Agent-based Simulation of Autonomous Cars

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Abstract—More and more highly automated vehicles arrive in the consumer market and fully autonomous vehicles are predicted to become available in the next few years. Autonomous vehicles promise to fundamentally change mobility—for users as for planners. Transport models and simulations are required to prepare for these changes. This paper suggests agent-based transport models as a suited mean to model future transport scenarios including autonomous vehicles. The multi-agent transport model MATSim is presented in detail and some possible research questions on autonomous vehicles—the future car fleet size, future demand patterns, and the interaction between public transport and autonomous vehicles—are introduced. Reason is given, why agent-based models are particularly suited to investigate these questions.

I. INTRODUCTION

Autonomous vehicles (AVs) might soon become a real transport option. AVs are expected to provide many benefits for passengers, like for example making driving less stressful and safer. For planners they promise potential for new concepts in transport system design and control: Fleets of AVs can be coordinated and optimized to provide a more user-friendly, safer and sustainable mobility than ever. Today though, AVs are not available yet. Still to exploit the benefits for individual passengers, transport planners and the society as a whole, preparatory research and sophisticated planning are necessary.

Many different tools for the modelling and simulation of transport systems are available. From the classic Four-Step models to state-of-the-art agent-based models, all have their special advantages and are suited for different research. The question arises what models to choose to investigate AVs. As AVs show the potential to fundamentally revolutionize the transport system, almost every assumption on transport, even the most basic ones, must be questioned and re-evaluated. Indeed, examples of current research on AVs encompasses already a wide palette of topics, for example the future car fleet size (e.g. [1]), new commuting patterns (e.g. [2] or [3]), and interactions between modes (e.g. [4]). More extensive and detailed lists of possible research questions on AVs are provided by [5] and [6].

As with other emerging transport modes, at least in transition, only a restricted number of travelers are interested in and/or have access to AVs. The reasons for this are manifold and include for example skepticism from potential users, high initial prices for new technologies, and the slow replacement time in the car market of more than ten years [7]. Different mode availability for different individuals requires that individual travelers must be differentiated in any model trying to capture the impact of AVs. Also the movements of individual vehicles must be distinguishable over longer time as vehicles are required by individual users at specified times at specified locations.

Transport macro-models, like for example the classic Four-Step model [8], model average flows of vehicles and people. They are useful for the estimation of large-scale transport scenarios and help in strategic decisions. In contrast, transport micro models such as for example VISSIM [9], model physically accurate representations of vehicles and travel behavior. They are used for the detailed simulation of individual intersections or other, spatially restricted complex traffic situations. The reason for the spatial, and often also temporal restriction is that the accurate representation of travelers requires substantial computational power. One approach that combines macro and micro models, at least to a certain extent, are agent-based models. Such models represent individual travelers using the concept of agents. Agents are independent entities representing individuals, with specific goals, preferences and strategies. Often agent-based models make also simplifying assumptions in the traffic simulation and thus allow the simulation of individual travelers in large numbers in wide spatial areas over longer times with reasonable computational power. Agent-based models are therefore a class of models which seems suitable for research on AVs.

The first part of this conceptual paper introduces agent-based models in more detail. Then presents the agent-based simulation framework MATSim and explains with several examples why this simulation framework is especially suited for the simulation of AVs. In the second part of the paper, the simulation of AVs with MATSim is sketched and examples of possible research questions are further elaborated and detailed reason is given why an agent-based model and MATSim in particular is suited to investigate them.

II. MULTI-AGENT TRANSPORT SIMULATION MATSIM

A. Agent-based Simulations

Agent-based simulations are state of the art transport models. Agent-based approaches combine activity-based demand generation and dynamic traffic assignments [10]. They cover all four steps of the classic, macroscopic Four-Step approach [8], which are demand generation, demand distribution, modal choice and traffic assignment. The basic idea in agent-based models is to treat the people of a synthetic population as individuals and maintain them during the full process across all four steps. This allows—in striking contrast to the more traditional, macroscopic models—to
model individual behavior in a detailed environment (representation of buildings, networks in navigation quality, etc.). The individual behaviors can in most cases be simulated with a few, relatively simple rules, but when executed in full-size populations, complex behavior at the macroscopic (systemic) level will eventually emerge. The outcome is a plausible approximation of the behavior observed in real transport systems. Several agent-based frameworks for transport simulation are available today [11]. The frameworks focus on different aspects (for example sophisticated traffic micro-simulation (e.g. TRANSSIMS [12]) or unification of different time horizons (e.g. SimMobility [13])) and have therefore different strengths and weaknesses. This paper presents the agent-based framework MATSim.

