Extended review of multi-agent solutions to Advanced Public Transportation Systems challenges

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ORIGINAL RESEARCH

Extended review of multi-agent solutions to Advanced Public Transportation Systems challenges

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Abstract

Over the past few decades, intelligent transportation systems (ITS) have emerged as an effective way to improve the performance of transportation systems. ITS provide innovative services, enhance travel safety, provide travellers with more choices, and make transportation systems more efficient. Multi-agent systems (MAS), which define autonomous interacting entities, are suitable for modelling distributed and intelligent systems in general and ITS in particular. This paper provides an in-depth review of multi-agent systems applied to Advanced Public Transportation Systems (APTS), a subclass of ITS dedicated to managing public transportation networks. We carefully analysed 38 papers in this study, published in 19 journals during 31 years (1990–2020). We perform a synthetic analysis of the trends in this domain and a qualitative analysis focused on multi-agent systems' dimensions and properties. We show that the MAS approach is well suited to the real-time management of disturbances thanks to their delegation process, and their pro-activeness and autonomy properties.

Keywords Literature Review · Intelligent Transportation Systems · Advanced Public Transportation Systems · Multi-agent Systems · Transport · Agent

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1 Introduction

Transportation systems face multifaceted issues: security issues, ecological issues, user quality-of-life issues, etc. One main difficulty concerns the constant increase of the transportation demand while the transportation supply and the infrastructure cannot be increased indefinitely for spatial, economic and ecological reasons. This gap between supply and demand may be addressed with the equipment of vehicles, travellers and infrastructure with new information technologies. The resulting transportation management systems are called Intelligent Transportation Systems (ITS). In this paper, we will consider the ITS dedicated to the public transportation networks, called Advanced Public Transportation System (APTS). Many researchers have developed artificial intelligence (AI) systems in the framework of APTS. This paper focuses more specifically on agent-based, and multi-agent approaches applied to solve APTS challenges.

Klügl et al. (2010) state multiple reasons to use agent-based systems and multi-agent systems (MAS) in transportation. Among other arguments, the authors underline that transport systems are usually (naturally) distributed, and the agent-based bottom-up modelling approach helps to consider the complexity of these systems. By definition (Wooldridge 2009), each agent is autonomous, and its behaviour can be specified to perceive the environment, act and react in a highly dynamic context. The interaction between agents may lead to emergent phenomena, e.g. the multiple-car-chasing-single-space phenomenon (Zargayouna et al. 2016). This capacity to represent complex systems is used to test strategies and multiple scenarios to tackle traffic congestion, resulting from the interaction between individual vehicle agents in multi-agent simulations.

In this survey, we address three research questions:

1. What are the APTS challenges that are tackled by MAS approaches? (RQ1)
2. What are the specific MAS features that are used in the APTS domain, and why? (RQ2)
3. How does the MAS paradigm benefit the APTS domain? (RQ3)

Our answers are based on a synthetic and qualitative analysis of a knowledge base (KB) resulting from the extensive bibliography on the use of agent technologies for APTS. The synthetic analysis deals with the analysis of the information about the papers (e.g. publication year, abstract, title) and the qualitative analysis focuses on the content of the papers. The research methodology is as rigorous as a Systematic Literature Review (SLR) but limited to the corpus of journal papers. Over the considered publication period (1990–2020), we found about a hundred survey papers for ITS. However, only 14 papers propose an SLR, and none specifically address MAS approaches. A unique paper (Porru et al. 2020) presents a review on mobility for public transportation and raises specific research questions based on mobility projects.

The remainder of this paper is organised as follows. Section 2 presents the basics of the APTS and MAS domains. Section 3 provides the background information on the methodology used in this paper. Section 4 presents the global analysis of the knowledge base. Section 5 provides the description in detail of the relevant research papers. Section 6 proposes a discussion about the answers to the research questions. Finally, Sect. 7 concludes this work.

2 Theoretical background

This section briefly recalls the background for the APTS domain (Sect. 2.1) and MAS approaches (Sect. 2.2).

2.1 Advanced Public Transportation System domain

The European commission[1] defines Intelligent Transport Systems (ITS) as “the application of information and communication technologies (ICT) in transport and infrastructure to improve safety, efficiency, and sustainability”. An “Advanced Public Transportation System” (APTS) is one of them and aims to increase public transportation systems’ efficiency and safety. The deployment of APTS (Ingvardson et al. 2017) is transforming the way public transportation systems operate and changing the nature of their services. In this paper, we consider as an APTS each digital system used to solve a problem related to public transportation networks.

Several possible classifications for ITS exist to analyse APTS positioning in the ITS field. Table 1 gives an overview of the alternatives from the state of the art and surveys of the ITS domain: ANPR (Automatic Number Plate Recognition Systems), APTS, ATIS (Advanced Traveler Information System), ATPS (Advanced Transportation Pricing Systems), ATMS (Advanced Traffic Management System), ATVS (Automated Vehicle Control Systems), AVCS (Advanced Vehicle Control Systems), AVSS (Advanced Vehicle Safety Systems), CVO (Commercial Vehicle Operations), CVS (Cooperative Vehicle System), EMS (Emergency Management System), IMS (Incident Management Systems), TMS (Transit Management Systems).

This summary shows that ATMS, ATIS and APTS are considered in each proposed classification in the literature. In addition, we believe that, with the growing interest in connected and autonomous vehicles, CVS (renamed as Connected Vehicle System) deserves to be included as a category. Therefore, we consider in this review the following categories: ATMS, ATIS, and CVS, to underline by comparison what characterises the APTS category.

2.2 Multi-agent system (MAS) paradigm

The main objective of many applications in the transportation domain is the management of distributed entities. We note that the multi-agent paradigm deals with systems consisting of many physically or logically distributed interacting

[1] https://www.mobilityits.eu/its-communictions-2 last visited 06 April 2023.

Table 1 Different Classifications for ITS categories

	ANPR	APTS	ATIS	ATPS	ATMS	ATVS	AVCS	AVSS	CVO	CVS	EMS	IMS	TMS
Bekiaris and Nakanishi (2004)		•	•		•	•			•				
Singh and Gupta (2015)		•	•		•						•		
Choi and Kim (1998)		•	•		•			•		•	•		
Figueiredo et al. (2001)		•	•		•		•		•		•	•	•
TMR (2016)	•	•	•	•	•					•			

components with a certain level of autonomy. With a bottom-up approach to system design, the MAS paradigm makes it easier to understand a complex reality through the reification of the components of the system to be managed.

There are several approaches for describing a MAS. Here we consider two of them. The first is based on the dimensions of a MAS, i.e., what has to be designed, and called the *Vowel* approach (Da Silva and Demazeau 2002). In this, the design of a MAS is based on four dimensions corresponding to the four vowels $\{A, E, I, O\}$:

(A) gents are active entities with local perception and local reasoning/decision. This dimension is focused on the agent's internal models.

