Towards an Integrated Mobility and Logistics Network for Autonomous Vehicles: Review and Opportunities of the Agent-based Approach

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***Abstract* — Similar to the present, the future Autonomous Vehicles (AVs) road network will very likely integrate vehicles for both mobility and logistics purposes. However, the performances of such systems are still not clear.**

Due to the agent-based approach's advantages in performing the complex spatial-temporal relation between agents, various studies adopt it for assessing the impacts of AVs, either on the system of mobility or on the system of logistics. Nonetheless, most of these current studies are focusing on the two systems in isolation. Within the domain of passenger mobility, many relevant papers/reviews can be found. Instead, an overall review of the current agent technology developments in autonomous logistics is lacking.

In order to fill this gap, this paper reports on a systematic review of autonomous logistics agent-based simulation studies. Thirty-two papers are extracted from ISI Web of Science and Google Scholar through keywords search. Generally, the agent-based approach proved applicable for analysing the autonomous logistics among all sectors (indoor, controlled outdoor, long-haul & last-mile), and it is still an emerging topic, especially for the long-haul and urban environments. Finally, our research offers an overview regarding the mobility and logistics integration, which will be referential for both AV researchers and urban planners.

I. Introduction

The freight transport volumes and performances have continuously grown during the past decades, increasing the ecological and environmental impacts of freight transport (1). Meanwhile, a KPMG study reveals that American, British and Chinese consumers are showing a noticeably increased preference for having goods moved to them, instead of travelling to stores as before (2). As a result, the public bodies and authorities strive to seek innovative solutions for the freight networks with higher productivity, reliability and flexibility (3).

Due to its enhancements in cost-saving, efficiency and productivity, the current technological advancements in autonomous vehicles (AVs) are considered as one of the most viable options. Besides, implementing AVs in the logistics setting offers several other advantages. Firstly, logistics provides an ideal environment for AVs, because it offers more controlled-environmental operations such as warehouses and remote outdoor locations. Next, it is expected that fewer trust and liability issues would happen when transporting stable goods instead of uncertain people. Thus, it is very likely that the logistics sectors will adopt self-driving technology sooner than passenger transport (4).

Assessing the impacts of AVs on society is of high importance for future decision making. Thanks to its ability in performing the complex spatial-temporal relationships between different stakeholders (5), the agent-based approach is capable of analysing various perspectives of AVs' impacts, which includes travel behavioural, land-use, environmental and economic. Two main benefits exist when modelling AVs by the agent technology: first, more elasticity is allowed when conducting different scenario analyses. Second, by simulating the movements and interactions of autonomous agents, researchers can acquire a better overview of the different impacts and outputs. Hence, the agent-based approach is adopted by various studies for modelling the overall impacts of future scenarios in the mobility network.

Autonomous logistical vehicles will inevitably share networks with other road users in the near future. Most likely, the future road network will integrate AVs for both mobility and logistics purposes. Since the mobility network holds relatively mature modelling studies using the agent-based approach (6), the integration of logistics through this method could be straightforward.

Ever since 1992, many freight practices in the decision support systems and automation system adopt the agent-based simulation, and it proves very suitable for transport logistics, due to its ability in distributing control, coping with partial data and simulating complicated systems (7). Yet, compared with mobility, the number of AV papers, and even more so agent-based AV papers, in the logistics domain is lower (4). Furthermore, an overall review of the agent technology development within autonomous logistics, is lacking.

As a result, the primary purpose of this paper is fulfilling the above gap. Divided by the segmentation for the potential AV usages in freight transportation (Indoor, Controlled Outdoor, Long-haul and Last-mile) (3), our research reviews the most state-of-the-art papers within each sector, respectively. Since the integration of mobility and logistics is more relevant to the long-haul and last-mile environments, more detailed attention is paid on them within the "Previous Studies" section. At the end of this paper, based on the relevant works, the authors compiled a research agenda towards the AV mobility and logistics network integration.