B. MATSim in Detail

MATSim is an activity-based multi-agent transport simulation. It combines the modelling of large scale transport scenarios with the simulation of individual vehicles and travelers. MATSim is an open-source framework written in JAVA under the GNU license. The core teams behind MATSim are the ILS at TU Berlin [14] and the IVT at ETH Zurich [15], but the international user and developer community is growing fast and steadily. While MATSim allows a black-box use for interested users, its real strength lies in its modular design around a core, which allows even people new to MATSim to customize it without much effort.

1) The MATSim-Loop

The central concept of MATSim is the so called MATSim-Loop (Fig. 1). In an iterative, co-evolutionary process agents optimize their daily plans until a stable state is reached. This stable state is a Nash Equilibrium [16] in which no agent can optimize its plan any further without other agents changing their daily plans too. It can therefore be interpreted as a Wardrop Equilibrium [17] of type one (user equilibrium where travelers are acting egoistically). The MATSim Loop consists of the five steps Initialization, Simulation, Scoring, Replanning and Analysis, of which the central three are iteratively repeated until the equilibrium is reached [18]. In the simulation step each agent tries to execute his plan as exact and as far as possible given the transport infrastructure and the other agents executing their plans simultaneously (which can e.g. lead to congestion). Traffic is simulated with a queue based traffic model [18]. In the scoring step, for each agent its current plan is rated with a utility function based on how well it was executed in the simulation step. In the replanning step for a given share of the agents the plans are modified in different ways (e.g. route and mode choices, activity durations, activity locations) and the loop starts anew.

![The MATSim Loop](image)

Figure 1. The MATSim Loop [19]

2) Events and Listeners

The modularity of MATSim is achieved with an Observer Pattern [20]. This means that during the simulation relevant events create short messages which are sent to the core. The core then distributes these messages to an arbitrary number of registered observers. These event observers or listeners are other modules of the MATSim framework but can also be any customized programs developed by the user. The event listeners can be of a passive nature and just observe the simulation to produce customized analysis of the simulation results, or of an active nature and change agents (e.g. plans) or the environment. Active observers however, can make changes only before or after any of the five basic steps of the MATSim loop.

3) Data Requirements

In minimum two data files are required to simulate a scenario with MATSim. The first is the network consisting of nodes and links. For the links allowed modes, speeds and performance characteristics (e.g. capacity, free-flow speed) must be defined. Network generators are available as part of the MATSim environment however, which allow the automatic creation of fully functional networks from Open Street Map [21] data [22]. The second required file is a description of the population. For each agent some basic socio-demographic characteristics as well as a basic daily schedule are required before activation of the module. The core then distributes these messages to an arbitrary number of registered observers. These event observers or listeners are other modules of the MATSim framework but can also be any customized programs developed by the user. The event listeners can be of a passive nature and just observe the simulation to produce customized analysis of the simulation results, or of an active nature and change agents (e.g. plans) or the environment. Active observers however, can make changes only before or after any of the five basic steps of the MATSim loop.

4) Extensions

Extensions, which add functionalities to the core, have been developed for MATSim. They are provided by the MATSim community making use of its modular design. They can be added to the simulation by simple activation. Here two of them are described because of their relevance for the simulation of AVs.

The first is an extension that allows the explicit simulation of public transport. Initially developed by Rieser [24] it provides non-agent public transport vehicles that follow public transport schedules and that can be used by normal agents. The simulation of these public transport vehicles however, requires additional data like a schedule file and a public transport vehicle definition file.

The second extension is the so called Within-Day Replanning extension initially developed by Dobler [19]. This extension allows agents to adapt their plans to the current situation in the simulation within the simulation step – something that is normally prohibited so that the system can reach a stable equilibrium. Because of this deviation from the equilibrium, a deep understanding of the problem is required before activation of the module.
5) **Limitations of MATSim**

MATSim has certain limitations which might be relevant for certain research questions on AVs. MATSim does for example simulate travelers and vehicles on a physical level with rather limited level of detail. The imputation of individual preferences to the agents, instead of using the same behavior for all the population, is possible and even advisable, but it is a challenging task and a research topic on its own. Before using MATSim one has to be aware too that MATSim requires more extensive data on the population than for example macro models – especially the creation of initial plans for a full population of agents is not trivial.