(E) nvironment is the "common space" where the agents are situated. This dimension focuses on the virtual or physical modelling of the space where agents are located.

(I) nteraction: the interaction is crucial in MAS because the agents have a local reasoning and a coherent global behavior must be guaranteed. This dimension focuses on protocols and models for communication, coordination and negotiation.

(O) rganization deals with the relationships between agents. This dimension focuses on the design of normative systems.

The second approach (Badeig et al. 2016) suggests that the model based on MASs for complex applications requires four main properties: autonomy, proactiveness, context awareness and situatedness.

- *Autonomy* suggests "the necessity to articulate the different types of autonomous entities (Agents, Users, etc.)".
- *Pro-activeness* is "the way to maintain a consistent coupling between the processing structures and dynamic environments".
- *Context-awareness* is the way "to design systems in which there is a need to constantly adapt to evolving situations that may be hard to capture".
- *Situatedness* is "supported by continuous interactions with physical elements in the environment like traces as a result of their activity".

The bibliography analysis through the prism of MAS dimensions and properties is complementary. The *vowel* approach is used to understand what characterises a MAS model, while the properties are used to understand the critical features of the system based on a MAS model.

3 Methodology based on Systematic Literature Review

We apply a research methodology based on a Systematic Literature Review (SLR) (Kitchenham 2004; Moher et al. 2009; Oliveira et al. 2016) on APTS and MAS but limited to journal papers. Three steps define the used SLR method: (1) Planning (Sect. 3.1) concerns the processes related to the organisation of the SLR and details the research questions, the knowledge base design, and the risk management; (2) Implementation (Sect. 3.2) concerns the processes related to the building of the knowledge base (KB) and the study of the papers to answer the research questions; and (3) Reporting (Sect. 3.3) provides the synthesis of the findings of the SLR.

3.1 Planning

We (the authors of this SLR) have defined the research questions we address. They concern the relations between the multi-agent domain and the intelligent transportation systems. We have defined how the data will be processed at each step of the methodology. Finally, we have identified and analysed the risks associated with each step.

3.1.1 Research questions

We propose to answer the following three research questions:

- RQ1: What are the APTS challenges that are tackled by MAS approaches? The answer will be based on a gathering process of the papers according to their main challenges. It is done thanks to a synthetic analysis of the papers based on title, abstract, keywords, introduction and conclusion.
- RQ2: What are the specific MAS features used in the APTS domain, and why? The answer will be based on synthetic and qualitative analysis with the *vowel* approach as a reading grid. The most important features for the APTS domain are inferred from the most representative *vowel* dimensions.
- RQ3: How did the MAS paradigm benefit the APTS domain? The answer to this question is a qualitative analysis. It deals with the identification of the main MAS models coming from the bibliography and how their properties benefit the APTS domain.

3.1.2 Knowledge base design

The knowledge base (KB) will be composed of two components: (1) the set of relevant articles; (2) a spreadsheet containing the description of the articles following defined criteria. We consider two types of criteria: (1) the inclusion criteria for the paper selection process; (2) the reading criteria for feeding the spreadsheet.

3.1.3 Risk management

The decisions that we make at each step of the review have associated risks that we summarize as follows.

- *Missing papers risk:* The building of the set of relevant articles depends on the inclusion criteria. To limit the risk of missing relevant papers, we define specific criteria to ensure that the chosen papers represent the main trends to answer the research questions. Moreover, having a comprehensive data set refined to the only relevant papers limits this risk.
- *Partial paper analysis risk:* The risk is that the analysis could be incomplete or oriented. We limit the incompleteness risk because we consider two points of view in our study. As stated earlier, we consider first which MAS model dimensions are relevant in the design of an APTS (with the *vowel* approach). Then we consider how the properties of a MAS model benefit the APTS functionalities. The analysis could be oriented if the reading dedicated to the MAS leads to remarks/conclusions that are potentially not independent. The *vowel* approach and the analysis based on properties should limit this risk. Indeed, they both focus on descriptions considered in most definitions of a MAS.

3.2 Implementing

At first, we have to build an initial data set of the KB for the different papers, and then collect all relevant information about these papers (spreadsheet part of the KB).

3.2.1 Data set building criteria

We consider the following criteria for a paper to be included in the study:

Publication type. With the massive number of publications (conferences, journals, reports, white papers, PhD theses, etc.) in the ITS field, we have to adopt an editorial position to discuss a coherent subset of works in detail. We decided only to consider peer-reviewed publications and, among them, only those published in peer-reviewed journals indexed by Scopus or Web of Science databases.

Publication period. The papers have to be published between 1990 and 2020. This period seems to be large enough to be representative and limits the number of missing papers.

Research question relevance. The papers must be related to the ITS field and based on a multi-agent approach. This criterion is used to design our requests with keywords combining the two terms or expressions:

- (i) “transport” OR “traffic”, AND
- (ii) “multi-agent system” OR “multiagent system” OR “agent”.

This criterion is not too specific (for instance, restricted to APTS) to avoid missing papers. However, the returned set contains papers matching keywords, such as traffic and MASs, but actually dealing with a different subject. Hence, after reading the abstracts, we filter out the papers with an irrelevant subject for this study (e.g. agents in computer networks) and the papers related to the following fields: logistics, maritime/air transport. Finally, we have decided not to include the papers concerning the demand modelling. Indeed, we think that, despite the interest in a more precise generation of activities, these papers are out of scope of this paper, which focuses on the systems rather than on the data feeding them.

To evaluate these papers, we, the authors of this extended review, have read the abstracts, objectives, methods, results and discussions. After reading and analysing these papers and after discussions, we collectively decided on the papers to include in the analysis. Each paper was read by two of us (the readers) to check if it was relevant to our focus. The decision to include an article is based on the favourable opinion of these two readers. An additional discussion and other readings were helpful for some papers to obtain a consensus.

3.2.2 Knowledge base building

Here we detail the information collected in the spreadsheet during the reading step of the papers. The following information is used:

- For all papers,
  - *Article type:* {survey papers, research papers}
  - *ITS category:* {APTS, ATIS, ATMS, CVS}
- For APTS papers,
  - *vowel dimension:* $\{A, E, I, O\}$ we consider at most two vowels per paper.
  - *Model:* the main model that is developed in the paper. The relevant values cannot be defined before reading.
  - *Issue:* the central issue of the APTS to which the paper is related. It is placed in one main issue, even if several issues are considered. It cannot be defined before reading.
  - *APTS objective:* What is the objective in the use of the APTS. It cannot be defined before reading.

3.3 Reporting

Here we consider two steps. The first step is the synthetic analysis of the papers, and the second one is the qualitative analysis.