II. Search Strategy

To collect all relevant publications of modelling AVs through the agent-based approach, the authors conducted a thorough literature search in the scientific databases: the ISI

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Web of Science and Google Scholar. For the timeliness of work, only papers published after 2014 are categorised. After a synonyms search of the potential keywords, papers contain "auto* logistics agent-based", "Platoon agent-based", "auto* guided vehicle agent-based", "harbour auto* agent-based", "auto* truck agent-based", "auto* long-distance intercity freight transport agent-based", "auto* long-haul freight transport agent-based", "auto* last-mile logistics agent-based", and "auto* road freight agent-based" in their titles, abstracts and keywords are extracted. The truncation term "auto*" was used to represent "autonomous", "automated", "automatic" and other potential words. Generally, this offered us a review list with 91 publications.

To improve search reliability, we evaluated the full abstracts and conclusions (if applicable) of each paper. A paper is considered as relevant if 1) the research is conducted through an agent-based approach; 2) the agents within its model are not only "autonomous" (which means they can govern their behaviours automatically based on characteristics), but also AVs (self-driving fleets); 3) it focuses on logistics and thus does not relate to AVs in human transportation, aviation or navigation; 4) the general research goal is studying AVs' impacts to the proposed system.

Based on the above criteria, a total of 32 papers are reviewed in this study, with research area on the general AVs in logistics (3 review papers), indoor and controlled outdoor logistics (9 papers + 1 review papers), long-haul logistics (8 papers) and urban logistics (9 papers). In regards to the publication date, about 70% (22 papers) is published in the recent four years (2017 to 2020).

III. Previous Studies

This section critically reviews the relevant papers based on prior described search strategies. In general, the agent-based approach has proved its ability for modelling AVs in the indoor and controlled outdoor logistics environments. Nearly the same situation occurs for the long-haul environment, where most of the research focuses on platooning. Instead, currently, the potential business models of urban logistics are still under discussion, not to mention the agent-based simulation studies.

A. *Indoor & Controlled Outdoor Logistics Environment*

"Automated guided vehicles (AGV)", i.e. all types of vehicles that do not need a human driver to move around, is the typical term used for representing AVs in the indoor and controlled outdoor freight environments. Compared to the outdoor environment characterised with uncertainties, implementing AVs within indoor and controlled outdoor is more straightforward. This is due to the infrastructure within those settings (e.g. warehouses, manufacturing sites, yard cranes and distribution centres) are more regulated and structured. This, in turn, creates ideal environments with less human interventions for AVs.

Typically, the indoor operations of the AGV system are in charge of connecting production and assembly processes. The U.S. first deployed such systems for business purposes in the early 1950s (3). Recently, researchers have detected that agent-based techniques may improve the reliability and productivity of autonomous transportation in the manufacturing systems. Firstly, due to its concern in agents' coordination, resolving agent-based approach would break down the robustness and scalability of the vehicles in the automated warehouse systems, hence, suitable for the developments of decentralised control solutions (8). Then, the innovative reconfigurable transportation systems (RTS), which through the agent-based algorithm, enable the dynamic selection of part routes in the warehouse inbound logistics. As a result, the scheme leads to a mean throughput boost up to 25% (9).

Similar to the indoor operations, AGVs are also commonly used as heavy goods shippers or in-site traffic carriers within the controlled outdoor environments.

The most representative outdoor environments are harbours and yard cranes, where various kinds of AVs are already employed at present (4). However, agent-based modelling is still a new technique for controlled outdoor logistics. Before 2015, only 2.1% of the papers on port and container simulations were built with the agent-based approach (10). In contrast, a shift occurred after the year 2015. That is, by implementing the vehicle automation technologies into the outdoor settings, more papers begin to assess the impacts and efficiency improvements to the yard field by the agent-based method. For instance: by replacing the conventional trucks with the Intelligent Autonomous Vehicles (IAV) for automated container loading at the container port terminals in northwest Europe, the agent-based simulation reveals its capability of fulfilling transportation goals, with a maximum 50 km/hour operating speed (11). Moreover, an agent-based simulation model is designed for the autonomous yard tractors (YTs), which are responsible for automatic pick-up and docking of semi-trailers in a distribution centre of Doesburg, Netherlands. The result suggested that three YTs will be sufficient in bringing an acceptable level of service (12).

