Agents meet Traffic Simulation, Control and Management: A Review of Selected Recent Contributions

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***Abstract*—In the last decades, transport demand has increased quickly due to several concurrent factors. The negative impacts of increased demand have many effects on both travelers themselves and communities and some actions need to mitigate them. To this purpose, progresses in different scientific fields as computer science, electronic, communication as well as studies on new and more sophisticated traffic simulation models contributed to realize Intelligent Transport Systems (ITSs), which provide advanced transport services for a better and efficient use of transport networks. The adoption of the software agent technology has given a significant contribution to the ITS development, due to their capability to both simulate traffic scenarios at different levels of detail and provide intelligent decision-making frameworks. Intelligent agents make it possible to study human behaviors and machine-to-machine interactions with the aim to simulate, control and manage transportation networks. Given their relevance, in the last years a great body of researches and surveys have been proposed in the literature on this matter. This paper wants to contribute by providing an overview of the most significant advancements produced during the period 2013- 2015.**

Keywords*—*Software Agents, Traffic Control, Traffic Management, Traffic Simulation.

I. Introduction

In the last decades, the combined effect of several factors such as growing population and number of vehicles, economic conditions, technological improvements has generated a quick increase of the demand for mobility which, in turn, produces negative impacts on the life quality in terms of environmental damages, traffic-jams and waste of time among the most significant [1]–[5]. Consequently, there is a need for solving or mitigating these problems. A great number of researchers have investigated on traffic issues in order to improve the performances of the transportation systems, mainly by proposing methods to optimize the use of existing resources [6]–[10].

Recent progresses in different scientific fields — e.g., computer science, electronic, communication among the others — have made available new tools and techniques addressed to realize Intelligent Transport Systems (ITSs). ITSs include a large variety of methods, technologies and models addressed to provide solutions to the transport system representation, control and management. Particularly, several ITSs are addressed to simulate, control and manage large transport networks in real-time [11], [12]. Among the ITS applications, an increasing attention is given to the advantages deriving by the adoption of the intelligent software agent technologies [13]–[15]. They can be defined as autonomous software entities able to deal with large, uncertain and/or dynamic systems in a centralized or distributed way. Software agents have learning and adaptive capabilities [16] as well as attitude to mutually cooperate and share their knowledge [17]–[20].

Moreover, software agents can simulate different behaviors and, to this aim, different agent classifications have been provided in the literature, as for instance in [21]–[23]. Agent most relevant characteristics of interest for the transportation science are: (*i*) *Ability*, when agent adopts high-levels of abstraction also in a local perspective. (*ii*) *Adaptivity*, when agents reveal a context-oriented attitude to interact with the surrounding environment (also in a real-time); (*iii*) *Autonomy*, that is the ability of working without the intervention of users, also by incorporating Belief-Desire-Intension (BDI) notions; (*iv*) *Flexibility*, in terms of exhibiting reactivity, pro-activeness and social ability simultaneously; (*v*) *Intelligence*, on the basis of their degree of reasoning and capability of learning; (*vi*) *Mobility*, when agents have the capability of migrating from a system to another. (*vii*) *Pro-activity*, when there is a goal-oriented approach; (*viii*) *Reactive or Deliberative* behavior, when agents can perceive the environment where they live and react to its changes; (*ix*) *Self-organization*, when they have the ability of coordinating themselves with the other agents to reach their individual goals; (*x*) *Social-oriented* attitude, versus collaboration and cooperation with other agents; (*xi*) *Temporal continuity*, which identifies the persistence over time; Obviously, each agent can show one or more characteristics at the same time.

The aforementioned properties of intelligent software agents (hereafter simply agents) are particularly suitable to cope with almost all the traffic issues by providing an intelligent decision-making framework [24] for both micro and macro approaches [25]. Furthermore, it is possible to simulate a great variety of both complex human behaviors and agent-to-agent interactions, with the consequent associated decision processes at different levels of detail and abstraction [26] so that agents often embed sophisticated techniques of Artificial Intelligence (AI). Finally, mutual interactions among agents and agents interactions with the environment where they live can be conveniently represented, usually as agents' stimulus/answers messages [27].

Due to their flexibility and properties, in the later years

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many studies have been produced on the use of agents for transportation issues, by covering several aspects and providing efficient solutions mainly for ITS purposes.

In this paper, an overview of the most recent and interesting advancements on the use of agents for coping with transport issues in the traffic simulation, control and management fields are presented. Moreover, to complete this overview some statistics have been carried out by considering: (*i*) the agents purpose for which they have been exploited; (*ii*) the specific intelligence approach embedded into the agents; (*iii*) the agent behaviors. The paper is structured as follows. Section II presents some interesting and recent papers dealing with different granularity of transportation applications, while some statistics about the current trends in applying agents to transportation issues are treated in Section III. Finally, Section IV draws the conclusions.