The synthetic analysis considers the meta-information about the papers and information from the title, abstract, keywords, introduction and conclusion. This gives an overview of the relationships between the MAS and APTS domains. For instance, the year of publication will help understand the evolution of the research in this field. Synthetic analysis also highlights the primary trend for the most relevant challenges for the APTS.

The qualitative analysis consists of reading the papers with analysis grids to extract comparable information. We used two analysis grids: the *vowel* approach (Da Silva and Demazeau 2002) and the properties (Badeig et al. 2016) (see Sect. 2.2). The *vowel* approach analysis helps to identify: (i) the component of the MAS model that is the most important in the design of an APTS solution, and (ii) the primary concern in the design. The analysis of the model with the properties grid gives direct information about the MAS paradigm benefits to the ITS functionalities.

4 Knowledge base description

In this section, we first present the results of KB building (Sect. 4.1), then we give the global trends of the KB based on the collected information (Sects. 4.2 and 4.3).

4.1 Knowledge base building

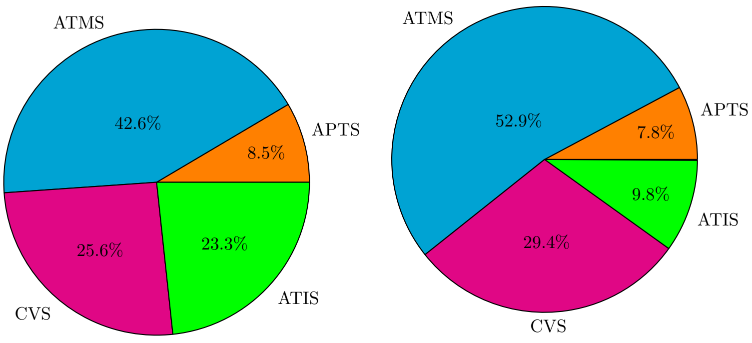
We first build the data set (using research engines) and then apply the inclusion criteria. The count of the journals to which at least one selected paper belongs gave 58 journals (cf. Annex 1): 29 journals in the ITS field, 20 journals in the AI field; and 9 journals in a related field, called in the following, *Computer Science and Industrial Informatics* (CSII). We executed the search for the last time on 28 February 2021, and we thus consider the journal papers concerning the period 1990–2020.

The number of all published papers for the considered journals over time, particularly the papers on ITS and MAS, grows exponentially (e.g. on ITS and MAS, from a unique paper (1990) to 82 papers for 2020). The total number of papers is 119 819 while the number of papers matching our request is 731. Therefore, we obtained a ratio of 0.6% for all these journals, with more matches in ITS journals (1.63% in ITS journals, 0.26% in AI journals, and 0.16% in CSII journals). For the APTS category, we observe a similar ratio with 0.031% for all journals (0.022% for ITS journals, 0.008% in AI journals, and 0.001% in CSII journals). Then, we refine the criteria, and the research question relevance to choose the papers to add to the KB. The result is 306 papers that are considered relevant for the review. Following this study, which requires substantial time to read the articles, we selected 268 papers and stored the related information in the spreadsheet. Among this set of papers, 16 are surveys and 252 are research papers.

4.2 Classification by types of papers

Some of the selected research papers were dedicated to surveying a specific subpart of the ITS domain. Here we present the analysis of these two types of papers: the surveys and an overview of the research papers.

The surveys usually deal with a specific ITS category or explore future trends. Half of the surveys were published after 2017, and no review considered the APTS category. The surveys focus essentially on the ATMS category (10 out of



(a) Distribution of papers for 2016–2020

(b) Distribution of papers after 2019

Fig. 1 Distribution of different research papers by category w.r.t. the period of publication

16 papers, 55.6% of the surveys). Four papers introduce surveys for ATIS, and four surveys concern CVS due to the recent interest in autonomous vehicles.

As expected by the surveys study, most research papers concern the ATMS category (approximately 42%). 25.1% of the papers explore ATIS, and 17.9% deal with CVS. Note also that the lack of a synthesis paper for APTS is surprising, although different researchers have studied this category (corresponding to about 14.7% of the papers).

4.3 Knowledge base overview

The objective of this section is to give a synthetic overview of the KB content. This overview is based on the analysis of the collected information.

4.3.1 Analysis based on the years of publication

The distribution of research papers by category for 2016–2020 underlines their relative importance for these categories. Figure 1 indicates that ATMS and ATIS represent a high number of papers for the period (2016–2020), and ATIS seems to decrease recently. CVS has a high ratio for the same period, which remains sound for the papers published in 2019 and 2020. However, the result for the APTS category exhibits a paradox. Although this category has been considered crucial for environmental considerations, this ratio is low (8.5%), and it even decreases to 7.8% for the period after 2019 (only four papers).

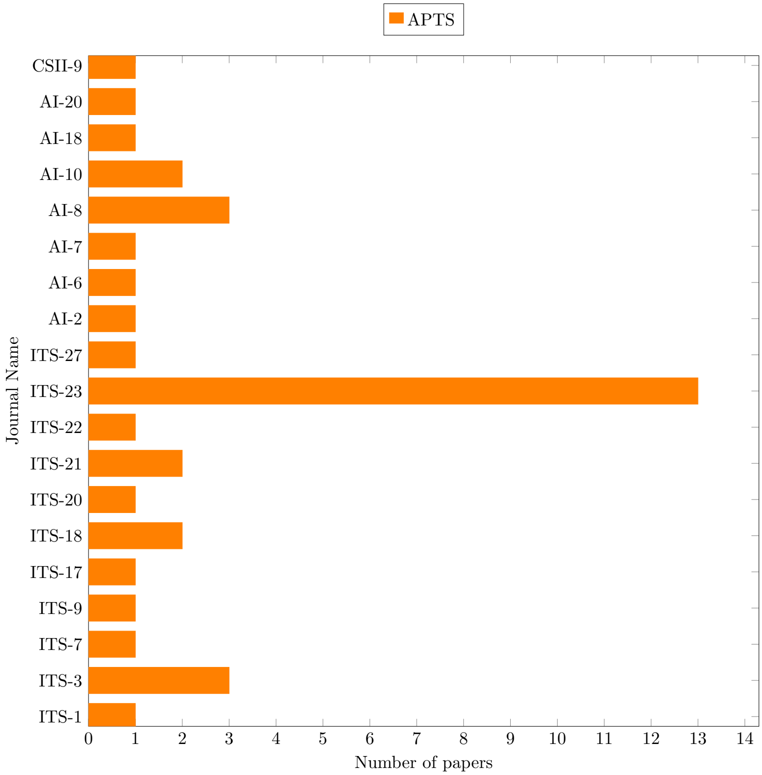


Fig. 2 Number of papers of the selected journals for the APTS category

4.3.2 Analysis based on the journal of publication

Figure 2 gives the distribution of the 38 research papers for the selected journals, which can be found in Annex 1 [2]). For clarity, we include the only journals providing at least one selected paper (19 journals).