Besides ports, our revision has also seen additional innovative attempts. For example, in order to evaluate the potential countermeasures for efficiency improvement of an AGV goods delivery system in a hospital, an agent-based simulation model was built. The model considers the interaction between AGVs, people, patients and elevators (13). As a result, the proposed agent-based approach helps depict the current and modified material flows within the hospital delivery system.

As for the research agenda, it is worth noting that most of the papers reviewed concluded their future works as finding "larger area" or "other test-beds". Therefore, further verifications are needed for the recent results.

B. *Long-haul Environment*

Besides some small-scale tests operating within the limited test areas and vehicles, AVs are not being implemented for long-haul logistics so far. Therefore, studies concerning autonomous logistics in this environment are all prediction based on current or hypothetical data.

Platooning, which stands for a group of vehicles driving simultaneously with minimal distances from each other, is the most revolutionary long-haul freight technology facilitated by self-driving. Consequently, most of the research and test projects about automated highway freight trucking are related to platooning (4). Platooning is unique and cannot be viewed purely as a single vehicle or group of vehicles. Since a dispatcher controls the movements of all vehicles, and the number of the individual vehicles within one platooning group is not stable (they can join and leave the band at any time). Therefore, an agent-based approach, where individual agents decide their movements based on characteristics, is especially suitable for platooning modelling. Many studies have implemented this approach.

While all are agent-based approaches, these studies can be classified into two levels: the macro and the micro simulations of platooning. The quantity ratio of papers is approximately fifty-fifty.

The micro-simulation is mainly in charge of modelling detailed interactions/algorithms for single vehicles/trucks to form the platooning. Innovative methodologies such as the *Multi-platooning Leaders Positioning* and *Cooperative Behavior Algorithms* (14), together with the *Distributed Control Protocol* (15) are built through the agent-based approach. MATLAB/Simulink develops the former, through which it maintains the constant spacing between followers and platoon leaders. Whereas in the latter case, the platooning stability under the presence of time-varying wireless communication delay is adequately ensured.

On the other hand, the macro-simulation is directed towards evaluating the performance of platooning on the network level. These studies also offer inspiring insights. First of all, the average waiting time of trucks in forming platooning is an important indicator of measuring system efficiency. The number of order requests and the number of platoons in the network proved to hold a negative relation with the waiting time (16,17). Moreover, the followers in the platooning no longer require drivers due to self-driving. Compared with the conventional trucks, platooning is expected to make economic saving at around €0.23 per kilometre, the hourly salaries of human drivers primarily influence this (18).

Some common research trends in both macro and micro agent-based platooning simulation include modelling the actual platoon (instead of a fixed number of participants) and more intelligent platoon options (e.g. route deviation when operating). Furthermore, this paper would also like to highlight two notable trends. Firstly, more than half of the recent platooning papers prefer decentralised platooning options over centralised (17–19). The advantage of the decentralised platooning is apparent: the system is more distributed, each participant within the platooning can use the latest data available (20). Secondly, integrating macro and micro simulations could potentially introduce more innovative vehicle communication algorithms, together with capturing individual vehicular interactions in the future (21). Therefore, it may be a potential research direction in the next stage.

C. *Urban Logistics Environment*

Urban logistics is mainly in charge of delivering freight and goods from the warehouses to their final destination, which is often referred to as "last-mile delivery". Since the last-mile service interacts directly with the final customers, it is a critical element for the logistics research. Within the global market, many customers' express dissatisfactions with their current last-mile experience. Hence, they would shift to faster and more frequent delivery services once offered (22). Furthermore, the current last-mile delivery occupies 41% of the total cost of moving goods in the supply chain, and therefore, the last-leg is less cost-efficient compared with other supply chain sectors (23).

On the supply sides, plenty of sectors within the urban network would benefit from replacing the current urban parcel services by AVs, including Autonomous Grocery Shopping, Home Delivery Logistics Network, Autonomous Parcels, Pack Station Based Solutions and Support Vehicles for Parcel Delivery (4).

