A Review of the Applications of Agent Technology in Traffic and Transportation Systems

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***Abstract*—The agent computing paradigm is rapidly emerging as one of the powerful technologies for the development of large-scale distributed systems to deal with the uncertainty in a dynamic environment. The domain of traffic and transportation systems is well suited for an agent-based approach because transportation systems are usually geographically distributed in dynamic changing environments. Our literature survey shows that the techniques and methods resulting from the field of agent and multiagent systems have been applied to many aspects of traffic and transportation systems, including modeling and simulation, dynamic routing and congestion management, and intelligent traffic control. This paper examines an agent-based approach and its applications in different modes of transportation, including roadway, railway, and air transportation. This paper also addresses some critical issues in developing agent-based traffic control and management systems, such as interoperability, flexibility, and extendibility. Finally, several future research directions toward the successful deployment of agent technology in traffic and transportation systems are discussed.**

***Index Terms*—Agents, intelligent transportation systems (ITS), mobile agent systems, multiagent systems (MAS).**

I. Introduction

AGENT-BASED computing is one of the powerful technologies for the development of distributed complex systems [1]. Many researchers believe that agents represent the most important new paradigm for software development since object-oriented design [2], and the concept of intelligent agents has already found a diverse range of applications in manufacturing, real-time control systems, electronic commerce, network management, transportation systems, information management, scientific computing, health care, and entertainment. The reason for the growing success of agent technology in these areas is that the inherent distribution allows for a natural decomposition of the system into multiple agents that interact with each other to achieve a desired global goal. The agent technology can significantly enhance the design and analysis of problem domains under the following three conditions [3]: 1) The problem domain is geographically distributed; 2) the subsystems exist in a dynamic environment; and 3) the subsystems need to interact with each other more flexibly.

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The domain of traffic and transportation systems is well suited to an agent-based approach because of its geographically distributed nature and its alternating busy-idle operating characteristics [4], [5]. From the traffic and transportation management perspective, the most appealing characteristics of agents are autonomy, collaboration, and reactivity. Agents can operate without the direct intervention of humans or others. This feature helps to implement automated traffic control and management systems. Agents are collaborative. In a multiagent system (MAS), agents communicate with other agents in a system to achieve a global goal. Agents can also perceive their environment and respond in a timely fashion to environmental changes. Agent-based transportation systems allow distributed subsystems collaborating with each other to perform traffic control and management based on real-time traffic conditions. A distributed vehicle monitoring testbed presented in [6] is an early example of the distributed problem-solving network. Recently, more and more agent-based traffic and transportation applications have been reported. Our literature survey shows that the techniques and methods resulting from the field of agent system and MAS have been applied to many aspects of traffic and transportation systems, including modeling and simulation, intelligent traffic control and management, dynamic routing and congestion management, driver-infrastructure collaboration, and decision support.

This paper reviews agent applications in traffic and transportation systems. These applications are classified into five categories: 1) agent-based traffic control and management system architecture and platforms; 2) agent-based systems for roadway transportation; 3) agent-based systems for air-traffic control and management; 4) agent-based systems for railway transportation; and 5) multiagent traffic modeling and simulation. The selected projects in each category are listed in a tabular format with information of project name, research group, application domain, and key features.

II. Architecture and Platforms of Agent-Based Traffic Control and Management Systems

The operation of agents is supported and managed by distributed software platforms known as agent systems. The name of MASs usually refers to systems that support stationary agents, and mobile agent systems support mobile agents. An agent system provides mechanisms for agent management, agent communication, and agent directory maintenance. A mobile agent system provides additional mechanisms to support the migration and execution of mobile agents. In an agent system, agencies are the major building blocks and are installed in each node of a networked system, in which agents

TABLE I
SYSTEM ARCHITECTURE AND PLATFORMS OF AGENT-BASED TRAFFIC CONTROL AND MANAGEMENT

Project name	Research group	Application domain	Key Features
TRACK-R agents	Garcia-Serrano et al. [7], Technical University of Madrid, Spain	Traffic management	Using international agent standard, FIPA, to design TRACK-R agents
	Tomas and Garcia [8], University Jaume I, Spain	meteorological incident management	Propose a FIPA compliant MAS for the management of non urban road meteorological incidents. The paper defines ontology, types of agents, and communication protocols for the proposed MAS
Mobile-C	Chen et al. [13], [9], [14], University of California, Davis, U.S.A.	Traffic detection and management	FIPA compliant MAS, support both stationary agents and mobile agents, hybrid control architecture
InTRYS and TRYSA2	Hernandez et al. [17], Technical University of Madrid, Spain	Traffic management	Comparison study of centralized and decentralized agent-based architecture for traffic management systems
aDAPTS	Fei-Yue Wang [4], [5], University of Arizona and Chinese Academy of Science	Traffic control and management	Describes both hardware and system implementation, and its field deployment in real-world urban traffic control using agent technology
	van Katwijk et al. [19], Delft University of Technology, The Netherlands	Test bed for multi-agent control systems in road traffic management	A test bed to experiment with different strategies for the application of multi-agent systems for dynamic traffic management and examine their applicability

reside and execute. To facilitate the interoperation of agents and agent systems across heterogeneous agent platforms, agencies designed to comply with agent standards are highly desired.