For the four categories, we note a strong concentration of publications in two ITS journals (ITS-23 – Transportation Research Part C: Emerging Technologies, and ITS-3 – IEEE Transactions on Intelligent Transportation Systems), with almost 40% of the total number of publications. For the period 2016–2020, the ratio is 42%. The APTS category papers have been published mainly in ITS-22 (13 papers, 34.2%), followed by ITS-3 and AI-8 (3 papers, 7.8% each). Moreover, ITS journals (27 papers) and AI journals (10 journals) are the most represented in this category (only a unique paper for CSII journals).

[2] The journals list results from the search on the different databases described earlier.

5 APTS papers overview

The analysis of the criteria “APTS objective” gives a classification of the research in three categories: (1) the passenger in the system (Sect. 5.1), i.e., the problem to solve is related to the passengers; (2) the system design (Sect. 5.2), i.e., the problem is related to the design of the transportation system; (3) the system operations (Sect. 5.3), i.e., the problem is related to the execution of the transportation system. For each paper, we propose a short description, and we highlight the main tackled issue.

5.1 The passenger in the system

These papers consider the system from the point of view of the passengers. The global objective is to improve the quality of the system as follows:

Identification of the passengers’ expectations to understand what are the leverage effects of modal shift. Ahanchian et al. (2019) propose a model to understand the individual actions for this modal shift. The actions are based on different evaluations for the costs (e.g., ticket price, fixed and variable operation and maintenance costs), the travel time, and socio-economic attributes (income, family structure, place of residence, car/bike ownership).

Adaptation of vehicles is another leverage for fostering the modal shift to public transport. Two approaches have been investigated for the bus design by evaluating the needs and preferences of travellers. Rexfelt et al. (2014) simulate the flow of passengers on-board of buses and at bus stops to assess how the bus design changes the passengers’ movements during the boarding/alighting. They propose a bus design to improve the performance of passenger flows in terms of dwell time. Schelenz et al. (2014) study and evaluate the performance of different bus designs from the passengers’ perspective. Alam and Werth (2008) model the passengers who enter/leave buses with preferences for the seats. Seat preference rules are attributes for each passenger agent (acquainting rule, standing passengers rule, attribute-specific rules related to their characteristics, senior/adult/young passenger rule). Cats and Hartl (2016) compare approaches to modelling on-board congestion in transit networks with two platforms, Visum (macroscopic approach) and BusMezzo (agent-based approach). The authors show that the calculation time is better for the macroscopic approach, but the multi-agent one considers better the congestion aspects. Schelenz et al. (2013) propose a bus passenger’s decision-making algorithm that could be applied to build a new bus design. The passengers have a ranked list of available seats (targets) according to their preferences (e.g. the entry door and the seat location) and select the most convenient one. The proposal evaluates several indicators, such as passenger satisfaction and dwell and exit times.

Traveller information management is used to improve passenger satisfaction. Bouman et al. (2016) propose a multi-agent model for public transport crowding dynamics based on minority games to *create new opportunities for passengers to* *avoid crowding and for operators to inform passengers and reallocate capacities quicker than before*.

Adaptation of transit areas enables better management of passenger flows. Zhang et al. (2008) present a cellular automata-based alighting and boarding micro-simulation model for passengers in Beijing metro stations. The authors propose different cooperative rules to solve the eventual conflicts between agents.

5.2 The system design

From this point of view, the papers tackle issues ranging from the design of new network types to system maintenance.

Improving direct transfer at connection points focuses on the reliability of public transport. Nesheli and Ceder (2015a, b) evaluate the benefit of several pre-computed operational tactics. The application is then formalised as an optimisation problem with constraint programming (OPL tool) that is linked with a multi-agent simulator based on MATSim. Their experiments are based on the bus network for the Auckland region, New Zealand.

Designing a network for Bus Rapid Transit (BRT) considers buses with dedicated lanes, and services are ensured with a high frequency to increase the quality of services of public transport. To evaluate if BRT could foster the modal shift from personal vehicles to collective vehicles, McDonnell and Zellner (2011) study the introduction of BRT. The authors check the effects of multiple BRT policy changes (e.g., exclusive bus lanes, increased bus frequency, pre-boarding ticket machines and express stops) on the behaviours of individual agents. The modal choice depends on the experience of the users to potentially reallocate buses.

New forms of services are another leverage to answer the passengers' requirements better. Satunin and Babkin (2014) propose a new approach to design a Demand-Responsive Transport service as a MAS where various autonomous agents represent the interests of the system's stakeholders. Chen and Nie (2017) analyse two different relative spatial position designs in an integrated e-hailing/fixed-route transit system: a zone-based design that operates e-hailing vehicles within a zone. Shou and Di (2020) deal with e-hailing based on a multi-agent reinforcement learning (MARL).

Considering security threats impacts the network design. Evaluating the risks of criminal attacks (crimes, terrorism) is necessary to protect the different users. In this context, Brown et al. (2014) consider a model based on a security game (game theory) and a multi-objective security optimisation problem for the metro of Los Angeles (USA) to analyse and handle security threats. They underline theoretical results such as the Pareto-optimality of obtained solutions.

Managing interactions between multiple network operators enables considering networks where different companies use the infrastructure. Tsang et al. (2011) describe the independent train-operating companies as agents and propose an agent negotiation model to study their interaction. Three negotiation strategies are defined to represent their possible objectives.

5.3 System operations

When the system is designed, it has to operate to satisfy travellers with the constraint of managing real-time events. All the following papers propose solutions to improve the real-time operations of the system.

Improving APTS design may help human regulators in their everyday operations. Fernandez and Ossowski (2011) propose multi-agent tools for transportation management based on a service-oriented computing approach for the users. Their main contribution refers to the integration of agent organisations and services for transportation management and to facilitating the on-the-fly adaptation, fault tolerance, and the extensibility of the ITS architecture. They illustrate two real-world applications in the transportation management field: (1) road traffic management and (2) bus fleet management.

Better including public transport in traffic is a way to improve the efficiency of the global transportation system. Bhouri et al. (2012) consider the problem of bi-modal traffic (vehicles and buses) based on a MAS model. The agents represent both mobile entities (buses) and the environment (bus routes, intersections, etc.). Based on a negotiation protocol (the contract net), the objective is to optimise traffic at the intersections and on the network. Ling and Shalaby (2005) propose to include Reinforcement Learning agents in the infrastructure at junctions to decrease the buses bunch all along their trips. The "bunch-splitting" agent has to split the bus bunch by modifying the signal-timing plan appropriately.