Remarkably, using AVs for last-mile delivery is still a forthcoming industry. At present, the specific operation patterns of autonomous urban delivery are still under various discussions. For instance, one kind of application is the autonomous robots launched from the trucks to deliver freights towards customers. These robots will return to the decentralised depots after finishing their tasks and will be ready for the on-board task again. After the pool evaluation, this approach proved more efficient than the current attended-home delivery by the conventional trucks, the truck fleets within the city can also be considerably reduced (24). Furthermore, attempts, for example, using the autonomous taxis which are free during the off-peak hours (25), or even renting private AVs for parcel delivery, are considered by researchers worldwide. In conclusion, several kinds of possibilities lie in the business.

Papers within the autonomous urban delivery are mostly hypothetical, not to mention systematic simulations of the future networks where implementing AVs for last-mile logistics. As far as the authors' concern, no published papers or projects have been found in this field. Nonetheless, this is deeply important since these AVs will interact with pedestrians, conventional vehicles and the upcoming shared autonomous vehicles (SAV) for mobility purposes. Understanding their impacts on many perspectives (e.g. congestion level, car ownership, environmental benefits) will be referential for the policy and decision-makers of the transport industry.

The agent-based model could be a useful technique for solving the above issues. For instance: through characterising the roles of five agent types (receivers, shippers, carriers, urban consolidation centres and administrators), a simulation framework which can be used in assessing current conventional urban logistics schemes is carried out in the Netherlands (26). Thanks to the agent-based approach, the framework can assess every agents' behaviour and performance under various scenarios, which potentially will be applicable for the future urban autonomous logistics setting. Furthermore, MATSim (Multi-agent transport simulation) simulates the model where the transport service companies rent privately-owned AVs for parcel delivery. Results indicate that such business configuration is possible for serving Berlin's parcel demand with sufficient vehicle idle times. Moreover, due to manual labour-saving, the overall costs are expected to reduce by 23% (27).

IV. Towards Mobility & Logistics Integration

The current road network is a combination of both people and freight transportation. According to the European data, 4901 and 1870 billion tonne-kilometres of passenger and freight transport volumes are carried out by road network during the year 2017 (28), which means an unneglectable percentage (30%) of the traffic volumes is for logistic. Besides, AVs for both mobility and logistics purposes are expected to drive simultaneously on the road networks in the near future. Hence, only through connecting passenger mobility with freight transport in an overall view, can the industry observe comprehensive understandings for the potential impacts of vehicle automation (29).

The reviews above indicate the possibility of agent-based modelling for AVs in the long-haul and last-mile delivery. However, the differences in organisational structures between passenger and freight transport are challenging for their integration: freight flows have fewer data available and are more heterogenic and asymmetric compared to passenger traffic (30). For solving this disparity, the authors implement a strategy which uses the agent-based household mobility model for omnichannel retail (both online & offline) as the input for the logistics agent-based model. As a result, freight transport is integrated with passenger transport in parallel. Although this study is not about self-driving fleets, similar methods will be referential for the investigation of future researchers (30).

It is also worth noting that the modes for people and freight transportation integration are uncertain. Except for AVs for mobility and logistics completing their tasks separately, another innovative solution is pooling the passenger and parcel requests into the mixed-purpose compartmentalised SAVs (31). The proposed AVs proved more profitable than manual truck deliveries when efficient routes are designed. However, both of these operation strategies are on an initial stage, more complex and realistic instances shall be validated.

V. Conclusion

This paper provides a systematic review of the current autonomous logistics papers implementing the agent-based approach. To sum up, the reviewed 32 papers proved the feasibility of modelling AVs in all logistics sectors (indoor, controlled outdoor, long-haul and last-mile logistics) through the agent-based approach. Although the exact business models are not clear, the future road network will likely integrate both mobility and logistics AVs. When analysing the impacts of AVs to this integrated network, a state-of-art agent-based approach, which finds different agent types for passenger and freight networks, will be referential.

Studies have assessed the impact of an integrated AV network in a qualitative manner (31,32). Therefore, by combining with the qualitative approach, future work should assess the integrated AVs' impacts of different actors and stakeholders across the mobility, logistics and technology sector quantitatively. Furthermore, through combining with the emerging business models (e.g. Shared economic, mobility-as-a-service, vehicle electrification), the overall numerical impacts of AVs on society as a whole can be assessed.

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