Although more and more studies have been reported to apply agent approaches to traffic and transportation systems, only few researches address the system architecture and the platform issues of agent-based traffic control and management systems. Table I summarizes some of the system-level researches reported in the literature. Garcia-Serrano *et al.* [7], Tomas and Garcia [8], and Chen *et al.* [9], [10] are three MASs that are designed for roadway traffic detection and management and are compliant with the IEEE Foundation for Intelligent Physical Agents (FIPA) standards, which is one of the major international agent standards. In [7], several Traffic Agent City for Knowledge-based Recommendation (TRACK-R) agents are designed to provide traffic route recommendation for humans or other agents. Each TRACK-R agent is responsible for a geographical area. Tomas and Garcia [8] propose an MAS to help traffic operators determine the best traffic strategies for dealing with nonurban roadway meteorological incidents. The agents in these two systems are implemented using the Java Agent DEvelopment Framework (JADE) agent platform [11], [12]. Chen *et al.* [9], [10], [13], [14] developed a mobile agent system called Mobile-C and designed an agent-based real-time traffic detection and management system based on Mobile-C. Mobile-C is an IEEE FIPA standard compliant multiagent platform for supporting C/C++ mobile agents in networked intelligent mechatronic and embedded systems. Mobile-C was originally developed to enhance the distributed computing and information fusion capability for a laser-based highway vehicle-detection system [15], [16]. Although it is a general-purpose multiagent platform, Mobile-C is specifically designed for real-time and resource-constrained applications with interface to hardware.

Commonly used control architectures of intelligent agent-based systems can be classified into hierarchical, heterarchical, and hybrid. Generally, the hierarchical approach decomposes the overall system into small subsystems that have weak interaction with each other. On the other hand, the heterarchical approach is a completely decentralized approach in which agents communicate with each other to make independent decisions. Since the distributed agents only have a local view, it becomes difficult to predict the network state from a global perspective. The hybrid approach combines the features of hierarchical and heterarchical approaches. Hernandez *et al.* [17] study and compare centralized hierarchical and decentralized heterarchical agent-based architectures for intelligent traffic management in an urban traffic network. Two agent-based intelligent traffic management systems, i.e., InTRYS and TRYSA2, target the same problem domain but differ significantly in the way that the traffic agents of the system are coordinated. InTRYS achieves agent coordination based on a traditional centralized mechanism, whereas TRYSA2 employs the decentralized coordination. Their experience shows that the decentralized architecture has advantages in synchronization, reusability, and scalability. However, regarding the complexity of the coordination task, the InTRYS approach defeats the decentralized system TRYSA2. This is because the TRYSA2 strategy may imply an exhaustive search for plans to be selected by the involved agents [17].

Most reported agent-based applications in traffic and transportation systems focus on developing MASs that consist of multiple distributed stationary agents. Mobile agent technology has not been widely applied in this area. To demonstrate the great value of mobile agents to intelligent transportation systems (ITSs), Chen *et al.* [9], [10] integrate mobile agent technology with MASs to enhance the flexibility and adaptability of large-scale traffic control and management systems. Different from stationary agents, mobile agents are able to migrate from one host in a network to other hosts and resume execution in remote hosts. Mobile agents can be created dynamically at runtime and dispatched to destination systems to perform tasks with most updated code and algorithms. Mobility offers great opportunity to address challenges in traffic control and management, such as quick incident diagnosis, dynamic system configuration, new control-strategy deployment, and data-transmission reduction.

To achieve flexible and intelligent control of traffic and transportation systems, Wang [4], [5], [18] developed an agent-based networked traffic-management system. The agent-based control decomposes a sophisticated control algorithm into simple task-oriented agents that are distributed over a network. The ability of dynamically deploying and replacing control agents as needed allows the network to operate in a "control on demand" mode to adapt to various control scenarios. The system architecture employs a three-level hierarchical architecture. The highest level performs reasoning and planning of task sequences for control agents; the middle level dispatches and coordinates control agents; and the lowest level hosts and runs control agents. The control agents are represented by mobile agents that could migrate from remote traffic control centers to field traffic devices or from one field device to another.

For the rapid prototyping of multiagent control systems in road traffic management, van Katwijk *et al.* [19] developed a testbed to allow designers of MASs to experiment with different strategies and examine the applicability of developed systems. The testbed consists of intelligent models for modeling intelligence of agents, a world model for representing traffic process, and an interaction model for modeling the interactions between agents. The communication in the testbed conforms to the FIPA standards.

III. Agent-Based Systems for Roadway Transportation

Major challenges that roadway transportation faces are increasing traffic congestion, accidents, transportation delays, and vehicle emissions. The Texas Transportation Institute and the Texas A&M University System 2009 Urban Mobility Report [20] presents detailed trend data from 1982 to 2007 for 439 urban areas in U.S. The report provides both local view and national perspective on the growth and extent of traffic congestion. According to the report, congestion costs (the cost of extra time and fuel) in 439 urban areas are increasing from $16.7 billion in 1982 to $87.2 billion in 2007. To address the current problems and meet the growing travel demand, the solution is either constructing additional conventional roadway infrastructure or applying new technology to efficiently and effectively use existing infrastructure [21]. It is widely recognized, however, that the opportunities for building new physical infrastructure are decreasing because of increasing cost, environmental impact, and space limitations.

ITSs are a promising solution to address the aforementioned problems. ITSs apply technological advances in computers, communications, and sensor technology to transform road transportation into an effectively managed, well-integrated, universally available, and affordable system. The information is the core of ITSs, and all ITS functions can be implemented by efficient and effective use of real-time traffic information [22]. The agent technology enhances interoperability and distributed computing capability of existing centralized information systems in ITSs. The distributed agent systems can combine information from multiple detection stations and systems, evaluate traffic flow, respond to traffic flow changes, and evaluate operational responses to traffic flow changes in real time. The integration of data from multiple detection stations and systems will help operations become more efficient by enabling a more comprehensive view of the environment. The distributed computing capability enables detection stations to cooperate with each other in a certain area to perform traffic information fusion, which will dramatically reduce the response time to incidents in emergency. Table II lists some of the agent applications in roadway transportation.