Online regulating actions proposal is a solution to help human regulators and the search for optimal planning and re-planning. Menda et al. (2019) consider temporally extended actions, allowing a state-of-the-art policy optimisation algorithm that they apply, among others, to real-time bus holding control. Balbo and Pinson (2005) propose a logical model based on a MAS to collect, update and assess information related to a disturbance (see the recent state of the art about disturbances in Ge et al. (2022)). In Balbo and Pinson (2010), the authors deal particularly with the interaction between humans and Decision Support Systems (horizontal/vertical cooperation). They present a transportation regulation support system based on a MAS that assists the bus network regulators in monitoring the real-time status of bus networks. The system is composed of Stop agents, Bus agents, and an active environment for interaction. In a similar approach, Boudali et al. (2008) introduce the bus regulation based on different criteria (e.g. the punctuality of the buses). The system focuses on the decision evaluation in a multi-criteria optimisation problem. The best solution is thus selected with a voting mechanism by the different agents. Zhao et al. (2003) describe a distributed control approach also based on the multi-agent negotiation, where stops and buses act as agents that communicate in real time to achieve dynamic coordination of bus dispatching at various stops. The negotiation between a Bus agent and a Stop agent is based on marginal cost calculations. Blum and Eskandarian (2002) present a MAS to optimise train flows in a network. The multi-agent systems comprise three types of agents: Constructor agents, Modification agents and Destroyer agents. Each agent executes a specific task in a global optimisation algorithm (to create seeds, propose solutions, and suppress non-promising solutions). Boudali and Ghedira (2009) propose a MAS for real-time regulation, optimising several criteria. They use a distributed Tabu search heuristic to generate Pareto solutions. The system considers two types of agents: Supervisor agents and Criteria agents. The best compromise solution is determined by a voting mechanism between Criteria agents. Darmoul and Elkosantini (2014) propose a decision support system with a MAS representing an artificial immune system to assist decision makers in performing several disturbance management functions, such as detecting disturbances and constructing reaction strategies. Ezzedine et al. (2005) propose a MAS representing an interface between humans and public transport supervision applications. Kieu et al. (2017) propose a multi-agent simulation to evaluate timed transfer strategies for schedule planning and operational control. Six strategies for timed transfers in operational control are tested, including a sensitivity analysis of the effectiveness of the strategies for different levels of transferring demand and scheduled headways. Semrov et al. (2016) propose a train rescheduling method based on reinforcement learning. The proposal is illustrated on a scheduling problem comprising a single-lane track with three trains. Abbink et al. (2010) also describe a train rescheduling approach in case of a disruption based on the behaviours of different types of agents (e.g. train driver, route-analyzer-agent, network agents). Narayanaswami and Rangaraj (2015) present a multi-agent system model for dynamic and real-time rescheduling of bi-directional railway traffic on a single track. They propose to dynamically dispatch the disrupted trains in real time, based on instantaneous system parameters and to reschedule conflicting trains with inherent deadlock avoidance. Dalapati et al. (2019) address the early detection and resolution of different types of collision in railway systems. They propose a MAS where each agent communicates and cooperates with others to generate a feasible solution. Yan et al. (2016) aim to find the optimal speed of trains to coordinate them. The authors show that their ant optimisation algorithm may determine trajectory plans more efficiently than standard algorithms (validation with Matlab). Li et al. (2015) also deal with the coordination between trains. The described model is based on Potential Fields and the LaSalles's invariance principle.

Maintenance of the vehicles is mandatory to ensure a sustainable system. Le Mortellec et al. (2013) discuss the diagnosis and the maintenance of trains. Their approach is based on a holonic model, in which each abstraction level may build a diagnosis on a subset of elements constituting the global system.

In addition, there are specific simulation tools that could be used whatever the category. Manser et al. (2020) propose to extend MATSim to design efficient large-scale public transport networks. Meignan et al. (2007) propose bus-network simulation tools and allow to analyse and evaluate a bus network at diverse space and time scales.

Table 2 Identification APTS Challenges

MAS features	Viewpoint	Public transport objective: Traveller in the system	System design	System operation
Autonomous	*Analysis*	(Ahanchian et al. 2019; Alam and Werth 2008; Schelenz et al. 2014, 2013)	–	–
decision	*Solving*	–	(Brown et al. 2014)	–
	Action	–	–	(Abbink et al. 2010; Balbo and Pinson 2005; Bhouri et al. 2012; Darmoul and Elkosantini 2014; Kieu et al. 2017; Li et al. 2015; Ling and Shalaby 2005; Menda et al. 2019; Narayanaswami and Rangaraj 2015; Semrov et al. 2016; Yan et al. 2016; Zhao et al. 2003)
Interaction	*Analysis*	(Cats and Hartl 2016; Rexfelt et al. 2014; Zhang et al. 2008)	–	–
modeling	*Solving*	(Bouman et al. 2016)	(Tsang et al. 2011)	–
	Action	–	–	(Balbo and Pinson 2010)
Bottom-up design	*Analysis*	–	–	(Le Mortellec et al. 2013)
	Solving	–	(Chen and Nie 2017; McDonnell and Zellner 2011; Nesheli and Ceder 2015b, a)	–
	Action	–	(Satunin and Babkin 2014)	(Dalapati et al. 2019; Ezzedine et al. 2005; Fernandez and Ossowski 2011)
Decision process	*Analysis*	–	–	–
agentification	*Solving*	–	–	(Blum and Eskandarian 2002)
	Action	–	–	(Boudali et al. 2008; Boudali and Ghedira 2009)

6 Discussion

In this methodology step, we answer the three research questions that we have defined. Table 2 presents all the papers following two dimensions: (1) the categories proposed in the previous section; (2) The most represented features of the MAS domain in the selected articles.

The MAS features are the following: (i) *Autonomous decision*, the focus is on the decision model of the agents; (ii) *Interaction modelling*, the focus is on the relation between agents; (iii) *Bottom-up design*, the focus is on the reification of the real-world system as a digital system following a bottom-up approach; (iv) *Decision Process Agentification*, the focus is on the design of a decision process not mimicking the real-world system. Because categories identify the objective for the use of the APTS, we add for each MAS feature a classification corresponding to the purpose of their use: (1) to understand the system (*Analysis*); (2) to build a solution (*Solving*); (3) to apply a solution (*Action*).

In that way a research paper in this table is a MAS solution to an APTS issue and a cell may be analyzed to give the transportation challenge and how MAS contributes to its resolution (RQ1). The crossing of MAS features with the *vowel* approach will explain why these features are relevant (RQ2). The analysis of the relation between the multi-agent models and the purpose of these proposals will identify the benefits of the MAS to the APTS domain (RQ3).

6.1 Answer to RQ1: what are the APTS challenges that were tackled by MAS approaches?

Traveller in the system

Most of the papers in this category use MAS features for analysis and are related to the *Autonomous Decision* and *Interaction Modelling* MAS features. It means that the issues are related to understanding passenger behaviour. It is necessary to better consider what influences the agent's decisions regarding its characteristics and objectives (*Autonomous decision*) and its relation with the others (*Interaction modelling*). The purpose of these researches is to use this knowledge about travellers to improve public transport service quality to foster the modal shift. The main transportation challenge is then to encourage the modal shift.