II. Micro and Macro Simulations

The decision processes underlying planning and management activities require the knowledge of the current and/or possible future states of the transportation networks. To this end, a great variety of models, architecture and approaches have been developed over time in order to simulate different aspects of a transportation system (such as traffic flows, congestion states, travel demand), to control and handle several network elements under different conditions and constraints with the final aim to obtain the realistic and useful results addressed to improve traffic conditions and environmental affects [28].

In such context, the benefits deriving from the adoption of agents are manifold. In fact, agents can be associated with several entities involved in the simulation – e.g., travelers, vehicles, signals, among the others – in order to represent autonomy and intelligence features and then reproduce their heterogeneous behaviors and interactions over time. It is worthwhile to note that the simulation of large and detailed transportation systems requires a considerable amount of computational resources, which often represented a limit to the dimension and the level of granularity of the simulation itself. However, new computational paradigms, as parallel and cloud computing [29], currently permit to simulate enormous transportation networks in a very detailed and realistic manner [30].

A common and highly distinctive criterion for classifying transportation agent tools is based on the adopted level of detail, e.g. microscopic or macroscopic. Agents fit well with both, although one of the main features of the agent-based simulations is the simplicity in adopting extremely accurate level of details. Therefore, a large body of agent-based investigations is carried out at a microscopic level which could be more complex to realize by using other approaches. On the contrary, when the study is based on a macroscopic level other approaches are usually more competitive than agents in terms of both design and use of computational/storage resources. Note that in this overview the mesoscopic approaches [31], [32] are not discussed because they have characteristics depending on how much their granularity is closed to micro or macro simulations.

Recently, promising opportunities are disclosed by virtual reality and the agent technology is perfect for simulating at a microscopic level the huge amount of mutual interactions taking place among the different simulated entities. For instance, an interesting multi-agent system, VR-ISSV, simulating traffic within a virtual reality platform is presented in [33], [34]. This system adopts different types of agents with a hierarchical modular approach characterized by reuse, reconfigurability and scalability. The vehicle behavior is simulated by means of a fuzzy-logic approach able to carry out the interactions with both the environment (e.g. road and weather) and the other vehicles included complex traffic maneuvers as lane changing and overtaking. Other useful references still dealing with virtual environment are [35]–[37].

In a very near future, autonomous vehicles will be a reality since many car companies are developing real drive prototypes. A particular proposal, based on the hypotheses of their forthcoming use, is in [38], where an auction approach to decide the crossing order at an intersection in presence of potential conflicts is discussed. More in detail, an auction mechanism among vehicles – assisted by agents – at traditional intersections is applied by using vertical and horizontal signals, traffic lights and autonomous reservation protocols which give priority to the vehicle (i.e. agent) with the best bid. The mechanism has been tested at a microscopic level on real city maps. In the highly automatized future scenarios, software agents are fundamental for applying protocols and operational paradigms, also derived from other contexts, as in [38]. Other papers of interest on agents and autonomous vehicles in microscopic simulations, which adopt more common approaches, can be found in [39]–[42].

Another interesting, although very complex, feature is the task of reproducing human behaviors as accurately as possible based on real data. To this purpose, different strategies can be adopted, although agents dealing with this type of problems often need to enclose complex artificial intelligence software engines (see the next Section). In this case, an example is represented by the traffic simulator described in [43] where agents use fuzzy-logic features for predicting the state of the transportation system and making possible fast productions of suitable solutions. The behavior of drivers derives by probe-car data for estimating the personality of individual drivers in selecting routes and taking into account various metrics of routes as number of turns, travel time and distances. A massively parallel execution of this system allowed simulating traffic flows in a large metropolitan area. The simulation of human driving behavior by means of an agent-based simulation is also the focus of [44] for traffic evacuation in emergency management tasks. In particular, the proposed system generates agent's driving behaviors based on multi-level driving decision models and, at each level, several widely used behavior models are combined together. The simulation allowed studying how the network evolves in presence of emergency events in order to identify critical situations and improve existing evacuation plans. Other interesting works implementing human driving behavior by using an agent approach are available in [45]–[48]. In this field, a number of works also tried to simulate pedestrian mobility by starting from the agent simulation of individual human behaviors. The simulation of driver and pedestrian behaviors share some fundamental features. However, in the first case the simulation of individual behaviors is more complex, in the second case the most difficult aspect to simulate is represented by the flows of crowds. In fact, for particular problems, such as evacuation procedures, pedestrian behavior is more random than vehicle behavior which, for example, are constrained to move along roads and must follow travel directions. Other remarkable papers on these subjects are [49]–[51].