A. Freeway Traffic Management

Logi and Ritchie [23] investigate the interjurisdictional traffic congestion management on freeway and surface street (arterial) networks. Their system is composed of two interacting real-time decision support agents, i.e., a freeway agent and an arterial agent, for analysis of congestion and for generation of suitable responses. The freeway agent supports incident management operations for a freeway subnetwork, and the arterial agent supports operation for the adjacent arterial network. Both agents continuously receive real-time traffic data, incident-detection data, and control status of the control devices on the network (signals, ramp meters, and changeable message signs). By performing an analysis of the input data and interacting with a human operator at their local traffic operation center (TOC), each agent generates suitable local control plans, which are aimed at reducing the impact of congestion at a local level. The system provides a dialog facility through a distributed user interface to allow operators at different TOCs to agree on the selection of a global solution. Van Katwijk and Van Koningsbruggen [24] propose an agent-based approach for the cooperation of traffic-control and management instruments. To improve traffic flow and provide safe and secure transport of people and goods, increasingly more traffic control and management instruments are installed on highways. The increasing number of deployed instruments sometimes causes conflicts when control tools are applied in the same area. By modeling individual instruments as intelligent agents, the cooperation of traffic control and management instruments can be achieved by the cooperation of distributed agents in a multiagent platform. Weyns *et al.* [25] present an agent-based anticipatory vehicle routing approach to avoid traffic congestion. The individual vehicles are able to dispatch lightweight agents for exploring alternate routes and inform the road infrastructure about its travel intention. Rothkrantz [26] reports a distributed routing model of a personal intelligent traveling-assistant system. The JADE agent platform is adopted in the system. Personal agents for each individual traveler communicate with the driver and the system to provide optimal advice to the traveler and update stored traffic information in the system.

B. Urban Traffic Control

The increasing urban traffic jams have motivated researchers to study innovative control strategies to efficiently manage the movement of traffic in the urban area. Agent-based approaches have been widely investigated in different areas of urban traffic control (UTC), such as the UTC model [27], [28], intersection signal control [29], [30], bus fleet management [31], [32],

TABLE II
AGENT APPLICATIONS IN ROADWAY TRANSPORTATION

Project name	Research group	Application domain	Key Features
CARTESIUS	Logi and Ritchie [23], Technische Universität München, Germany	Traffic congestion management	Two interacting knowledge-based agents for inter-jurisdictional traffic congestion management
IDTMIS/UTC	Roozemond [27], [29], Civil Engineering and Geoscience, Delft University of Technology, Netherlands	Urban Intersection Control	A theoretical UTC model based on several Intelligent intersection Traffic Signaling Agents (ITSA), Road Segment Agents (RSA), and some authority agents
	Guo et al. [28], Tsinghua University, China	Urban traffic control	A conceptual three-layer urban traffic control model
	Choy et al. [30], National University of Singapore, Singapore	Traffic signal control	Hierarchical multi-agent architecture, embedded fuzzy-neural decision-making modules, on-line learning capability
	Zhao et al. [33], University of Southern California, U.S.A.	Bus-holding control	Achieve dynamic coordination of bus dispatching through the negotiation between a bus agent and a stop agent
CORBA-A	Zhang et al. [36], Tsinghua University, China	Traffic data management	Distributed MAS architecture, the software implementation is based on the combination of CORBA and agents
TRYSA2	Ossowski et al. [39], Rey Juan Carlos University of Madrid, Spain	Decision support for urban traffic control	An application of TRYSA2 system for distributed decision support of urban traffic control
	Srinivasan and Choy [45], National University of Singapore, Singapore	Traffic signal control	A single layer cooperative multi-agent architecture, the cooperative zones of individual agents can be updated and allocated dynamically
aDAPTS	Wang [4], [5], Chinese Academy of Sciences, Beijing, China	Urban traffic control and management	A hierarchical three-level agent platform for urban traffic control. The platform integrates mobile agent concept with multi-agent systems
ACTAM	Chen et al. [46], National Chiao-Tung University, Taiwan	Traffic signal control	The modular design of an adaptive and cooperative traffic signal agent
HUTSIG	Kosonen [48], Helsinki University of Technology, Finland	Traffic signal control	Allow on-line simulation that takes real-time detector data to model traffic situation
	Moreno et al. [53], DEIM, URV	Taxi dispatch	Customers can request a taxi from his/her PDA through a personal agent running in a JADE-LEAP agent system
NTuCab	Seow et al. [54] – [56], National University of Singapore	Taxi dispatch	Propose a taxi dispatch system that attempts to minimize the total waiting time of a group of customers
	Ossowski et al [59], [60]. University of Rey Juan Carlos, Spain	Decision support systems	Define an abstract architecture for multi-agent decision support system. Instantiate each type of agents in the abstract architecture for two case studies in the domain of traffic management
SATIR	Balbo and Pinson [61], Paris Dauphine University, France	Decision support systems	Propose an interaction model called ESAC (Environment as Active Communication Support) to allow agents to interact directly, sending and receiving messages through logical filters of emission, reception, and interception
SATIR	Balbo and Pinson [62], Paris Dauphine University, France	Disturbance modeling and decision support systems	Knowledge related to the network dynamics that is stored in vehicle sensors is incorporated into disturbance modeling and decision support system

bus-holding control [33], the dynamic route-guidance system [34], the integration of UTC and route-guidance system [35], and distributed traffic data process and management [36], [37].

The traditional UTC approaches are mostly centralized, which are difficult to implement and maintain when the number of traffic components increases [38]. Bazzan [38] and Ossowski *et al.* [39] propose a decentralized traffic control [38] and a distributed decision support system (DDS) [39] to overcome the aforementioned weakness of centralized approaches. The study in [39] shows that the DDS based on a decentralized "emergent" coordination model enhances the scalability of the system. The introduction of new agents produces a shift in the social equilibrium and leads to new baseline coordination without any further modifications to the agent knowledge, whereas the same action needs to completely reconsider the priority relations in a centralized approach.