C. **Applications of MATSim**

Among many current applications of MATSim two are especially relevant for AVs and will therefore be presented here in more detail: Car sharing because it is expected, for several reasons, that AVs will likely hit the market in this form, and taxi-fleet coordination because large fleets of shared AVs will face similar coordination issues as today’s taxi fleets. A list of all known current applications and developments of MATSim can be found in [25].

1) **Car Sharing**

For several reasons car sharing is the most likely form of organization that researcher assume the supply of AVs will take (see for example [1] or [3]). The study and simulation of car sharing is therefore very interesting for the research on AVs. In MATSim car sharing is studied by Ciari et al. (e.g. [26] or [27]). The research questions they focus on are for example the supply and demand system of car sharing, and how and under what circumstances such a system works. Both questions are highly relevant for AVs should they indeed be supplied via car sharing.

Agent-based models are suited for the research on car sharing because currently car sharing vehicles are still scarce if a full city is considered and it is therefore relevant where a car sharing vehicle is when. An average car over a longer time interval will not satisfy customers. Therefore, as travel is the result of individual needs for activities at different locations, the detailed durations and locations of individual activities need to be represented in the distribution patterns of the car sharing supply. This applies for AVs too, at least until they are so established that they can be assumed to be generally available to any traveler at any time anywhere – an assumption which is often made about normal cars today. Currently in MATSim station-based, free-floating and one-way car sharing can be modelled [26]. Current results [27] suggest that the usage of different pricing schemes not only has an increasing or decreasing effect on the average usage of car sharing, but also structurally affects the interactions of different car sharing offers. The agent-based modelling explicitly allows to observe complex interactions between the spatiotemporal availability of car sharing vehicles and the users’ behavior. The realism of some aspects of car sharing in MATSim is still unclear however, for example the purposes for which people use car sharing and the modal substitution connected to car sharing.

2) **Taxi-Fleet Coordination**

As AVs can be seen as taxis without a human driver, a similar organization as with taxis today can be expected for AVs. If they are centrally controlled and dispatched, as most taxi services today, they respectively their controller will face similar issues. Therefore research on taxis is one more very interesting research field when planning for AVs. Maciejewski et al. (e.g. [28]) is studying taxi services and optimal dispatching strategies with MATSim. As part of this work, he developed a dynamic route optimizer as an extension for MATSim. This optimizer dispatches taxis upon requests by agents following different strategies. As with car sharing the precise time and location of requests and when they are served is crucially for the perceived level of service. Therefore the same argumentation applies to taxis as does for car sharing why agent based models are suited for the research of taxi services. Results from the MATSim studies by Maciejewski [28] suggest that the proportion between supply and demand is crucial for the need for special dispatching strategies. If the supply is sufficiently high, all strategies perform almost equally well and even the simplest satisfy. Only if the demand notably exceeds supply the more sophisticated strategies outperform the simpler ones.

III. **POSSIBLE APPLICATIONS TO AVS**

This part of the paper focuses on the application of MATSim to AVs. It presents how AVs will be simulated in MATSim using so called MATSim-Servants and then presents three current research topics around AVs which can be studied using MATSim. The first example is investigating car fleet size requirements given a system of shared AVs which can be studied using MATSim. The first example is investigating.

A. **MATSim-Servants**

To simulate fully autonomous vehicles MATSim must be able to simulate unmanned cars. A new extension is planned for MATSim to provide this. With this extension so called MATSim-Servants will be introduced, which are able to react to agents’ trip requests. In a car sharing context, the agents order the servant similar to a taxi. The servant then transports the agents and afterwards either goes to a next customer or relocates following redistribution strategies. In a private car context the servant transports the agents on request but afterwards searches for an idle parking lot. Also the servant is available only to a restricted group of agents (e.g. a family). In both contexts servants can also be ordered by the agents to do utilitarian trips from a given position A to a given position B without any passenger. In any case MATSim Servants require to a certain extent a paradigm change in MATSim as they will not have their own plans but...
only serve other agents. Investigations on the equilibrium search and stability of the transport system will be required if a large share of such “planless” servants are present.