Another topic widely investigated when using agents within a microscopic approach is the control and managing of the transportation network. For instance, a Newells simplified kinematic wave and linear car following models have been used in [31] to represent traffic flow states. An agent-based simulator evaluates traffic dynamics and vehicle emission/fuel consumption impacts of different traffic management strategies. There are also several scientific contributions, as in [52] and [53]. Some extensions of these studies consider new social phenomena involving alternatives mobility modes as car-sharing and car-pooling [54], [55]. The management of traffic signals is another interesting topic considered by many authors. A complex proposal is SURTRAC (Scalable Urban Traffic Control) [56], a real-time adaptive traffic signal control system integrating a multi-agent platform working in a decentralized, scalable and reliable manner. Its main peculiarities are that each intersection allocates its green time – independently and asynchronously by the other – based on current incoming vehicle flows, urban (grid-like) road networks are managed with multiple (competing) traffic flows and last, but not least, it operates in real-time. Furthermore, the coordination among monitored entities (traffic lights) is realized only at a neighboring level and provides them the ability of balancing incoming flows for establishing larger green waves. In such a way, the system is highly reactive to quick changes in traffic conditions and can respond by suitably managing the traffic signals. Tests conducted on a nine-intersection road network achieved major reductions in travel times and vehicle emissions over pre-existing signal control, and in [57] by integrating also a route choice system. Other valuable papers on the same theme are [58]–[60].

In the transportation field, the use of agents for carrying out a macro simulation has a minor appeal with respect to the microsimulation for the reasons previously specified. However, a number of interesting researches there exist, although sometimes they are combined with a micro simulation acting at a different level [61]–[63]. Here, the authors propose a new method to derive time-varying tolling schemes by using the concept of the Network Fundamental Diagram (NFD). NFD is based on the marginal cost pricing for studying the congestion price. A simulation applied to the test case study of Zurich has been realized by means of agents working at a macroscopic level. In [64] a not intrusive grid of agent-based sensors able to monitor traffic parameters for determining traffic flows on the roads is proposed. Such system adopts a grid of agent-based sensors, each one associated with a road and able to collect, analyze and aggregate acoustical vehicle data. Each road-agent, based on a distributed trust-system, improves its performances only by interacting with its own neighbors. Therefore, in this case the road traffic flows are not derived by simulating vehicles as individual entities but by considering each link (i.e. road) of the transportation network in terms of interaction with the environment (i.e. vehicles and other roads). A new real-time traffic signal control based on fuzzy logic and wireless sensor network to collect traffic information is presented in [65] where traffic flows are modeled at a macro level, as in the previous paper. A cooperative and hybrid agent for traffic signal control optimizes the green time effective utilization rate. The experimental simulation shows the capability of this approach to increase the capacity of the intersection by reducing the vehicle delay and adapting the green time to the real-time traffic flow changes better than other control techniques.

III. Current Trends in Applying Agents to Transportation Issues

In order to sketch the current trends in applying the agent technology to the transportation field, in this section some statistical results derived by an investigation carried out on 250 papers written in the 2013-2015 are presented. Even though three years are a narrow time, however the quick evolution of agent technologies in the last years made the scientific production in the examined period on the top for number and variety. In any case, the statistics presented in this section should be considered just an indication. More in detail, the 250 papers have been chosen among the most significant and the most cited papers; they have been considered and analyzed with respect to: (*i*) the purpose for which the agent technology was adopted; (*ii*) the type of "intelligence" embedded into the agents; (*iii*) the behaviors of the agents.

The first analysis explored the main goals of the researches that adopted the agent technology. To this aim, the papers have been grouped in six classes based on the goal of the corresponding paper, although the class borders are fuzzy. The first three classes focus only on a main topic, while the second three are a combination of the first ones. More specifically, the considered classes are:

1) Modeling: it includes all the contributions mainly focused on simulations, e.g. about network states, behaviors, vehicle flows, crowd flows.
2) Control & Management: it collects all those papers involving monitoring, setting, supervising and similar activities on the transportation networks such as, for instance, those involving traffic light cycles, transport demand, fleets and so on.
3) Planning: it is referred to all the works having the aim of designing network components, evacuation plans, bus schedules, among the others;
4) Modeling + Control & Management;
5) Modeling + Planning;
6) Control & Management + Planning.