Wang [40] pioneered the work on agent-based control that uses mobile agent technology to transform control algorithms to control agents so that "control on demands" can be achieved similar to that of "programming on demands." Later, this idea was generalized to distributed control systems (DCS) by modifying and reorganizing DCS operating environments and proposed the architecture and operating mechanism for agent-based DCS (or aDCS) [41] and utilized aDCS in networked smart house systems and *in situ* copper leaching control processes [42] for the operation of network enabled devices [18] and for the fuzzy programming of robotic excavation [43]. Finally, they have developed an agent-based distributed and adaptive platform for transportation systems (aDAPTS) [4], [5], which is one of the earliest agent-based systems deployed for real-world UTC. In the aDAPTS platform, an UTC system is divided into three levels: organization, coordination, and execution. Agents at each level perform different roles. The distributed traffic control is achieved through the collaboration of agents at different levels. The platform also introduces the mobile agent concept to allow control agents to migrate from remote traffic centers to field traffic control devices or from one device to another.

Intersections are always the bottleneck of urban transportation systems. A number of researches have explored the use of distributed autonomous agents for proactive and cooperative intersection control. Roozemond [27], [29] proposed an agent-based urban intersection control system that reacts to changes in the traffic environment and adapts itself to changing environments based on internal rules. The proposed system consists of several intersection traffic signaling agents (ITSAs), road segment agents (RSAs), and some authority agents. The ITSAs manage the intersection controls helped by RSAs. The authority agents control and coordinate ITSAs to achieve a globally optimal system performance. In [29], Roozemond further studies the ITSA internal models and control algorithms that can handle proactive and real-time urban intersection control. Choy *et al.* [30] and Srinivasan *et al.* [44] present a hierarchical MAS that consists of three layers of agents with the lowest layer of intersection controller agents (ICAs), the middle layer of zone controller agents (ZCAs), and the highest layer of regional controller agents (RCAs). A ZCA controls several preassigned ICAs, and one RCA controls all of the ZCAs. The implementation of agents is based on neural network and fuzzy logic theories. The system provides online learning facilities, including reinforcement learning, learning rate and weight adjustment, and dynamic update of fuzzy relations using evolutionary algorithm, to allow agents dynamically adapting to changing environment. Evaluation of the proposed system shows that the multiagent approach reduces the total mean delay by 40% and the total vehicle stoppage time by 50% comparing with the Green Link Determining benchmark. Srinivasan and Choy [45] investigate a single-layer cooperative multiagent architecture for traffic signal control. Each agent in the system is assigned to control the traffic signal of an intersection in the traffic network. Each agent has its own cooperative zone, and the cooperative zones of individual agents can be updated and allocated dynamically. The agents within a single cooperative group will make a group decision pertaining to their respective outputs. The performance of the proposed cooperative MAS is tested on a large traffic network and compared with two other approaches.

There are some other agent-based applications for urban traffic signal control. Chen *et al.* [46] propose an adaptive and cooperative traffic light agent model for decentralized traffic signal control. Gregoire *et al.* [47] design a traffic light controller based on a learning agent. Kosonen [48] reports a multiagent traffic signal control system based on online simulation that takes real-time detector data to model traffic situation. Ferreira *et al.* [49] present a decentralized approach for urban intersection control. Each agent optimizes signal control based on local states, sensors, and "opinions" from neighboring intersection agents. Deng *et al.* [50] adopt a centralized server/client agent architecture for vision-based adaptive traffic signal control. Yang *et al.* [51] and France and Ghorbani [52] propose hierarchical MASs for UTC. The cooperative traffic control network presented in [51] uses reinforcement learning for local traffic optimal control and genetic algorithm to achieve global optimization by modifying the parameters of the reinforcement learning.

The bus-holding control problem is one of the critical issues in advanced public transportation systems. Zhao *et al.* [33] propose a negotiation-based multiagent framework to achieve the dynamic coordination of bus dispatching at various stops. The proposed MAS architecture consists of two types of agents: stop agent and bus agent. A stop agent represents the activity at a given stop and maintains knowledge of several neighboring stops. A bus agent interacts with a stop agent when it is at or near a particular stop. The negotiation between a bus agent and a stop agent is conducted based on marginal cost calculations. A bus agent may also negotiate with several stop agents nearby to get an optimal solution in a wider range. With the increase number of taxis, particularly in urban areas, taxis are becoming a convenient means of paratransit. To improve the quality of the service, agent-based taxi dispatch approaches have also been investigated. Moreno *et al.* [53] report their implementation of using a lightweight agent system, i.e., JADE-LEAP, in mobile devices. As a case study, the MAS architecture for taxi dispatch is presented. Five types of agents, i.e., personal agent, taxi station, taxi agents, traffic agent, and visualizer agent, are defined in the system. The personal agent is implemented using Fujitsu-Siemens Loox 600 PDAs with JADE-LEAP agent system. Other types of agents run on a standard PC within the main container defined in the JADE agent system. The main idea of the systems is that a customer requests a taxi from his/her personal digital assistant (PDA) through a personal agent. The request is sent to the taxi station. Based on the customer's request, the taxi station sends out the call for proposal to all available taxi agents. The taxi agents calculate the time needed to reach the customer and send the proposal back to the taxi station. The taxi station selects a taxi that can reach the customer with the shortest time and sends the taxi information to the customer. Different from most taxi dispatch systems whose goal is to find a shortest waiting time for a customer, Seow *et al.* [54]–[56] propose a multiagent taxi-dispatch system in which collaborative taxi agents negotiate among themselves to minimize the total waiting time of a group of customers.