System design

Most of the papers are related to the relationship between public transport and other transport system components. Several issues are encountered, such as network infrastructure design (BRT) or new services (connection with On-Demand Transport systems). The MAS are used in that case in the problem-solving process (Solving), in evaluating the proposals by simulation, or in support of specific proposals for the resolution such as negotiation. In all these cases, the reification of the real-world system is required. This requirement explains why the main used MAS feature is the bottom-up design. The common challenge is the improvement of the efficiency of the supply with the proposal of alternatives to the current public transport network design. As for the previous category, the satisfaction of the challenge will benefit the

Table 3 Estimated ratio for each vowel and their interdependencies

	Ratio for each vowel (pair of vowels) (%)
'A'	42.6
'E'	20.4
'I'	33.3
'O'	3.7
'A-E'	10.8
'A-I'	24.3
'A-O'	0
'E-I'	10.8
'E-O'	0
'I-O'	0

travellers and contribute to fostering the modal shift. We can notice that the point of view of transport operators is mostly not considered except in Tsang et al. (2011). However, we think that optimising business quality could also be a challenge.

System operations

The system is already defined in this category, and most papers propose regulation actions when disturbing events happen. The objective is either the daily management of a public transportation line, the optimisation of transfers at connection points, or the impact reduction of (and on) traffic. The researches focus on the real-time management of the network (Action) with the processing of operational decisions. The challenge is to ensure the adaptation in real time to disturbing events in the public transport supply. There are almost no works related to the analysis (except (Le Mortellec et al. 2013), which concerns the maintenance) of the system behaviour to propose a structural adaptation of the network. From our point of view, the missing challenge is the consideration of the concept of *Mobility As A Service* (MaaS) (Becker et al. 2020; Hensher and Xi 2022). For example, Hensher and Xi (2022) underline that MaaS aims to "overcome the market segmentation by offering transport services to the individual traveler's needs". It is not considered by the studied multi-agent research, while it is a relevant challenge for public transportation networks. It could be seen as a transverse challenge because (i) it concerns the travellers and could contribute to the modal shift; (ii) it also concerns system design because it should simplify the transition between networks, and then the system's efficiency has to be studied; (iii) finally, it looks also at system operations because the regulation has to be considered from a multi networks point of view.

6.2 Answer to RQ2: what are the specific MAS features that were used in the APTS domain and why?

Following the *vowel* approach, the focus on a vowel or a combination of vowels influences the design of the resulting system. Thus, using this reading grid of a MAS, we underline which dimension(s) of the MAS paradigm was important for the designer. Table 3 presents two aspects of this analysis introduced by the *vowel* approach (there are at most two vowels per paper).

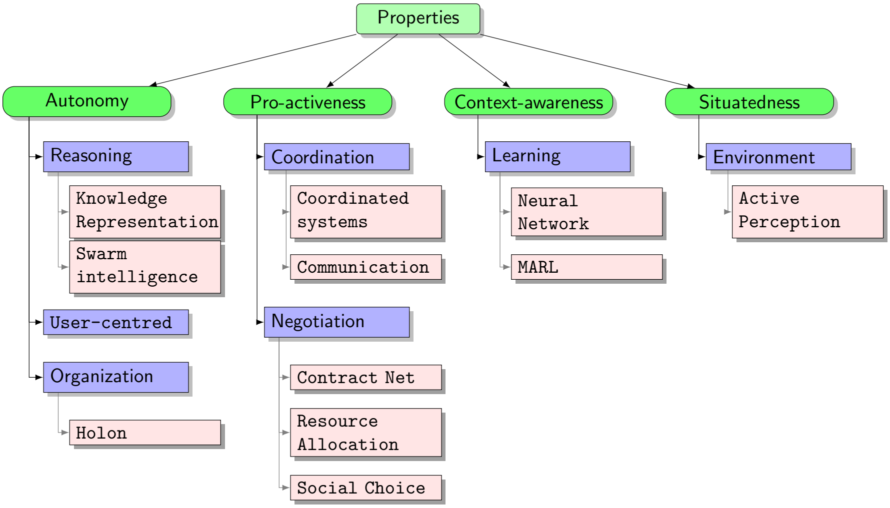


Fig. 3 Global view of different models

The works on APTS focus primarily on (A)gent design, then on the (I)nteraction, and are barely interested in the two other vowels. We believe that the *vowel* approach leads to in-depth considerations of design choices and completes the previous discussion. Indeed, the inter-dependencies between the vowels build the global system dynamics and the implementation of the MAS applications.

The most represented inter-dependencies are 'A-I', then 'E-I' and 'A-E'. This order relation of the inter-dependencies means that the objective is focused on the design process. The design process in these contexts deals with the relationships between the individual plans among the autonomous agents and their direct effects on the world (resource sharing, temporal constraints). The environment seems to be designed as the core of the global system.

The design process based on the agent and its interactions ('A' and 'I' vowels, 'A-I' inter-dependency) remains primordial. The other vowels are also considered, but not to the same degree. This result is confirmed by Table 3, with one of the papers concerning the Autonomous Decision or Interaction Modeling features that directly address the 'A' and 'I' dimensions. One central APTS task is the real-time management of disturbances or disruptions. These may be numerous, and the decisions to resolve the problems must be taken as quickly as possible to avoid additional consequences. MAS enabling a delegation process to the agents is a solution to scale and accelerate the decision processes. It may explain why one-third of the research papers belong to the intersection between *Autonomous Decision* and *System operations*.

6.3 Answer to RQ3: how did the MAS paradigm benefit the APTS domain?

Identifying the models used to satisfy a property of the system is necessary to understand how the MAS paradigm benefits the APTS domain. Figure 3 briefly presents the main models introduced by the studied papers. To discuss how models contribute to APTS, we consider two viewpoints. The first one is related to the use of APTS for analysis, solving and action. The objective is to highlight why these models benefit to this use. The second is related to the APTS design with the objective of highlighting how the users benefit from the model.

Autonomy
This property is related to the decision process of agents: Autonomous agents take their decisions without external interventions. This property tackles the complex dimension of the public transportation domain; i.e., it becomes possible to decentralise the decision process in the agents to understand better the real-world system's behaviour or scale in the resolution process. The last advantage will be completed in the section related to the pro-activeness property that considers, in addition, the strategy/processes to achieve the decision.

