact of six land use regulation scenarios on transit use for work and urban form	Metropolitan rail lines; employment distribution; Residential location; Household income; Household size; Car ownership; Age; Gender	Work travel behaviour and Urban Form	Inspired to the Cook, DuPage, Kane, Lake, McHenry, Will Counties of Chicago, USA	YES 1995 GIS	Strategic	Dynamic	Competitive	Field experiment
Shukla et al. 2013	Predicting university commuter behaviour and its impact on the transportation system	Demographic features; Info on the role in the Campus; Travel info	University commuters (students and staff)	Wollongong Campus, New South Wales, Australia	Yes 2011	Strategic	Dynamic	–	Conceptual framework
Natalini & Bravo, 2014	Testing ex ante the impact of public policies willing to foster commuting choices with lower GHG emissions	Transport mode choice by the agent; price of the transport mode	Commuting choices of Inhabitants	USA: various cities	Yes 2009	Strategic	Dynamic	Cooperative	Field experiment

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