Research initiatives such as the Defense Advanced Research Projects Agency (DARPA) Grand Challenge [57] have shown that an autonomous vehicle is capable of driving in traffic and performing complex maneuvers such as merging, passing, parking, and negotiating intersections. Dresner and Stone [58] have studied a multiagent approach for autonomous intersection management. They developed a simulation environment to demonstrate that an agent approach has a potential to significantly outperform current intersection control technology—traffic lights and stop signs. The method can also be extended to control human-driven vehicles in addition to autonomous vehicles, as well as give priority to emergency vehicles without significant cost to civilian vehicles.

C. DDSs

Another noticeable agent application in the transportation domain is the multiagent approach to the construction of DDS. In a distributed agent-based DDS [59], each distributed entity is controlled by a decision support agent. These distributed decision support agents collect and supply decision relevant data and provide reasoning services to analyze the meaning of this information. The further study of this approach leads to an abstract architecture for multiagent DDS [60], aiming to provide design guidelines for this type of system. This paper also shows how each type of agents in the abstract architecture is instantiated for two case studies in the domain of traffic management. Balbo and Pinson [61], [62] apply the multiagent methodology for the development of a distributed DDS for urban public transportation system management. In [61], the authors introduce an original interaction model called environment as active communication support (ESAC) to allow agents to interact directly, sending and receiving messages through logical filters of emission, reception, and interception. In [62], Balbo and Pinson present their approach of dynamic modeling of a disturbance process through a multiagent-based incident model. Through this model, knowledge relative to the network structure and knowledge relative to the network dynamics (stored in stop agents and in bus agents, respectively) are gathered to help human regulators in their monitoring tasks. The research works presented in [63] and [64] also deal with the regulation of traffic within a dynamic transportation system through a multiagent DDS.

IV. Agent-Based Systems for Air-Traffic Control and Management

The geographical and functional distribution and the highly dynamic nature of air traffic control (ATC) make it an ideal candidate with many potential applications that can be modeled with MAS [65], such as collision avoidance [66], [67] and air traffic flow management [68]. The optimal aircraft sequencing using intelligent scheduling (OASIS) presented in [69] is a real-time agent-oriented system developed to support air traffic management. OASIS distributes air-traffic-management tasks into two classes of autonomous and cooperating agents: aircraft agents and global agents. Each aircraft agent associates with an arriving aircraft and performs computation or reasoning relevant to the aircraft. The global agents, including *Coordinator*, *Sequencer*, *Trajectory Checker*, *Wind Model*, and *User Interface*, handle interaircraft coordination and reasoning. The system helps alleviate air traffic congestion by maximizing runway utilization through arranging landing aircrafts into an optimal order and monitoring the progress of each individual aircraft in real time.

Air traffic knowledge management is vitally important for ATC and management. Iordanova [70] points out the limitations of current systems and proposes conflict-free planning for air traffic supported by an agent-based architecture of integrated operational DDSs for airports, airlines, and ATC. The coordination and adequate sharing of air traffic knowledge by these three parties ensure planning of conflict-free air space time use offline before an aircraft takes off, monitoring the flights, and keeping them conflict free and efficient use of air space time.

Most agent-based ATC systems are designed and implemented in MAS architecture. The agents in these systems do not act alone. Wangermann and Stengel [71], [72] propose using principled negotiation for an intelligent aircraft/airspace system to allow both aircrafts and airlines to optimize their operations. Wollkind *et al.* [73] propose using cooperative multiagent negotiation for air traffic conflict resolution. The coordination capability of agents in MAS is promising in many ATC and management systems. For example, the multiagent approach to real-time traffic synchronization, presented in [74], demonstrates that the agent's collective behavior can offer efficient solutions to this collaborative problem.

Although MAS offers a number of advantages, such as decentralization and collaboration, it also increases the complexity of the system. Is MAS necessary and efficient for all applications? Nitschke [75] conducts a comparison study of MAS and single-agent system (SAS) architectures in ATC systems. The research results show that the MAS architecture has better performance for addressing a given set of goals for simulation scenarios utilizing a large number of aircrafts, and the SAS has better performance for addressing the same set of goals in simulation scenarios utilizing a small number of aircrafts.

V. Agent-Based Systems for Railway Transportation

Railway dispatching or scheduling has been usually modeled using classical technologies, such as operations research and constraint programming. These technologies are suitable to model static situations where the information is complete, but they lack the ability to cope with the dynamics and uncertainty of freight-train-traffic management [76]. The complexity of dispatching and scheduling problems in the transportation domain has attracted researchers from the multiagent community. Fischer *et al.* [77] present an MAS system that models a society of transportation companies whose goal is to deliver a set of dynamically given orders satisfying the given cost and time constraint. The distributed scheduling is achieved by giving individual vehicles local planning capability, and the global scheduling plans are generated from local decisions and problem-solving strategies. The proposed conceptual system and further study [78] lead to two practical applications, i.e., the TeleTruck system [79] and a railroad scheduling system [80]. Another example of using the agent approach to solve the dynamic scheduling problem is the decentralized agent system presented in [81].

The multiagent approach has been used in railway dispatching and scheduling problems. Tsen [82] has successfully solved the train line-planning problem using A-Teams [83]. Blum and Eskandarian [84] use a delegation model to improve agent collaboration in A-Teams to improve its efficiency for railroad flow optimization. Cuppari *et al.* [76] employ Complex Application Specification Environment based on Logic Programming, which is a logic programming-based environment, to prototype an MAS for the management of freight train traffic. The work presented in [85] uses a multiagent approach to the scheduling system for train coupling and sharing. The system is incremental, which takes incomplete task specifications into account, and generates an initial plan using contract-net protocol. The postoptimization of the initial solution is achieved by means of the simulated trading protocol. The external events can initiate a revision of an agent plan through the plan execution monitoring unit of the agent.