To be autonomous, agents need a model of the system and a reasoning process to make decisions. The different models used by the agents are often based on reasoning with considerations for the Knowledge Representation and the design. Knowledge Representation covers the various models introduced in the studied papers, namely (i) Behavioural rules describing the actions to achieve w.r.t. contextual situations (Abbink et al. 2010; Ahanchian et al. 2019; Alam and Werth 2008; Cats and Hartl 2016; Chen and Nie 2017; Manser et al. 2020; Kieu et al. 2017; Meignan et al. 2007; Nesheli and Ceder 2015a, b), and (ii) another reasoning model based on immune systems (Darmoul and Elkosantini 2014). Swarm intelligence covers the following fields: Ant Colony (Yan et al. 2016), Potential Fields (Zhang et al. 2008; Ling and Shalaby 2005), or Social Forces (Rexfelt et al. 2014; Schelenz et al. 2014, 2013), which satisfied the need to consider the influence between autonomous decisions. Autonomy may be bounded by the social organisation's constraints that are a way to reduce the complexity: For example, a particular multi-level model useful for ITS systems like a holonic model (Le Mortellec et al. 2013; Li et al. 2015).

The advantage is thus to represent the consequences of constraints/preferences from the individual viewpoint (Ahanchian et al. 2019; Alam and Werth 2008; Cats and Hartl 2016) or the group (Rexfelt et al. 2014; Schelenz et al. 2014, 2013) to improve the comfort of travellers (mostly bus design and also station area design). It explains why seven out of eight papers of the traveller in the system category are based on models ensuring this property. The second advantage is to represent the public transportation network following a bottom-up approach for generic simulation purposes (Manser et al. 2020; Meignan et al. 2007) or when the simulation is a part of the solution (Kieu et al. 2017; Nesheli and Ceder 2015a, b). The other models supporting the autonomous property for the solving (Chen and Nie 2017) or the acting (Yan et al. 2016; Ling and Shalaby 2005) belong to Swarm intelligence. It means that the solution results from the interaction between the individual decisions. From the point of view of the APTS design, the user of the system will gain autonomy with better designed Decision Support System tools and platforms. In this context, certain considerations concerning APTS design may thus be also useful: the user (Adaptive) Interfaces (Ezzedine et al. 2005) and ontologies (Fernandez and Ossowski 2011).

Pro-activeness

This property considers that agents have to be able to adapt their strategies/processes to reach their objectives if the current state of the system does not ensure the success of the current strategy/process. For APTS, this property deals with the uncertainty and incompleteness characteristics of the environment in the transportation domain. The adaptation must be made collectively or at least consider other stakeholder decisions. It means that the decision process has to be supported by additional models to ensure its adaptation.

Game Theory (Bouman et al. 2016; Brown et al. 2014) and Constraint Solving Problem (Dalapati et al. 2019) are models that propose a coordination process to build a common solution. Similarly, Negotiation-based Approaches that investigate the way the search for a compromise between the agents are often used with several declinations: One of the most popular MAS models (Contract Net Protocol) is often used in the extended version based on marginal costs (Bhouri et al. 2012; Tsang et al. 2011; Zhao et al. 2003); Allocation shared resources for a given demand (McDonnell and Zellner 2011); A more complex approach for negotiation (Social Choice) including Auction (Satunin and Babkin 2014; Narayanaswami and Rangaraj 2015) and Vote (Boudali et al. 2008; Boudali and Ghedira 2009) models. All these models executed within MAS solutions are based on continuous adaptation processes and are looking for compromise. Provided that the environment where APTS are deployed is uncertain and incomplete, a constant adaptation process of the solution is mandatory to follow the non-predictable evolutions of the environment.

These models supporting the property pro-activeness are in Table 2 used in acting (six among eleven papers) or solving (five among eleven papers). They contribute to the *System design* category where Negotiation models are required to improve the relationship between supply and demand in designing new types of lines (McDonnell and Zellner 2011; Boudali et al. 2008), or when different objectives have to be considered for security purpose (Brown et al. 2014) or multi-operator networks design (Tsang et al. 2011). There are also contributions in the *System operation* category where the objective is to regulate the network and is therefore concerned in the first place with the uncertainty and incompleteness characteristics of the environment. The solution may be built collectively (Dalapati et al. 2019) or result from a negotiation between the system components.

From the APTS design point of view, exchanging messages based on communication protocols may facilitate the coordination between agents focusing on the delay for the messages and may become crucial in a MAS system (Blum and Eskandarian 2002).

Context-awareness

For APTS use, this property implies that MAS can support decisions or actions according to the state of the transportation network. The learning techniques are thus used in APTS studies to ensure this property: a model of learning based on Neural Networks (Menda et al. 2019), Multi-Agent Learning based on Reinforcement Learning (MARL) (Semrov et al. 2016; Shou and Di 2020).

These few works contribute to Table 2 the category *System operation* and are related to the MAS feature *Autonomous decision*. This classification enforces that this property is required to regulate the transportation network in real time.

From the APTS design perspective, the context-awareness property means that the operators' context data are filtered, or potential decisions are proposed to avoid a mental overload. In Balbo and Pinson (2005), a logic model of a disturbance is proposed to aggregate and update information related to a disturbance.

Situatedness

For APTS use, this property emphasises that an agent is embedded in an environment. It considers that many of the characteristics of the agents' behaviour are more linked to the environment than agents' internal representations or reasoning. It implies that MAS considers interactions with the environment in the solution design. In Balbo and Pinson (2010), active perception with logical filters are placed in the environment filters for the communications between agents. From the APTS design point of view, it means that the deployment in the environment could be considered. However, we found no papers related to the deployment of a MAS in a public transportation network.

54% of the papers deal with the property Autonomy whilst 32% are related to Proactiveness, 11% to context-awareness and only 3% to situatedness. It confirms that the MAS paradigm is at this time more related to the problem resolution step than the deployment step.

7 Conclusion

Information technologies supported the challenges of transportation systems and opened a new research field, namely Intelligent Transportation Systems (ITS). Artificial Intelligence and particularly multi-agent systems may offer solutions to these challenges. Based on the use of agent technologies, we believe it is helpful to propose a survey of the different existing works. This paper highlighted some trends in the evolution of research undertaken in the APTS (Advanced Public Transportation System) domain, an ITS dedicated to public transportation network management.

The methodology for this survey is based on a Systematic Literature Review (SLR). Few (usually non-systematic) surveys describe ITS, but they do not specifically consider MAS approaches, and no one is specific to APTS. The proposed SLR method is defined by three main steps: (i) planning (explanation of the general process and an introduction of the period – for the journals); (ii) implementing (the search strategy for the relevant papers based on the requests with well-defined keywords) leading to a selection and information collection process to support a collective decision to include the paper into our survey, (iii) reporting, which provides a synthesis of the findings and analysis. We obtained results based on synthetic views (type of paper, year of the publication, the journal of publication). The study showed that APTS is the poor sibling in the ITS family, despite its relevance to environmental issues. For the journals focusing on ITS and MAS, the results revealed that the ITS journals are the most represented (particularly *Transportation Research Part C: Emerging Technologies* and *IEEE Transactions on Intelligent Transportation Systems*).