B. Examples of Research Topics

The research on AVs is still at a very early stage and therefore the palette of research needs is very large and diverse ([5], [6]). Here three examples of relevant research topics are introduced for which the use of agent-based approaches appears to be particularly beneficial.

1) Car-Fleet Size

The influence of AVs on the future car-fleet size is a research topic that already received some attention. Assuming that AVs will be mostly used as car sharing vehicles, several sources suggest a decrease in the total number of cars (e.g. [1] or [2]). It can be argued however, that the concept of private ownership of cars will survive the arrival of AVs. Reasons are for example that the level of service of car sharing might be too low, especially in the non-urban areas. Also, although the value of cars as status-symbols seems to decline especially among the younger generations, there are nevertheless still many individuals seeing cars not only as a tool but also as a lifestyle object with an emotional value. Finally, also strictly practical aspects, not directly related to mobility, are known to play a role. For example some people point at shared solutions as inconvenient because they could not leave their personal belongings in the car after every trip. If the concept of private car ownership survives the arrival of AVs, the total car fleet size will likely not change notably or even increase. Using MATSim servants, different scenarios will be simulated in MATSim on an agent-based level of detail to investigate the question of the car fleet size under different assumptions. An agent-based model is necessary because, as with taxis, transport requests occur at precise locations at precise times and have to be served within a given time frame. An average number of cars on a link or in an area, as it is produced by transport macro models, cannot deliver that. Micro-models could be an alternative, but to get a plausible insight at the system level, at least full cities including agglomerations must be simulated. In this sense, a compromise approach in terms of physical simulation of vehicles, as the one of MATSim, seems the best option.

2) Demand Patterns

With AVs new demand patterns are expected. The demand is expected to become more evenly distributed and to show less variability (e.g. [29] or [30]). The total demand is expected to increase as several developments connected to AVs induce demand: If car travel will become effortless or even entertaining, more people might want to travel more often and for longer distances. If cars can be used to transport goods or other members of the family without needing a driver, more empty trips just to move the vehicle from one person or job to the next person or job can be expected. If cars can be sent to park themselves, they will travel longer distances to find parking lots, in extreme scenarios they even have only one parking lot per car (for example at home or at the office) and the car returns to this parking lot after each job. All this leads to more demand and to new demand patterns. With these developments however, demand also becomes more individual and more specific. Especially if different individuals coordinate themselves to use a shared car (e.g. a family or community), the use patterns of this car may become very complex. The ability of MATSim to maintain individuals as the fundamental modeling unit over the whole simulation makes it inherently suitable to represent such patterns and therefore to cope with this research question.

3) Public Transport Interaction

AVs can be a blessing and a curse for public transport at the same time. On the one hand, AV’s might be used on the first and last mile of other transport systems, most of all public transport systems [31]. This would facilitate the access to public transport and thus stimulate the usage of public transport systems. On the other hand, allowing travelers to relax and do something else (e.g. reading or working) while safely traveling is one of the aspects that distinguish public transport from private transport. This advantage would disappear if AVs provide this too (for a paper that investigates this aspect see for example [4]). This could lead to drastic changes in the modal split and new challenges for the public transport suppliers. If the capacity of the road network cannot be drastically increased at the same time however, these changes in the modal split will lead to congestion. Agent-based models are well suited to model and study the impacts of such phenomena, as they are driven by rational behavior at the individual level, but have an uncertain impact at the systemic level.

IV. Conclusion

Autonomous vehicles might impact mobility as much as smart phones impacted communication. The first is arriving in society while the latter has already transformed a whole sector. Nokia, once the undisputed leader in the mobile phone market, has been reduced to a marginal role within a few years. A few years into the future and some leading car manufacturers might be essentially out of the car business too. Fundamental changes for the industry and the society are approaching. Preparatory research is needed. Many research questions on AVs require – at least in the beginning of the AV era – the individual modelling of travelers and vehicles. Being at precise pick up locations at precise times is a requirement for AVs and crucial for the level of service they provide. The activity-based multi-agent transport simulation framework of MATSim allows the quantitative investigation of individual AVs at large scale in a realistic environment with individual travelers adapting their mobility behavior dynamically. This makes it suitable for the modeling of AVs.

REFERENCES