The agent approach has also been used for other railway applications. To model railway access negotiation, Tsang and Ho [86] employ a multiagent approach in which a train services provider (TSP) and an infrastructure provider (IP) are represented by individual software agents. An IP–TSP transaction is simulated by the negotiation protocols and the reasoning models of the IP and TSP agents. For flexible train traffic control and conflict avoidance, Proenca and Oliveira [87] have designed a multiagent railway control system. The system consists of two subsystems: control and learning. The "Control" subsystem is responsible for traffic management and guidance in the network. It includes three types of agents: "Supervisor," "Train," and "Station." The "Learning" subsystem has the objective of analyzing the past accumulated situation descriptions and infers rules that anticipate train conflicts and improve traffic-control processes.

VI. Multiagent Traffic Modeling and Simulation

Traffic and transportation systems consist of many autonomous and intelligent entities, such as man-driven vehicles, signal lights, and variable signs, which are distributed over a large area and interact with each other to achieve certain transportation goals. MASs provide a suitable way to model and simulate traffic systems since they offer an intuitive way to describe every autonomous entity on the individual level. In a multiagent traffic-simulation system, each intelligent traffic entity is modeled as an agent. Agents can work cooperatively with each other. MASs have been widely used to investigate traffic-related problems, such as route guidance, urban traffic management and control (UTMC), collaborative driving [88], [89], railway traffic control [90], combined rail/road transport [91], ATC [92], [93], and the optimization of airport operation [94]. Table III lists some of the multiagent-based traffic modeling and simulation applications.

Burmeister *et al.* [65], [95] present a framework for modeling the drivers' behavior in traffic simulations. The driver–vehicle elements are modeled as agents. The agent architecture consists of five types of modules: *Sensors*, *Effectors*, *Communication*, *Motivation*, and *Cognition*. *Sensors* perceive the environment; *Effectors* take actions; the *Communication* module is responsible for communication with other agents; the *Motivation* module models the agent's long-term goals, roles, and preference, whereas the *Cognition* module monitors and controls the agent's individual, communicative, and cooperative activities. It analyzes the sensor data and selects the most appropriate actions with respect to the intention. Zhang *et al.* [96] propose a multiagent framework for single-lane traffic simulation. In this framework, the major entities involved are modeled as agents, such as driver–vehicle agents, segmentation agents, traffic light agents, and vehicle-dispatching agents. The driver–vehicle agents are described by three-layer architecture, including strategic layer, tactical layer, and operational layer. Fischer *et al.* [97] introduce a simulation tool called AGENDA and its application in transportation simulation. The authors apply techniques developed in MAS, such as task decomposition and task allocation, decentralized planning, and negotiation to the scheduling of the transportation orders among shipping companies and their trucks. Meignan *et al.* [98] report a multiagent-based simulation tool that allows analyzing and evaluating a bus network. The main features of the simulation tool include the visualization of a bus network, static evaluation of a bus network, and simulation of bus operation. Three main components, i.e., buses, travelers, and road traffic, are considered in the simulation system. Buses and travelers are modeled as agents who move in an environment and interact with each other under the constraints proposed by the environment.

Agent-based driver behavior modeling addresses driving tasks both at strategic level [99], [100] and tactical level [101]–[103]. Tasks at the tactical level are those to achieve short-term objectives, such as accelerating, braking, or lane changing. The more sophisticated tasks, such as route choice behavior and navigation, are determined at the strategic level. A number of researches have been reported to propose and implement agent-based architectures for modeling driver route-choice behavior. Bazzan *et al.* [104] propose using beliefs, desires, and intention (BDI) agents to take the drivers' mental attitudes into consideration in traffic modeling. Rossetti *et al.* [99], [105] propose an extension to an existing microscopic simulation model called Dynamic Route Assignment Combining user Learning and microsimulAtion (DRACULA) to assess the influence of exogenous information on the drivers' decision making. Dia [100] proposes the use of an agent to model individual drivers based on behavioral surveys. Driver–vehicle units (DVUs) are modeled as autonomous software agents that can be assigned a set of goals to achieve. Agent-behavior parameters are defined, and their values are determined based on a field behavioral survey. The drivers' behavior model interfaces with a microscopic traffic simulation tool to simulate the movement of individual DVU between their origins and destinations. Wahle *et al.* [106], [107] study the impact of dynamic information on traffic systems with the consideration of the drivers' reaction. The behavior of drivers is modeled by a two-layered agent architecture, i.e., tactical layer and strategic layer. The tactical layer describes the tasks of driving on a short time scale. The strategic layer is responsible for sophisticated problems, such as route choice and decision making.

Adler *et al.* [3], [108] and Park and Kim [109] study the agent-based approach for route guidance and dynamic traffic assignment, respectively. The cooperative traffic management and route guidance system presented in [3] and [108] extends the ITS National Architecture Market Package ATIS6 by adding a middleware layer that is comprised of agents and agent negotiation protocols. Agents in the system represent travelers (Agent-IRANS), information service providers (Agent-ISP), and system operators (Agent-TMC), respectively. A principled negotiation is used to guide interactions between Agent-IRANS and Agent-ISP to make route choice and capacity allocation satisfying the objectives of both drivers and system operators. At the tactical task level, Hidas [102], [103] has developed a lane-change model based on the autonomous agent concept and implements it in an ARTEMiS traffic simulator. The model incorporates vehicle interactions for "forced" and "cooperative" lane changing, which are essential for lane changing under congested traffic conditions. Panwai and Dia [110] study a car-following model based on a reactive agent structure and a neural network approach. The validation result shows that the neural agent models outperform the existing car-following models, such as Gipps and psychophysical family of car-following models.