The results of this analysis are reported in Table I, in terms of absolute values and percentages on the whole number of considered papers, and depicted in Figure 1. As it can be seen, the most popular classes are respectively the "Modeling" and the "Control & Management" that together represent more than the 70% of all the selected papers.

class	number	percentage
Modeling	109	43.6
Control & Management	72	28.8
Planning	20	8.0
Modeling + Control & Management	26	10.4
Modeling + Planning	17	6.8
Control & Management + Planning	6	2.4

TABLE I. AGENT PURPOSE.

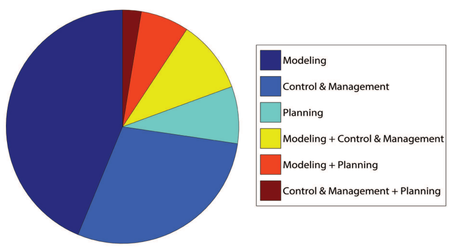

Fig. 1. Agent purpose.

After, the typology of AI embedded into the agents has been considered. Given the number of existing techniques only the most popular among them have been directly considered. More in detail, the following seven classes have been defined, namely:

1) Logic approaches (e.g. first or higher-order logics, Markov logic)
2) Fuzzy logic;
3) Neural Networks;
4) Genetic Algorithm;
5) Reinforcement Learning;
6) Other techniques;
7) Not Specified (i.e. the used approach is not described or not clearly identifiable).

Also the results of this second investigation are still reported in Table II, in terms of absolute values and percentages on the whole number of papers considered, and depicted in Figure 2. As the results show, the family of AI techniques within the logic approaches are mostly implemented, although an important part of them just adopt a basic logic. Fuzzy logic and reinforcement learning are the other two main AI techniques which meet the preferences of scientists, while a very high number of papers do not provide an adequate description of the implemented AI approach or its description is not sufficiently clear to permit its classification.

Finally, the last statistic deals with the behaviors of each agent. In fact, each agent usually has more than one behavior at the same time. More in detail, the considered behaviors are

class	number	percentage
Logic approaches	81	32.4
Fuzzy logic	27	10.8
Neural Networks	17	6.8
Genetic Algorithm	3	1.2
Reinforcement Learning	45	18.0
Other techniques	31	12.4
Not Specified	46	18.4

TABLE II. AGENT AI APPROACH.

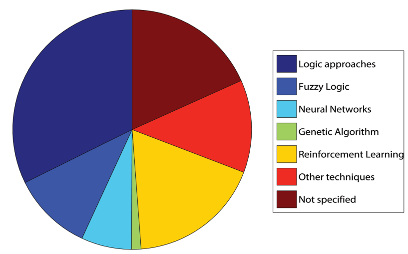

Fig. 2. Agents AI approach.

those previously listed in Section I, with the exceptions of the "intelligence" behavior – because in this study we considered only intelligent agents – and "flexibility" – which, in turn, is already a composed behavior (see Section I). More in detail, the considered behaviors are:

1) Autonomy;
2) Reactive or Deliberative;
3) Social-oriented;
4) Adaptivity;
5) Self-organization;
6) Pro-activity;
7) Temporal continuity;
8) Mobile.

These results are presented in Table III, organized similarly to the other tables and shown in Figure 3. The behaviors more adopted by agents are evident, while Self-organization and mobility are behaviors that have meet more rarely the interest of researches with respect to the considered sample.

IV. CONCLUSIONS

Transportation researches and application tools can receive many benefits from the use of agent technology. In fact, complex behaviors and interactions involving users and entities can be simulated by implementing sophisticated decision processes at different levels of detail and abstraction. Therefore, intelligent software agents are really key factors for a suitable development of ITS systems.

In this context, this short overview has discussed and classified some selected, very recent and innovative papers grouped for granularity and analyzed with respect to their aim,

class	number	percentage
Autonomy	193	18.3
Reactive or Deliberative	224	21.2
Social-oriented	86	8.1
Adaptivity	184	17.4
Self-organization	20	1.9
Pro-activity	153	14.5
Ability	58	5.5
Temporal continuity	132	12.5
Mobility	7	0.6

TABLE III. AGENTS BEHAVIORS.

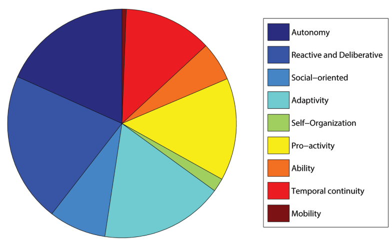

Fig. 3. Agents behaviors.

the agent intelligence and the agent behaviors. Obviously, other classifications are possible but we think that the one proposed here represents an equilibrium between the transportation and the computer science point of views.

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