The relevant 38 research papers are presented in detail, and a global analysis has been proposed. We have introduced the main concepts, proposed a classification of the papers in three categories and proposed an answer to each research question based on the crossing between the classification and two analysis grids, i.e. the *vowel* approach and the MAS properties. The proposed APTS categories are: (i) *Traveller in the system*, (ii) *System design*, and (iii) *System Operations*. The analysis of this classification gives the following challenges: (1) Fostering the modal shift; (2) Improving the efficiency of supply; (3) Ensuring the adaptation in real time of the public transport supply to the disturbing event (for short: manage real-time disturbances). This analysis answers the first research question. We can go further by highlighting that the category *System Operations* concentrates half of the research papers, and half of them, 1/4 of all selected papers, are focused on regulation. We can conclude that the challenge named “manage real-time disturbances” is where numerous researchers have adopted a MAS approach.

To answer the second research question, we completed the analysis using the *vowel* approach that underlines the importance of the agent and the interaction dimensions in the modelling for APTS. Correlated with identifying the main challenge, it emphasises that the delegation process to the Agents supported by the MAS approach answers to the APTS need to manage real-time disturbances on the network.

Finally, we studied the selected papers according to the used models to answer the third research question. In this last analysis, we investigated the four main properties of agent models in complex systems (autonomy, pro-activeness, context-awareness, situatedness). We showed that most papers essentially focused on the properties of pro-activeness and autonomy. This last result shows that with these properties, the MAS approach is well suited to tackle the challenge of managing real-time disturbances in an uncertain and incomplete environment.

As an additional result, we identified three future research avenues for MAS related to the APTS. First, we believe that MAS could be relevant for research about MaaS from the APTS perspective. There is indeed research about MAS and MaaS, but we did not find research about APTS in this context. Perhaps it is because APTS is embedded in the MaaS system, but we consider this inclusion is not obvious, and MAS could help take into account the identified challenges of APTS. The second future research is increasing the business quality to increase the benefits for companies. Better consideration of the companies in the search for compromise could do this. A side effect could be an increase of the global research in this field, and therefore an answer to the paradox exhibited in Sect. 4.2. Finally, the analysis about the *Situatedness* property showed that there is no work where the MAS proposal is physically deployed. The last future work is to deploy these solutions in the physical environment and to tackle challenges like communication quality or resilience to failures.

Appendix A: Selected journals

The different journals have been alphabetically sorted into three categories (Table 4): ITS journals, AI journals and CSII journals. These journals will be designated by a reference code corresponding to the type of journal added by a unique number.

Table 4 List of selected journals

ITS journals	
ITS-1	Case Studies on Transport Policy (Elsevier)
ITS-2	IEEE Intelligent Transportation Systems Magazine (IEEE)
ITS-3	IEEE Transactions on Intelligent Transportation Systems (IEEE)
ITS-4	IEEE Vehicular Technology Magazine (IEEE)
ITS-5	International Journal of Sustainable Transportation (Taylor & Francis)
ITS-6	International Journal of Transport Economics (Academia Editoriale)
ITS-7	Journal of Advanced Transportation (Hindawi / Wiley)
ITS-8	Journal of Intelligent Transportation Systems Research (Springer)
ITS-9	Journal of Intelligent Transportation Systems: Technology, Planning and Operations (Taylor & Francis)
ITS-10	Journal of Traffic and Transportation Engineering (on-line, Elsevier since 2014)
ITS-11	Journal of Transport Economics and Policy (Univ. of Bath)
ITS-12	Journal of Transport Geography (Elsevier)
ITS-13	Journal of Transportation Engineering: Part A Systems (ASCE)
ITS-14	Journal of Transportation Engineering: Part B Pavements (ASCE, on-line)
ITS-15	Journal of Transportation Systems Engineering and Information Technology (Elsevier)
ITS-16	Networks & Spatial Economics (Springer)
ITS-17	Public Transport (Springer)
ITS-18	Transport Policy (Elsevier)
ITS-19	Transport Reviews (Taylor & Francis online)
ITS-20	Transportation Letters (Taylor & Francis online)
ITS-21	Transportation Research Part A: Policy and Practice (Elsevier)
ITS-22	Transportation Research Part B: Methodological (Elsevier)
ITS-23	Transportation Research Part C: Emerging Technologies (Elsevier)
ITS-24	Transportation Research Part D: Transport and Environment (Elsevier)
ITS-25	Transportation Research Part E: Logistics and Transportation Review (Elsevier)
ITS-26	Transportation Research Part F: Traffic Psychology and Behavior (Elsevier)
ITS-27	Transportation Science (INFORMS)
ITS-28	Transportmetrica A – Transport Science (Taylor & Francis online)
ITS-29	Transportmetrica B – Transport Dynamics (Taylor & Francis online)
AI journals	
AI-1	Annals of Mathematics and Artificial Intelligence (Springer)
AI-2	Applied Intelligence (Springer)
AI-3	Applied Artificial Intelligence (Taylor & Francis online)
AI-4	Artificial Intelligence (Elsevier)
AI-5	Artificial Intelligence Review (Springer)
AI-6	Autonomous Agents and Multi-Agent Systems (Springer)
AI-7	Decision Support Systems (Elsevier)
AI-8	Engineering Applications of Artificial Intelligence (Elsevier)
AI-9	Expert Systems Applications to Urban Planning (Springer)
AI-10	Expert Systems with Applications (Elsevier)
AI-11	IEEE Computational Intelligence Magazine (IEEE)

Table 4 (continued)

AI journals	
AI-12	IEEE Expert Intelligent Systems and their Applications (IEEE)
AI-13	International Journal of Artificial Intelligence (World scientific)
AI-14	International Journal of Decision Support Systems Technology (IGI global, open-access)
AI-15	International Journal of Knowledge-Based and Intelligent Engineering Systems (IOS press)
AI-16	International Journal on Artificial Intelligence Tools (World scientific)
AI-17	Journal Of Experimental And Theoretical Artificial Intelligence (Taylor & Francis online)
AI-18	Knowledge Based Systems (Elsevier)
AI-19	Knowledge Engineering Review (Cambridge Univ. Press)
AI-20	Progress in Artificial Intelligence (Springer)
CSII journals	
CSII-1	Communication of the ACM (ACM)
CSII-2	Computer Standards & Interfaces (Elsevier)
CSII-3	Computers and Industrial Engineering (Elsevier)
CSII-4	Engineering (Elsevier)
CSII-5	European Journal of Operational Research (Elsevier)
CSII-6	IEEE Internet Computing (IEEE)
CSII-7	Information Sciences (Elsevier)
CSII-8	Personal and Ubiquitous Computing (Springer)
CSII-9	Simulation Modelling Practice and Theory (Elsevier)

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