TABLE III
AGENT APPLICATIONS IN TRAFFIC MODELING AND SIMULATION

Project name	Research group	Application domain	Key Features
	Burmeister et al. [65], [95] Daimler-Benz Research Systems Technology, Germany	Traffic simulation	The driver-vehicle elements are modeled as autonomous and intelligent agents. Each agent consists of five types of modules: sensors, effectors, communication, motivation, and cognition
MARS	Fischer et al. [97], the German Research Center for Artificial Intelligence, Germany	Simulation tool	An agent-based simulation tool that provides different cooperation methods based on negotiation, which are required for solving scheduling problems in the transportation domain
Extension of DRACULA	Rossetti et al. [105], [99], Informatics Institute, PPGC/UFRGS, Brazil	Driver behavior modeling	Using BDI (Beliefs, Desires, and Intentions) agents and an agent-based framework to assess drivers' decision making behavior
	Dai [100], University of Queensland, Australia	Driver behavior Modeling	Modeling dynamic driver's behavior based on a field behavioral survey of drivers conducted on a congested real-world commuting corridor
	Whale et al. [106], [107], Gerhard-Mercator-University, Germany	Driver behavior Modeling	Using a two-layer agent architecture to study the impact of dynamic information on traffic systems with the consideration of drivers' reaction
CTMRGS	Adler et al. [3], [108], U.S.A.	Cooperative traffic management and route guidance	A cooperative traffic management and route guidance system based on the integration of multi-agent systems and principled negotiation
SAPIENT	Sukthankar et al. [101], Carnegie Mellon University, U.S.A.	Tactical driving	Using a set of distributed reasoning agents to independently recommend driving decisions based on their local assessment of the tactical situation
SITRAS	Hidas [102], [103], University of New South Wales, Australia	Modeling lane changing	Develop a lane change model based on autonomous agent concept and is implemented in ARTEMiS traffic simulator
ITSUMO	Da Silva et al. [111], Brazil	Urban mobility simulation	A simulation tool that is capable of performing simulations, such as driver behavior, traffic lights coordination, and traffic jam prediction
COTSCS	Li et al. [112], University of Edinburgh, U.K.	Urban traffic problems	A three-layer cooperative traffic scheduling and controlling system for urban traffic problems
	Liu et al. [113], Shanghai Jiao Tong University, China	Demand bus simulation	The separation of design model and domain model allows domain experts and system users to be involved in the system design
UDMLA	Salim et al. [114], Monash University, Australia	Model for intersection safety	Integration of intelligent software agents and ubiquitous data stream mining for intersection monitoring, collision warning and avoidance
PEDFLOW	Kukla et al. [115], Napier University, United Kindom	Modeling of pedestrians	A microscopic model of pedestrians' movement
PLATFORM	Gambardella et al. [91], Switzerland	Combined rail/road transport planning	A software platform that consists of intermodal transport planner and a simulation system. The agent-based planner organizes transport plans for dispatching intermodal transport units. The simulation system, composed of road simulation, rail simulation, and terminal simulation models, verifies the feasibility of these plans and measures their performance
ATFMGC	Li et al. [92], University of Brasilia, Brazil	Air traffic flow management	Combining grid computing with multi-agent coordination to improve air traffic flow management computational efficiency
	Halle et al. [88], [89], Canada	Collaborative driving	Comparison of centralized and decentralized platoon coordination
MAS-T2er	Rossetti et al. [121], University of Porto	Artificial traffic control system	A framework consists of a JADE implementation of transportation system, a microscopic traffic simulator, and a control strategies inductor

In UTMC systems, the multiagent models are used to solve traffic problems, such as traffic mobility [111], cooperative traffic scheduling and controlling [112], demand bus simulation [113], intersection safety [114], and pedestrians' flow modeling [115]. Da Silva *et al.* [111] present a multiagent traffic simulation tool that is based on a microscopic model of simulation. The simulation system is designed to use both offline and online information and can be used to simulate several aspects of traffic scenario, such as the driver behavior, traffic light coordination, and traffic-jam prediction. Li *et al.* [112] design a cooperative traffic scheduling and controlling system (COTSCS) based on a three-layer agent model. The highest layer is the global urban traffic agent that supervises and controls all the traffic agents in the urban region. The middle layer is composed of group traffic control agents that communicate and coordinate lower-layer agents in a subarea. The lowest layer agents are used to model individual traffic entities that control and execute individual plans. Liu *et al.* [113] propose a multiagent simulation framework to evaluate the usability of the demand bus system. The unique feature of the presented work is that it divides the computational model into the design model and the domain model. The design model is created by computer scientists. It defines the system architecture, communication protocols, and other platform-related information.

The domain model is created by domain experts, stakeholders, and users. It focuses on the research problem from the domain point of view. This approach allows domain experts and system users to be involved in system design, and as a result, the developed system can be closer to reality. Doniec *et al.* [116] propose a multiagent behavior model to handle traffic simulation at intersections. Each simulated vehicle (agent) coordinates its action with other vehicles present at the intersection or approaching to the intersection. The coordination mechanism [117] is based on perceptions of the surrounding traffic situation. The proposed model also provides agents with anticipatory abilities that allow the agents to reason about their actions and avoid gridlock situations. Vasirani and Ossowski [118] present a market-inspired approach for urban road traffic management, which allows for cars to individually reserve space and time at an intersection. In the proposed approach, a driver agent is able to make a reservation request with an intersection manager agent when it approaches the intersection. The marketplace is regulated by a set of rules to specify how to make a reservation, how to use it, and how to withdraw a reservation. These rules are implemented by agent interaction protocols such as the purchasing protocol.

Combining transportation models with agent-based transportation systems, Wang [119] proposes the concept of artificial transportation systems (ATSs). The ATSs have been studied to support system analysis and decision making [120], [121]. Wang and Tang [120] outline the basic concept and the key research topics in the development of ATS. Major components to form an artificial system for transportation, logistics, and ecosystems are also defined. Rossetti *et al.* [121] report an ATS framework for the assessment of intelligent transportation solutions. The framework consists of a JADE implementation of real-world transportation system, a virtual domain subsystem based on an agent-based microscopic traffic simulator, and a control strategy inductor that coordinates two subsystems and tunes the behavior of system elements to improve the overall performance.

A number of open-source agent-based traffic simulators have also been developed. For example, the MultiAgent Transport Simulation Toolkit [122] is a toolbox for the implementation of large-scale agent-based transport simulations. It can be used for agent-based traffic flow simulation and other applications. Simulation of Urban Mobility [123] is a portable microscopic road-traffic-simulation package designed to handle large road networks.

VII. Discussions

In this section, we discuss the following issues: system interoperability, the ability to handle uncertainty, and system extensibility, to share our visions of future research directions.

First, interoperability is critically needed in making decisions based on information across systems, organizational and jurisdictional boundaries, or application scenarios in which the integration of multiple agent systems is needed [124]. To tackle the interoperability issue, IEEE FIPA, which is a consortium of companies, government agencies, and schools, has been working on producing software standards for heterogeneous and interacting agents and agent-based systems. The goal of FIPA standards is to guarantee interoperability between agents by coordinating different aspects of systems, including system architecture, agent communication, agent management, and agent message transportation. To achieve this goal, FIPA provides specifications for an agent communication language to express exchanging messages, ontologies to define semantic contents of these messages, and agent platform architecture to support interagent communication. FIPA is one of two major international agent standards, i.e., IEEE FIPA standards [125] and OMG's Mobile Agent System Interoperability Facility. FIPA has been increasingly accepted in the agent community, and the compliance with FIPA standards has been recognized as a crucial property for the interoperability of agents [126]. To increase the system interoperability, the future development of agent-based traffic and transportation systems is recommended to be compliant to FIPA standards.

Second, most reported agent-based applications are based on MASs. These systems consist of multiple functional stationary agents that are intelligent and cooperative. The coordination between agents is achieved through certain types of protocols. The agent system architectures include simply interacting agents, centralized hierarchical architecture, and decentralized architecture. The use of MASs provides a clear added value of high degree of autonomy and cooperability to conventional systems. However, MASs have a limited ability to deal with uncertainty in dynamic environments. To overcome this weakness, we have proposed using mobile agents for ITS applications in [9] and [10].

The purpose of introducing mobile agents into traffic and transportation systems is to increase the flexibility and the ability of the system to deal with uncertainty in a dynamic environment. A stationary agent executes only on the system where it begins execution, and the code of stationary agents, including control algorithms and provided services, cannot be changed during execution. On the other hand, a mobile agent is not bound to the system where it begins execution. It has the unique ability to transport itself from one system in a network to another. The ability to travel allows a mobile agent to move to a system that contains an object with which the agent wants to interact and then to take advantage of being in the same host or network as the object. The mobile agent technology has been increasingly studied, and its strengths, such as reduced network load, overcoming network latency, supporting disconnected operation, working in heterogeneous environments, and the ability to deploy new software components dynamically, has been identified by several researches [127], [128].

The strength of mobile agents has great value in traffic-control and management systems. There are instances where Homeland Security attempts to track individual vehicles. A mobile agent with vehicle signatures filtering and recorrelating data between stations as needed might be a good solution for this purpose. Mobile agents can help reduce the delay of incident response. Traffic information system is usually distributed. If a mobile agent can migrate to detection stations near the incident scene and process data locally, then it will significantly reduce the delay of incident response. Mobile agents also help to achieve the cooperation between distributed roadway electronics and moving vehicles, which is one of the U.S. Department of Transportation's major ITS efforts. The communication of moving vehicles with roadside information infrastructure relies on expensive and fragile wireless network connections. Tasks requiring a continuous connection between a moving vehicle and a traffic information network are probably not economically or technically feasible. To solve this problem, tasks can be encapsulated as mobile agents and dispatched to the roadside network. After being dispatched, the mobile agents become independent to the system that created them and can continue their tasks even if the connection to the home system goes down. The moving vehicle can reconnect at a later time to collect the results from mobile agents. More importantly, mobile agents can enhance the ability of traffic-control and management systems to handle the uncertainty introduced in a dynamic environment. Since mobile agents can be generated dynamically, new services, operations, or control algorithms can be implemented as mobile agents. These software components can be dynamically deployed to remote machines as they are part of the preinstalled components.

Third, more attention needs to be paid on the openness and scalability design of systems, which is particularly important in large-scale distributed dynamic systems for future extension.

VIII. Conclusion

Software agents and their applications in traffic and transportation systems have been studied for over one decade. A number of agent-based applications have already been reported in the literature. These applications propose and investigate different agent-based approaches in various traffic and transportation related areas. The research results clearly demonstrate the potential of using agent technology to improve the performance of traffic and transportation systems. Most agent-based applications, however, focus on modeling and simulation. Few real-world applications are implemented and deployed. In general, the design, implementation, and application of agent-based approaches in the area of traffic and transportation are still immature and need to be further studied. The integration of new technologies, such as mobile agent technology, should be considered to enhance the flexibility of systems and the ability to deal with uncertainty in dynamic environments.

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Chen, B., Cheng, H.: A review of the applications of agent technology in traffic and transportation systems. IEEE Trans. Intell.Â Mannion P., Duggan J., Howley E. (2016) An Experimental Review of Reinforcement Learning Algorithms for Adaptive Traffic Signal Control. In: McCluskey T., Kotsialos A., MÃ¼ller J., KlÃ¼gl F., Rana O., Schumann R. (eds) Autonomic Road Transport Support Systems. Autonomic Systems. Transportation systems are networks, and much of the value of a network is contained in its information: For example, whether a traffic signal â€œknowsâ€ there is traf-fic waiting to pass through an intersection; whether a vehicle is drifting out of its lane; whether two ve-. hicles are likely to collide at an intersection; whether a roadway is congested with traffic; what the true cost of operating a roadway is; etc.Â Intelligent transportation systems include a wide and growing suite of technologies and applications.